ELECTRONIC MEASUREMENTS AND INSTRUMENTATION

(For the Students of B.E./B.Tech.)

Dr. R.S. SEDHA

S. CHAND

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Preface

The primary focus of the subject **"Electronic Measurements and Instrumentation"** is to develop understanding of various instruments used for measuring, monitoring and recording physical phenomena. The scope of this subject is vast and appears to be growing due to increased use of sensors and automatic control in manufacturing and process control applications. However, the measurement of temperature, pressure, level and flow is common among most of the engineering industries including petrochemical, power plants, Integrated circuit manufacturing and aircraft engines industry.

The "Electronic Instrumentation and Measurements" curriculum in most of the Indian Universities and abroad include topics ranging from Units, Measurements and Standards, Measurement Errors, Transducers for Electrical and Non-electrical quantities, Measurements using Electrical and Electronic Instruments, Measurement of Resistance, Inductance and Capacitance, Oscilloscopes, Signal Generators and Analysers, Instrument Calibration, Graphic Recording Instruments, Display Devices, Signal conditioning, Data Acquisition Systems, Telemetry, Biomedical Instruments and Virtual Instruments.

In this book, I have included all the basic material required at the undergraduate level for the engineering students.

To help students for preparing and doing well in the examination, I have included "Examination questions" from several Indian Universities until Dec 2012, as solved examples. The sections on "Descriptive Questions" and "Multiple Choice Questions" are also there to include the theory type examination questions and objective questions respectively.

I wish to express my sincere thanks to my friends and colleagues in various technical universities and engineering colleges for their valuable feedback in preparing this book.

Any errors, omissions and suggestions for the improvement of this book brought to my notice will be thankfully acknowledged and incorporated in the next edition.

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Chapter 1

Units, Dimensions and Standards

Outline

Objectives

After completing this chapter, you should be able to:

- Understand the meaning of unit.
- Know the difference between the fundamental and derived unit.
- Know the SI units for various physical quantities.
- List the advantages and disadvantages of S.I units.

1.1 Introduction

There are several types of quantities in the field of engineering which need to be measured or expressed in day-to-day work. This includes physical, chemical, mechanical quantities etc. In order to record or to compare magnitude of quantities some magnitude of each kind must be taken as basis or unit. To measure or to define any quantity we need a well-defined unit. There are fundamental and supplementary fundamental units. These units are used to define all quantities. Many systems like SI (International System of Units), CGS (Centimetre-gram-second System), MKS (Metre-kilogram-second) etc. are developed to define the physical quantity.

1.2 Unit

The standard measurement of any physical quantity is known as Unit. The number of times the unit occurs in any given amount of the same quantity is the number of measure. For example 100 metres, we know that the metre is the unit of length and that the number of units of length is one hundred. The physical quantity, length, is therefore defined by the unit metre.

1.3 Fundamental and Derived Units

The units which are independent and are not related to each other are known as ***Fundamental Unit***. These units do not vary with time, temperature and pressure etc. There are seven fundamental units, as given below:

Fundamental Units: *length, mass, time, electric current, temperature, luminous intensity and quantity of matter.*

The units which are derived from fundamental units or which can be expressed in terms of the fundamental units are called ***Derived Unit***. Every derived unit originates from some physical law defining that unit. This unit is recognized by its dimensions, which can be defined as the complete algebraic formula for the derived unit. Like area, volume, velocity etc. For example, the area of rectangle is proportional to its length (l) and breadth (b) or $A = l \times b$. If the metre has been chosen as the unit of length, then the unit of area is m^2. The derived unit for area (A) is then the square metre (m^2).

For convenience, some derived units have been given new names. For example, the derived unit of force in the S.I. system is called the Newton (N), instead of the dimensionally correct name kg- m/s^2.

1.4 International System of Units

The International System of Units (abbreviated S.I. from the French *Système international d'unités*) is the modern form of the metric system and is generally a system of units of measurement devised around seven base units and the convenience of the number ten. It is the world's most widely used system of measurement, both in everyday commerce and in science.

Table 1.1 Definitions of Standard Units

Physical Quantity	***Standard Unit***	***Definition***
Length	metre	The length of path travelled by light in an interval of 1/299 792 458 seconds
Mass	kilogram	The mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, S`evres, Paris
Time	second	9.192631770×10^9 cycles of radiation from vaporized caesium-133 (an accuracy of 1 in 10^{12} or 1 second in 36000 years)
Temperature	kelvin	The temperature difference between absolute zero and the triple point of water is defined as 273.16 kelvin
Current	ampere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross-section placed 1 metre apart in a vacuum and producing a force of 2×10^{-7} Newtons per metre length of conductor
Luminous intensity	candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz ($\times 10^{12}$ Hz) and with a radiant density in that direction of 1.4641 mW/steradian. (1 steradian is the solid angle which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	mole	The number of atoms in a 0.012 kg mass of carbon-12

The system has been nearly globally adopted. Three countries which have not adapted are Burma (Myanmar), Liberia, and the United States.

The International System (or S.I. system) of Units consists of a set of units together with a set of prefixes. The units of S.I. can be divided into two subsets. There are seven base units: Every base unit represents different kinds of physical quantities. From these seven base units, several other units are derived. In addition to the S.I. units, there is also a set of non-S.I. units accepted for use with SI which includes some commonly used units such as the litre. Table 1.1 shows the standard units and definition.

The S.I. system is divided into three classes: Fundamental Unit shown in Table 1.2, Supplementary Unit shown in Table 1.3 and Derived Unit shown in Table 1.4.

Table 1.2 S.I. Fundamental Units

Quantity	*Standard Unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature	Kelvin	K
Luminous intensity	candela	cd
Matter	mole	mol

There are two supplementary units which are added to the S.I. system of units.

Radian for the plane angles: The plane angles subtended by an arc of a circle equal in length to the radius of the circle. It is denoted as rad.

The solid angle subtended at the centre of a sphere by the surface whose area is equal to the square of the radius of the sphere. It is denoted as sr.

Supplementary units are neither base units nor derived from base units. It is given in Table 1.3 below:

Table 1.3 Supplementary Fundamental Units

Quantity	*Standard unit*	*Symbol*
Plane angle	radian	rad
Solid angle	steradian	sr

The number of quantities in science is without limit, and it is not possible to provide a complete list of derived units. However, Table 1.4 shows some examples of derived unit:

Table 1.4 S.I. Derived Units

Quantity	*Standard Unit*	*Unit Standard*
Area square	metre	m^2
Volume cubic	metre	m^3
Velocity	metre per second	m/s
Acceleration	metre per second squared	m/s^2
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s^2
Density	kilogram per cubic metre	kg/m^3

Specific volume	cubic metre per kilogram	m^3/kg
Mass flow rate	kilogram per second	kg/s
Volume flow rate	cubic metre per second	m^3/s
Force	Newton	N
Pressure	Newton per square metre	N/m^2
Torque	Newton metre	Nm
Momentum	kilogram metre per second	kgm/s
Moment of inertia	kilogram metre squared	kgm^2
Kinematic viscosity	square metre per second	m^2/s
Dynamic viscosity	Newton second per square metre	Ns/m^2
Work, energy, heat	joule	J
Specific energy	joule per cubic metre	J/m^3
Power	watt	W
Thermal conductivity	watt per metre Kelvin	W/mK
Electric charge	coulomb	C
Voltage, e.m.f., pot. diff.	volt	V
Electric field strength	volt per metre	V/m
Electric resistance	ohm	Ω
Electric capacitance	farad	F
Electric inductance	Henry	H
Electric conductance	siemen	S
Resistivity	ohm metre	Ωm
Permittivity	farad per metre	F/m
Permeability	Henry per metre	H/m
Current density	ampere per square metre	A/m^2
Magnetic flux	Weber	Wb
Magnetic flux density	tesla	T
Magnetic field strength	ampere per metre	A/m
Frequency	hertz	Hz
Luminous flux	lumen	lm
Luminance	candela per square metre	cd/m^2
Illumination	lux	lx
Molar volume	cubic metre per mole	m^3/mol
Molarity	mole per kilogram	mol/kg
Molar energy	joule per mole	J/mol

1.5 Advantages of S.I. Units

Although there are several advantages of S.I. units yet the following are important from the subject point of view:

1. S.I. unit measurement is a coherent system of units, *i.e.*, a system based on a certain set of fundamental units, from which all derived units are obtained by multiplication or division without introducing numerical factors.

2. S.I. unit measurement is a rational system of units, as it assigns only one unit to a particular quantity. For example, joule is the unit assign to all types of energies. This is not so in other system of units. For example, in MKS system of units, mechanical energy is in joules, heat energy is in calories and electrical energy is in Kilowatt hour.
3. S.I. unit measurement system is an absolute system of units. There are no gravitational systems of units in this system. Thus the use of factor '*g*' is eliminated.
4. S.I. unit measurement system is a metric system, *i.e.*, the multiples and the submultiples of units are expressed as the exponents of 10.
5. In the current electricity, the absolute unit of electrical quantities like ampere (A) for electric current, volt (V) for potential difference, ohm (Ω) for resistance, Henry (H) for inductance, farad (f) for capacitance and so on, happens to be the practical units of these quantities.

The S.I. system of units applies to all branches of science, but the MKS system of units is confined to mechanics only.

1.6 Disadvantages of S.I. Units

Following are some of the disadvantages of S.I units:

1. The non S.I. "time units" minute and hour will still continue to be used until the clocks and watches are all changed to kilo seconds and mega second etc.
2. The base unit kilogram (kg) includes a prefix, which creates an ambiguity in the use of multipliers with gram.

1.7 Prefixes and Suffixes

It is often convenient to use units which are a multiple or fraction of the basic unit. The metric system, formally known as the International System of Units, defines a number of prefixes to denote powers of ten. The current official set is tabulated here: Prefixes used by the International System of Units (S.I.)

Prefixes used by the International System of Units (S.I.) are shown in Table 1.5.

Table 1.5

Prefix	*Factor*	*Symbol*
Exa	10^{18}	E
Peta	10^{15}	P
Tera	10^{12}	T
Giga	10^{9}	G
Mega	10^{6}	M
kilo	10^{3}	k
Hector	10^{2}	h
Deca	10	da
Deci	10^{-1}	d
Centi	10^{-2}	c
Milli	10^{-3}	m
Micro	10^{-6}	μ
Nano	10^{-9}	n
Pico	10^{-12}	p
Femto	10^{-15}	f
Atto	10^{-18}	a

1.8 S.I. Electrical Units

Table 1.6 below shows the S.I Units for electrical quantities.

Table 1.6

Physical Quantity	*Quantity symbol*	*SI Unit*	*Unit Symbol*	*Expression in SI base units*	*Alternative expressions*
frequency	v, f	hertz	Hz	s^{-1}	-
force	F	newton	N	$kg\ m\ s^{-2}$	$J\ m^{-1}$
pressure	p	pascal	Pa	$kg\ m^{-1}\ s^{-2}$	$N\ m^{-2}$
energy (all forms)	E, U, V, W etc.	joule	J	$kg\ m^2\ s^{-2}$	Nm = C V = V A s
power	P	watt	W	$kg\ m^2\ s^{-3}$	$J\ s^{-1}$ = VA
electric charge	Q	coulomb	C	A s	-
electric potential difference	$E, \varphi, \zeta, \Phi, \eta$ etc.	volt	V	$kg\ m^2\ s^{-3}\ A^{-1}$	$J\ A^{-1}\ s^{-1} = J\ C^{-1}$
electrical capacitance	C	farad	F	$A^2\ s^4\ kg^{-1}\ m^{-2}$	$C\ V^{-1}$
electrical resistance	R	ohm	Ω	$kg\ m^2\ s^{-3}\ A^{-2}$	$V\ A^{-1}$
electrical conductance	G	siemens	S	$A^2\ s^3\ kg^{-1}\ m^{-2}$	$A\ V^{-1} = \Omega^{-1}$
magnetic flux	Φ	weber	Wb	$kg\ m^2\ s^{-2}\ A^{-1}$	$V\ s = T\ m^2$
magnetic induction	B	tesla	T	$kg\ s^{-2}\ A^{-1}$	$Wb\ m^{-2} = N\ A^{-1}\ m^{-1}$
inductance	L, M	henry	H	$kg\ m^2\ s^{-2}\ A^{-2}$	$V\ A^{-1}\ s = Wb\ A^{-1}$
luminous flux	Φ	lumen	lm	cd sr	-
illumination	E	lux	lx	$cd\ sr\ m^{-2}$	$lm\ m^{-2}$
Celsius temperature	t	degree Celsius	°C	K	-
plane angle	$\alpha, \beta, \gamma, \theta, \Phi$	radian	rad	mm^{-1}	dimensionless
solid angle	ω, Ω	steradian	sr	$m^2\ m^{-2}$	dimensionless

1.9 S.I. Unit for Temperature

The S.I. unit for temperature is the Kelvin (K). Temperature can be expressed using three different scales: Fahrenheit, Celsius, and Kelvin. Although 0 K is much colder than 0°C, a change of 1° K is equal to a change of 1°C. Three temperature scales are shown in Fig. 1.1.

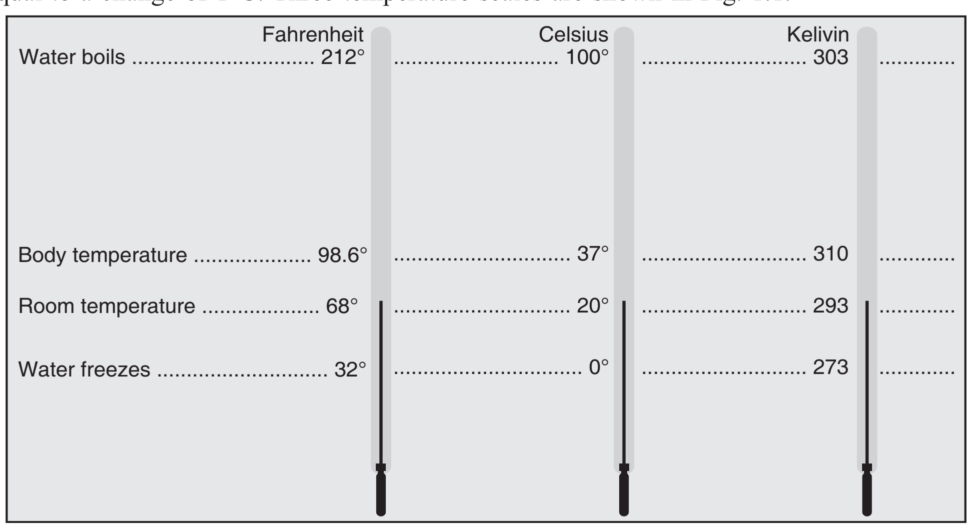


Fig. 1.1.

Table 1.7 shows the conversion of temperature from degree Celsius to Farenheit or Kelvin and vice versa. Go through the examples for more clarity.

Table 1.7

To convert	*Use this equation*	*Example*
Celsius to Fahrenheit °C → °F	$°F = \left(\frac{9}{5} \times °C\right) + 32$	Convert 45°C to °F. $°F = \left(\frac{9}{5} \times 45°C\right)$
Fahrenheit to Celsius °F → °C	$°C = \frac{5}{9} \times (°F - 32)$	Convert 68°F to °C $°C = \frac{5}{9} \times (68°F - 32) = 20°C$
Celsius to Kelvin °C → K	K = °C + 273	Convert 45°C to K. K = 45°C + 273 = 318 K
Kelvin to Celsius K → °C	°C = K – 273	Convert 32 K to °C. °C = 32 K – 273 = –241 °C

1.10 Other Unit Systems

There are various unit systems that have been derived in the past and were used in different parts of the world. These systems are given below:

Systems of Mechanical Units

There are four general systems of mechanical units used in engineering. All these systems are given below:

(*a*) **FPS System.** In FPS system the units of fundamental quantities, length, mass and time are foot, pound and second respectively.

(*b*) **English System.** The English system of units uses the foot (ft), the pound-mass (lb), and the second (s) as the three fundamental units of length, mass and time respectively. For example the unit of density will be expressed in lb/ft^3 and unit of acceleration in ft/s^2.

(*c*) **CGS System.** In CGS system the units of fundamental quantities, length, mass and time are centimetre, gram and second respectively.

(*d*) **MKS System.** In MKS system the units of fundamental quantities, length, mass and time are metre, kilogram and second respectively.

Systems of Electrical Units

The three basic concepts and three fundamental units are sufficient for description and measurement in mechanical science, experience shows that, in electrical science, four concepts or dimensions and four arbitrarily defined fundamental units are necessary to obtain a complete system of dimensions and units. At least one of these four units must be electrical in character. The various electrical unit systems used are:

(*a*) **The CGS Electrostatic System of Units (CGS ESU).** It is an absolute system based on the centimetre, gram and second as the fundamental mechanical units and permittivity (ε) of medium as fourth fundamental unit. The unit of permittivity is of such a size that the measured number of permittivity for free space is unity.

(*b*) **The CGS Electromagnetic System of Units (CGS EMU).** It is another absolute system based on the centimetre, gram and second as the fundamental mechanical units and permeability (μ) of medium as fourth fundamental unit. The unit of permeability is of such a size that the measured number of permeability for free space is unity.

(*c*) **The MKS System of Units.** It is an absolute system based on the metre, kilogram and second as the fundamental mechanical units and permeability (μ) of medium as fourth fundamental unit. The unit of permeability is of such a size that the measured number of permeability for free space is 10^{-7}.

1.11 Dimensions

The unique quality of every quantity which distinguishes it from all other quantities is called dimension.In mechanics the three fundamental units are length, mass and time. Their dimensional symbols are:

Length = [L], Mass = [M], Time = [T]

There are some more units which are, charge, temperature and current.

Charge = [Q], Temperature = [K], Current = [I]

The square brackets indicate the dimensional notation only.The system of unit employs, mass,length, time and charge as four fundamental concepts. The system of unit employing mass, length, time and current as four fundamental concepts is termed as S.I. system. The dimension of various electrical and magnetic quantities can be derived from the known relationship between them. Some are given below:

1. Current = [I]

2. Charge

Charge is the quantity of electricity = Current × Time

$$[Q] = [IT]$$

3. Potential Difference

Potential Difference = (Work done)/(Quantity of electricity)

$$[V] = \frac{[E]}{[Q]} = \frac{[M\,L^2\,T^{-2}]}{[IT]} = [M\,L^2\,T^{-3}\,I^{-1}]$$

4. Resistance

$$\text{Resistance} = \frac{\text{Potential Difference}}{\text{Current}}$$

$$[R] = \frac{[V]}{[I]} = \frac{[M\,L^2\,T^{-3}\,I^{-1}]}{[I]} = [M\,L^2\,T^{-3}\,I^{-2}]$$

The various powers of the fundamental units represent the dimensions of any derived unit. For example the dimension symbols for the derived unit of speed is LT^{-1} and that for acceleration is LT^{-2}. All other mechanical quantities are expressed in terms of three fundamental quantities *i.e.* length, mass and time.

1.12 Standards

A standard of measurement is a physical representation of a unit of measurement. A unit is realized by reference to an arbitrary material standard or to natural phenomena including physical and atomic constants. For example, the fundamental unit of mass in the international system (SI) is the kilogram, defined as the mass of a cubic decimetre of water as its temperature of maximum density of 400°C.

1.13 Classification of Standards

The standards are classified according to their function and application in following type:

1. International Standards

2. Primary Standards

3. Secondary Standards
4. Working Standards

1.14 International Standards

The international standards are defined by international agreement. They represent certain units of measurement to the closest possible accuracy that production and measurement technology allow. These standards are periodically checked by absolute measurements in terms of the fundamental units. These standards are maintained at international bureau of weights and measure and are not available to the ordinary users for measurements.

International ohm: It is defined as the resistance offered by a column of mercury having a mass of 14.4521 grams, uniform cross-section areas length of 106.300 cm, to the flow of constant current at the melting point of ice.

International ampere: It is an unvarying current, which when passed through a solution of silver nitrate in water deposits silver at the rate 0.00111800 grams/sec (g/s).

1.15 Primary Standards

The primary (basic) standards are maintained by national standards laboratories in different parts of the world. A primary standard is a standard that is accurate enough that it is not calibrated by or subordinate to other standards. The main function of the primary standards is the calibration and verification of secondary standards. These standards are not available for use outside the national laboratories.

1.16 Secondary Standards

Secondary standards are the basic reference standards used in industrial measurement laboratories. These standards are maintained by the particular involved industry and are checked locally against other reference standards in area. Secondary standards are generally sent to the international standards laboratories on a periodic basis for calibration and comparison against the primary standards. They are then returned to the industrial user with certification of their measured value in terms of the primary standard.

1.17 Working Standards

Working standards are the principle tools of a measurement laboratory. They are used to check laboratory instruments for accuracy and performance. These standards are used to perform comparison measurements in industrial application. For example, manufacturers of components such as capacitors, resistors etc. use a standard called a working standard for checking the component values being manufactured, e.g. a standard capacitor for checking of capacitance value manufactured.

SUMMARY

In this chapter you have learned that:

1. The standard measurement of each kind of physical quantity is known as Unit.
2. The units which are independent and are not related to each other are known as fundamental units.
3. The international system of units consists of a set of units together with a set of prefixes.
4. The unique quality of every quantity which distinguishes it from all other quantities is called dimension.
5. A standard of measurement is a physical representation of a unit of measurement.
6. The international standards are defined by international agreement.

7. The main function of the primary standards is the calibration and verification of secondary standards.
8. Secondary standards are maintained by the particular involved industry and are checked locally against other reference standards in area.
9. Working standards are used to check and laboratory instruments for accuracy and performance.

GLOSSARY

Derived units: The units which are derived from fundamental units or which can be expressed in terms of the fundamental units are called derived units.

Dimension: The unique quality of every quantity which distinguishes it from all other quantities is called dimension.

Fundamental Unit: The units which are independent and are not related to each other are known as fundamental units.

International System: The international system of units consists of a set of units together with a set of prefixes.

Primary Standards: The primary (basic) standards are maintained by national standards laboratories in different parts of the world.

Secondary standards: Secondary standards are the basic reference standards used in industrial measurement laboratories.

Standard: A standard of measurement is a physical representation of a unit of measurement.

Unit: The standard measurement of each kind of physical quantity is known as Unit.

DESCRIPTIVE QUESTIONS

1. What is a unit? Explain briefly.
2. What are the different types of the units?
3. What is a Derived unit?
4. What are the Fundamental units?
5. Which types of the units are mostly used in the field of engineering?
6. What are the Standards?
7. Describe the Classification of different Standards?
8. What is the difference between the unit and standard?
9. Explain the Difference between the Primary and Secondary Standard.
10. Explain the Difference between the Fundamental and Derived Unit.

MULTIPLE CHOICE QUESTIONS

1. The unit of quantity of electricity is
   (*a*) volt (*b*) coulomb (*c*) ohm (*d*) joule
2. Electromotive force is provided by
   (*a*) resistance (*b*) a conducting path
   (*c*) an electric current (*d*) an electrical supply source
3. The coulomb is a unit of
   (*a*) power (*b*) voltage
   (*c*) energy (*d*) quantity of electricity

4. In order that work may be done

(*a*) a supply of energy is required
(*b*) the circuit must have a switch
(*c*) coal must be burnt
(*d*) two wires are necessary

5. The ohm is a unit of

(*a*) charge
(*b*) resistance
(*c*) power
(*d*) current

6. The unit of current is the

(*a*) volt
(*b*) coulomb
(*c*) joule
(*d*) ampere

7. Value of Femto is

(*a*) 10^{-9}
(*b*) 10^{-12}
(*c*) 10^{-15}
(*d*) 10^{-18}

ANSWERS

1. (*b*) **2.** (*c*) **3.** (*d*) **4.** (*a*) **5.** (*b*) **6.** (*d*)
7. (*c*)

Chapter 2

Measurement Errors

Outline

Objectives

After completing this chapter, you should be able to:

- Understand the concept of an error in the instruments.
- Explain the different types of errors.
- Understand the difference between accuracy and precision.
- Explain the significant figure and resolution.
- Describe the statistical analysis of errors.
- Understand the arithmetic mean, deviation mean, average deviation, standard deviation and variance

2.1 Introduction

An instrument is a device for determining the value or magnitude of a quantity or variable. As technology expands the demand for more accurate instruments increase and produces new developments in instrument design and application. On the other hand, measurement is a process by which one can convert physical parameters to meaningful number.

This chapter provides an introduction to different types of error in measurement and to the methods generally used to express errors, in term of the most reliable value of the measured variable.

2.2 Methods of Measurements

The methods of measurements may be classified according to following types:

1. Direct Methods. In the direct method of measurement, we compare the unknown quantity directly with the primary or secondary standard. For example if we want to measure the length of the bar, we will measure it with the help of the standard measuring tape or scale that acts as the secondary standard. Here we compare the unknown quantity directly with the standard scale. The scale is expressed as a numerical number and a unit.

The direct comparison method of measurement is not always accurate. In above example of measuring the length, there is limited accuracy with which our eye can read the readings, which can be about 0.01 inch. Here the error does not occur because of the error in the standards, but because of the human limitations in taking the readings.

2. Indirect Methods. There are number of quantities that cannot be measured directly by using some instrument. For instance we cannot measure the strain in the bar due to applied force directly. In such cases indirect methods of measurements are used.

In this method the unknown quantity to be measured is converted into some other measurable quantity. Then we measure the measureable quantity. For example the strain can be measured in terms of the electrical resistance of the bar.

2.3 Classification of Instruments

The instruments may be classified according to the following types:

1. Electrical and Electronic Instruments. The measuring instrument that uses mechanical movement of electromagnetic meter to measure voltage, current, power, etc. is called electrical measuring instrument. These instruments use the d'Arsonval meter. While any measurement system that uses d'Arsonval meter with amplifiers to increase the sensitivity of measurements is called electronic instrument.

2. Analogue and Digital Instruments. An analogue instrument is the instrument that uses analogue signal to display the magnitude of quantity under measurement. The digital instrument uses digital signal to indicate the results of measurement in digital form.

3. Absolute and Secondary Instruments. In absolute instrument the measured value is given in term of instrument constants and the deflection of one part of the instrument *e.g.* tangent galvanometer. In these instruments no calibrated scale is necessary. While in secondary instruments, the quantity of the measured values is obtained by observing the output indicated by these instruments.

2.4 Classification of Secondary Instruments

The secondary instrument may be classified into the following categories:

1. Indicating Instruments. The magnitude of quantity being measured is obtained by deflection of the pointer on scale, and the output is indicated either in analogue or digital form like ammeter, voltmeter, and wattmeter. Three forces were acting on the pointer to deflect it in proportional to the quantity being measured, these forces are of the following types:

(*a*) **Deflecting Force.** This force gives the pointer the initial force to move it from zero position, it's also called deflecting force.

(*b*) **Controlling Force.** This force control and limits the deflection of the pointer on scale which must be proportional to the measured value, and also ensure that the deflection is always the same for the same values.

(*c*) **Damping Force.** This force is necessary to bring the pointer quickly to the measured value, and then stop without any oscillation.

2. Recording Instruments. An instrument which makes a record in any recorded medium of the quantity being measured in order to save information and use it in another time. The instruments like recording devices, X-Y plotter, and oscilloscope and recording instruments.

3. Controlling Instruments. These instruments give information to control the original measured quantity or control the other devices, like a computer.

2.5 Characteristics of Measurement Systems

The characteristics of measurement systems are classified in to the following two types:

1. Static Characteristics
2. Dynamic Characteristics

Both characteristics of measurements systems are discussed one by one in the following pages.

2.6 Static Characteristics

The static characteristic of a measurement instrument is the characteristics of the system when the input is either held constant or varying very slowly. The static characteristics are of the following types:

1. **Sensitivity.** The sensitivity of measurement is a measure of the change in instrument output that occurs when the quantity being measured changes by a given amount
2. **Linearity.** It is normally desired that the output reading of the instrument is linearly proportional to the quantity being measured. An instrument is considered linear if the relationship between output and input can be fitted in a line if it is not a straight line it should not be concluded that the instrument is inaccurate, it is a misconception.
3. **Reproducibility.** In the measurement, the given value may be repeated or measured assuming that environmental conditions are same for each measurement. We say that the measuring instruments have a certain amount of inherent uncertainty in their ability to reproduce the same output reading after some time.
4. **Range and Span.** It defines the maximum and minimum values of the inputs or the outputs for which the instrument is recommended to use. For example, for a temperature measuring instrument the input range may be 100-500°C and the output range may be 4-20 mA. Span is algebraic difference of the upper and lower limits of the range.
5. **Static Error.** This error shows the deviation of the true value from the desired value.
6. **Loading Effects.** It's the change of circuit parameter, characteristic, or behaviour due to instrument operation.
7. **Accuracy and Precision.** Refer to Art 2-7 for details about accuracy and precision.
8. **Resolution.** Refer to Art 2-10 for details on resolution.

2.7 Accuracy and Precision

Accuracy is a closeness with which the instrument reading approaches the true value of the variable under measurement. Accuracy is the degree to which instrument reading match the true or accepted values. It indicates the ability of instrument to indicate the true value of the quantity.

Accuracy refers to how closely the measured value of a quantity corresponds to its "true" value.

Precision is a measure of the reproducibility of the measurement *i.e.*, its measure of the degree to which successive measurements differ from one other. It is the degree of agreement within a group of measurements or instruments. For example if any resistance has true value 3.385,695 Ω, it always read 3.4 MΩ in scale reading.

Let us consider two voltmeters of the same model, both meters have knife-edged pointers and mirror-backed scales to avoid parallax, and they have calibrated scales. They may therefore be read to the same precision. If the value of the resistance in one meter changes considerably, its reading may be in error by a fairy large amount. Therefore the accuracy of the two meters may be quite different.

The precision is composed of two characteristics

1. Conformity
2. Significant Figures

Both conformity and significant figures are discussed one by one in the following pages.

2.8 Conformity

Consider, for example that a resistor, whose true resistance is 3,385,695 Ω is measured by an ohmmeter. This consistently and repeatedly indicates 3.4 MΩ. The observer cannot read the true value from the scale. He estimates from the scale reading consistently a value of 3.4 MΩ. This is as close to the true value as he can read the scale by estimation. Although there are no deviations from the observed value, the error created by the lamination of the scale reading is a precision error. The conformity is necessary in measurements.

2.9 Significant Figures

An indication of the precision of the measurement is obtained from the number of significant figures in which the result is expressed. Significant figures convey actual information regarding the magnitude and the measurement precision of a quantity.

For example, if a resistor is specified as having a resistance of 65 Ω, its resistance value should be closer to 65 Ω than to 64 Ω or 66 Ω. If the value of resistor is described as 65.0 Ω, it means that its resistance is close to 65.0 Ω than it is to 64.9 Ω or 65.1 Ω. In 65 Ω there are two significant figures 6 and 5, while in 65.0 Ω there are three significant figures 6, 5 and 0.

Example 2.3. *Three resistors have values 72.3, 2.73 and 0.612 Ω respectively with uncertainty of one unit in the last figure in each case. Find the sum of three resistors connected in series.*

Solution. Given: $R_1 = 72.3\ \Omega$, $R_2 = 2.73\ \Omega$ and $R_3 = 0.612\ \Omega$.

We know that the resistors are in series,

$$R_S = R_1 + R_2 + R_3$$
$$= 72.3 + 2.73 + 0.612 = 75.642\ \Omega$$

The result cannot be expressed as 75.642 Ω as even the figure in the tenth place *i.e.* 6 is in doubt. Therefore the resultant resistance is 75.6 Ω with 6 as first doubtful figures. **Ans.**

2.10 Resolution

Resolution is the smallest amount of input signal change that the instrument can detect reliably. If the input is slowly increased from some arbitrary input value, it will again be found that output does not change at all until a certain increment is exceeded. This increment is called resolution or discrimination of the instrument. Thus the smallest increment in input which can be detected with certainty by an instrument is its resolution or discrimination.

Example 2.4. *A digital voltmeter has a read-out reading from 0 to 9,999 counts. Determine the resolution of the instrument in volt when the full scale reading is 9.999 V.*

Solution.

The resolution of this instrument is 1 or 1 count in 9,999.

$$\text{Resolution} = \frac{1}{9999}\ \text{count} = \frac{1}{9999} \times 9.999\ \text{volt}$$
$$= 10^{-3}\ \text{V} = 1\ \text{mV}\ \textbf{Ans.}$$

2.11 Dynamic Characteristics

The dynamic characteristics of a measurement instrument describe the behavior of the instrument when the desired input is not constant but varies rapidly with the time. Following are the main types of dynamic characteristics:

1. Speed of Response. It is defined as a rapidity with which a measurement system responds to a change in measured quantity. It gives information about how fast the system reacts to the changes in the input.

2. Measuring lag. Every instrument takes some time to respond to the change in the measured variable. This retardation or delay in the response of the instrument is called measuring lag. The measuring lag is of the following two types:

(*a*) **Retardation Lag.** The response of measurement system begins immediately after a change in measured quantity has occurred.

(*b*) **Time Delay Lag.** The measurement lags of this type are very small and are of the order of a fraction of a second and hence can be ignored. In this case, response begins after the application of input and is called after "dead time". Such a delay shifts the response along time axis and hence causes the dynamic error.

The largest change of input quantity for which there is no change in the measured quantity is known as dead zone.

3. Fidelity. It is the ability of an instrument to produce a wave shape identical to wave shape of input with respect to time. It also shows the change in quantity without dynamic error.

4. Dynamic Error. It is the difference between the true value changing with time & value indicated by measuring system without static errors.

2.12 Measurement Error

No measurement can be made with perfection and accuracy, but it is important to find out what the accuracy actually is and how different errors have entered into the measurement. Error occurs due to several sources like human carelessness in taking reading, calculating and in using instrument etc. Some of the time error is due to instrument and environment effects.

Errors come from different sources and are classified in three types:

1. Gross Error
2. Systematic Errors
3. Random Errors

2.13 Gross Error

The gross error occurs due to the human mistakes in reading or using the instruments. These errors cover human mistakes like in reading, calculating and recordings etc. It sometimes occurs due to incorrect adjustments of instruments.

The complete elimination of gross errors is impossible, but we can minimize them by the following ways:

1. It can be avoided by taking care while reading and recording the measurement data.
2. Taking more than one reading of same quantity. At least three or more reading must be taken by different persons.

2.14 Systematic Errors

A systematic error is divided in three different categories: instrumental errors, environmental errors and observational errors.

1. Instrumental Errors

The instrument error generate due to instrument itself. It is due to the inherent shortcomings in the instruments, misuse of the instruments, loading effects of instruments. For example in the D' Arsonval movement friction in bearings of various moving components may cause incorrect readings. There are so many kinds of instrument errors, depending on the type of instrument used.

Instrumental errors may be avoided by

(*a*) Selecting a suitable instrument for the particular measurement application

(*b*) Applying correction factors after determining the amount of instrumental error

(*c*) Calibrating the instruments against a standard.

2. Environmental Errors

Environmental errors arise as a result of environmental effects on instrument. It includes conditions in the area surrounding the instrument, such as the effects of changes in temperature, humidity, barometric pressure or of magnetic or electrostatic fields.

For example when making measurements with a steel rule, the temperature when the measurement is made might not be the same as that for which the rule was calibrated.

Environmental errors may be avoided by

(*a*) Using the proper correction factor and information supplied by the manufacturer of the instrument.

(*b*) Using the arrangement which will keep the surrounding condition constant like use of air condition, temperature controlled enclosures etc.

(*c*) Making the new calibration under the local conditions.

3. Observational Errors

These errors occur due to carelessness of operators while taking the reading. There are many sources of observational errors such as parallax error while reading a meter, wrong scale selection, the habits of individual observers etc.

To eliminate such observational errors, one should use the instruments with mirrors, knife edged pointers, etc. Now a day's digital display instruments are available, which are much more versatile.

2.15 Random Errors

These errors are due to unknown causes and occur even when all systematic errors have been accounted for. In some experiments some random errors usually occur, but they become important in high-accuracy work.

These errors are due to friction in instrument movement, parallax errors between pointer and scale, mechanical vibrations, hysteresis in elastic members etc.

When we measure a volume or weight, you observe a reading on a scale of some kind. Scales by their very nature are limited to fixed increments of value, indicated by the division marks. The actual quantities we are measuring, in contrast, can vary continuously. So there is an inherent limitation in how finally we can discriminate between two values that fall between the marked divisions of the measuring scale. The same problem remains if we substitute an instrument with a digital display. There will always be some point at which some value that lies between smallest divisions must arbitrarily toggle between two numbers on the readout display. This introduces an element of randomness into the value we observe, even if the true value remains unchanged.

These errors are of variable magnitude and sign and do not obey any known law. The presences of random errors become evident when different results are obtained on repeated measurements of one and the same quantity.

2.16 Absolute Error

Measurement is the process of comparing an unknown quantity with an accepted standard quantity. Absolute error may be defined as the difference between the measured value of the variable and the true value of the variable.

$$\delta A = A_m - A$$

where

δA = absolute error

A_m = expected value

A = measured value

2.17 Relative Error

The relative error is the ratio of absolute error to the true value of the quantity to be measured. Mathematically, the relative error can be expresses as,

$$\text{Relative error } \varepsilon_r = \frac{\text{Absolute error}}{\text{true value}} = \frac{\delta A}{A}$$

when absolute error is negligible $\delta A = \varepsilon_o$, then A_m = A

$$\text{Relative limiting error } \varepsilon_r = \varepsilon_o / A_m = \delta A / A_m$$

$$\text{Percentage error} = \varepsilon_r \times 100 = \varepsilon_o / A_m \times 100$$

It may be carefully noted that relative error is the ratio of absolute error and original value, where absolute error is the difference between original value and approximated value

$$\% \text{ Error} = \frac{\text{Absolute value}}{\text{Expected value}} \times 100$$

$$= \frac{\delta A}{A_m} \times 100 = \frac{A_m - A}{A_m} \times 100$$

The relative accuracy,

$$\text{Relative Accuracy} = 1 - \left| \frac{A_m - A}{A_m} \right|$$

Example 2.1. *A voltage has a true value of 1.50 V. An analog indicating instrument with a scale range of 0-2.50 V shows a voltage of 1.46 V. What is the value of absolute error?*

Solution. Given: A_m = 1.46 and A = 1.50.

We know that the absolute error,

$$\delta A = 1.46 - 1.50 = -0.04 \text{ V} \textbf{ Ans.}$$

Example 2.2. *The expected value of the voltage across a resistor is 80 V. However, the measurement gives a value of 79 V. Calculate (i) absolute error, (ii) % error, (iii) relative accuracy, and (iv)% of accuracy.*

Solution. Given: A_m = 80 and A=79.

(*i*) Absolute Error

We know that the absolute error is given by,

$$\delta A = A_m - A = 80 - 79 = 1 \text{ V} \textbf{ Ans.}$$

(*ii*) % Error

We know that the percentage error,

$$\% \text{ Error} = \frac{\delta A}{A_m} \times 100 = \frac{A_m - A}{A_n} \times 100$$

$$= \frac{80 - 79}{100} \times 100 = 1.25 \ \% \ \textbf{Ans.}$$

(*iii*) Relative accuracy

We know that the relative accuracy,

$$\text{Relative Accuracy} = 1 - \left| \frac{A_m - A}{A_m} \right|$$

$$= 1 - \left| \frac{80 - 79}{80} \right| = 0.9875 \ \textbf{Ans.}$$

(*iv*) % of accuracy

We know that % accuracy,

$$a = \text{Relative Accuracy} \times 100$$

$$= 0.9875 \times 100 = 98.75 \ \% \ \textbf{Ans.}$$

Alternatively percentage accuracy by following method also

$$a = 100 \ \% - \% \text{ error}$$

$$= 100 \ \% - 1.25 \ \% = 98.75 \ \% \ \textbf{Ans.}$$

2.18 Concept Map

The different types of error in the measurement system are shown in a concept map in the Fig. 2.1. As seen from the map, it describes how the numerical results of measurements differ from pure numbers, uncertainty that arise from systematic and random errors. It also show what causes systematic error and random error and so on.

2.19 Basis of Statistical Analysis

Statistical analysis is about making sense of a set of data or a series of observations. Most people whether they realize it or not, have conducted some kind of statistical analysis, even something as basic as balancing a cheque book. Statistical analysis can summarize and even illuminate a set of data, depending on type of analysis performed. Techniques of analysis range from simple measure, such as means and standard deviations, to more complex analysis as regression.

Steps in Statistical Analysis. The major steps involved are statistical analysis including data collection and entry, examination of the data, summarizing the data and reporting finding. Steps in statistical analysis are given below:

1. Data Collection and Entry. This is the first step involved in statistical analysis. In some cases, data will be available for the problem under investigation. You might, for example, keep data as a routine task. For example, a teacher who keeps a record of student grades on class work, test and homework assignments is conducting statistical analysis. In other cases, however, you must collect your own data. Once you collect your data, you might need to alter its format to meet your analytical needs. Data from a customer satisfaction survey, for example, has to be numerically coded in such a way that you can analyze customer responses. The data for your analysis can be entered into a spreadsheet such as Excel.

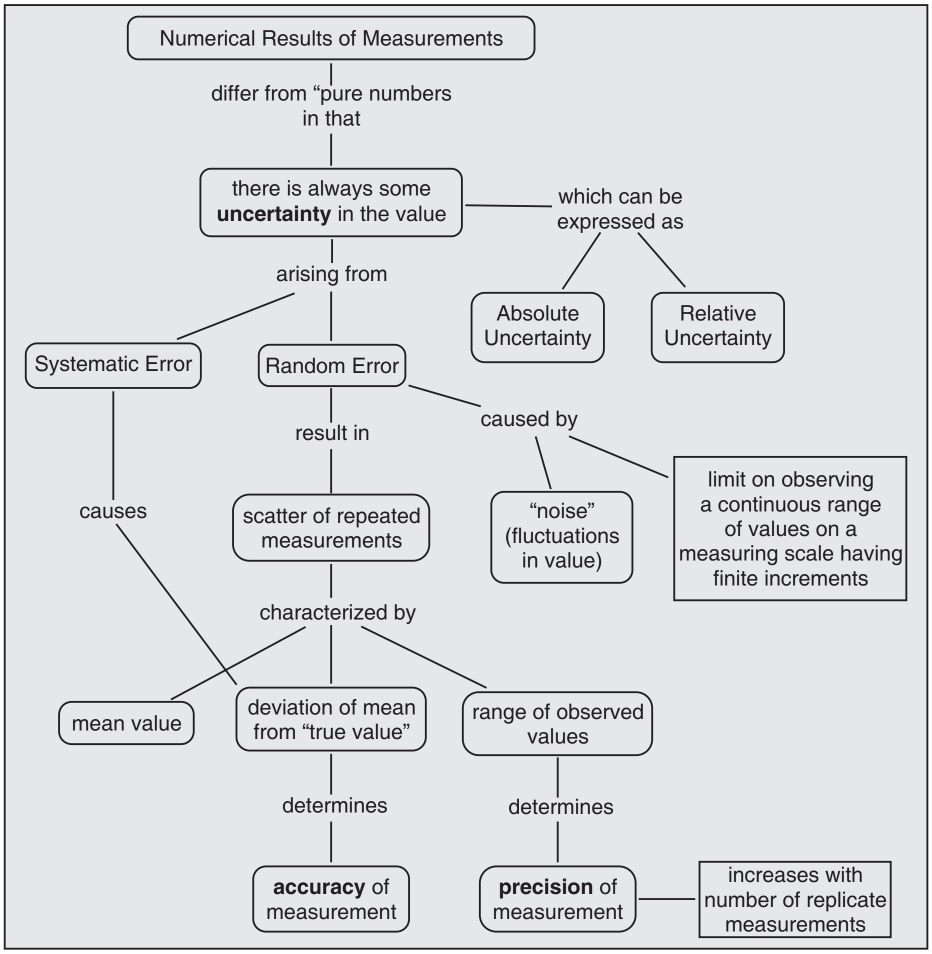


Fig. 2.1.

2. Visual Examination. The second step in performing statistical analysis is visual examination. It's strange that even trained statisticians sometimes do not take the time to examine their data before conducting analyses. At this stage of the analysis, it is sometimes useful to produce some kind of visual display or graph that will tell you more about data being collected. The most appropriate type of graph will depend on the type of data. Pie charts, for example, are an excellent choice with financial or budget data. Other graphs include bar graphs and line charts.

3. Data Summaries. The third step involved in statistical analysis is summarizing the data for making meaning out of this data. The purpose of summarizing the data is to arrive at one of two numbers that describe the characteristics of a much larger set of data. A classroom teacher, for example, might calculate an average grade for each student to summarize the quantity of each student's work over a semester grading period. Key summaries in basis statistical analyses include measures of central tendency and measures of dispersion or spread.

4. Central Tendency. Measures of central tendency are generally known as averages and include such measures as the mean and median. The mean is calculated by summing the values in a set of data and dividing the total by the number of values. If the data are arrayed in order from the highest value to the lowest, the median is the middle value, where half of the values are higher and the other half are lower.

5. Dispersion. Measures of spread or dispersion include the range, which is difference between the highest and lowest values in the data, and the standard deviation. The latter measure is more complex to calculate and generally requires a computer or at least a calculator. The standard deviation is the square root of the variance, which is the mean of the sum of squared deviations from the mean score.

6. Presenting Findings. You can present the results of your statistical analyses in the form of tables or graphs. Spreadsheet programs such as Excel can perform most basic statistical analyses, as well as present the finding in tables or graphs. Excel can perform a variety of statistical procedures, both basic and advanced. Spreadsheet programs, however, are not specifically designed for more complicated analyses. Many scientists and university researches use specialized statistical software packages such as SPSS and SAS to analyses data.

2.20 Statistical Analysis

We have already discussed in the last article that statistical analysis is about making sense of a set of data or a series of observations. The statistical analysis of "measurement data" is important because it allows an analytical determination of the uncertainty of the final test result. To make statistical analysis meaningful, a large number of measurements are usually required. The systematic and random errors are evaluated and studied by statistical procedures. The systematic errors should be small as compared to random errors, because statistical data cannot remove fixed bias contained in all the measurements.

The mathematical analysis of the various measurements is called statistical analysis of data. For statistical analysis, the same reading is taken number of times by using different instruments in different ways.

The analysis of data is done by different method as listed below:

1. Arithmetic Mean
2. Deviation from the Mean
3. Average Deviation
4. Standard Deviation
5. Variance

Now we shall discuss all these methods one by one in the following pages.

2.21 Arithmetic Mean

The arithmetic mean is, also called the average or average value, it is the quantity obtained by summing two or more numbers or variables and then dividing by the number of numbers or variables. The arithmetic mean is important in statistics.

The best approximation will be made when the number of readings of the same quantity is very large. Theoretically, an infinite number of readings would give the best, although in practice, only a finite number of measurements can be made. The arithmetic mean is given by the following expression.

$$\overline{x} = \frac{x_1 + x_2 + x_3 + x_4 + ... + x_n}{n} = \frac{\sum x}{n}$$

Where $\overline{x}$ = arithmetic mean

$x_1, x_2, x_3, ..., x_n$ = the readings taken

and n = number of readings

2.22 Deviation from the Mean

Deviation is the departure of a given reading from the arithmetic mean of the group of readings. Let the deviation of the first reading, x_1 be d_1, and for the second reading, x_2 be d_2 and so on. Then deviations from the mean can be expressed as

$$d_1 = x_1 - \overline{x}$$

$$d_2 = x_2 - \overline{x}$$

and

$$d_n = x_n - \overline{x}$$

where $d_1, d_2, d_3, ..., d_n$ = deviation

The deviation from the mean may have a positive or a negative value and the algebraic sum of all deviations must be zero.

2.23 Average Deviation

The average deviation is an indication of the precision of the instruments used in making the measurements. The average deviation is the sum of the absolute values of the deviations divided by the number of readings. The absolute value of the deviation is the value without the sign. Average deviation is expressed as

$$D = \frac{|d_1| + |d_2| + |d_3| + ... + |d_n|}{n} = \frac{\sum |d|}{n}$$

where D = average deviation

2.24 Standard Deviation

It shows how much variation there is from the average (mean) value. It also knows as root-mean–square deviation. The standard deviation σ of an infinite number of data is the square root of the sum of all the individual deviations squared, divided by the number of readings. Standard deviation is expressed as

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n}} = \sqrt{\frac{\sum d_t^2}{n}}$$

where σ = Standard deviation

and $d_1, d_2, d_3 .... d_n$ = deviations from the mean value.

In actual practice, the possible number of observations is finite. The standard deviation of a finite number of data is given by,

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n-1}} = \sqrt{\frac{\sum d_t^2}{n-1}}$$

2.25 Variance or Mean Square Deviation

It describes how far values lie from the mean. The variance is the square of the standard deviation. It is denoted as V.

$$V = \sigma^2 = \frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n}$$

Variance for finite number,

$$V = \sigma^2 = \frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n-1}$$

where V = Variance

Example 2.5. *By using a "micrometer screw", the following readings were taken of a certain physical length:*

1.34, 1.38, 1.56, 1.47, 1.42, 1.44, 1.53, 1.48, 1.40, 1.59 mm. Calculate the following:

(i) *Arithmetic mean,*

(ii) *Average deviation,*

(iii) *Standard deviation, and*

(iv) *Variance.*

Solution. Given: $x_1 = 1.34$, $x_2 = 1.38$, $x_3 = 1.56$, $x_4 = 1.47$, $x_5 = 1.42$, $x_6 = 1.44$, $x_7 = 1.53$, $x_8 = 1.48$, $x_9 = 1.40$ and $x_{10} = 1.59$.

(*i*) Arithmetic mean

We know that the arithmetic mean,

$$\bar{x} = \frac{\sum x}{n} = \frac{x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10}}{n}$$

$$= \frac{1.34 + 1.38 + 1.56 + 1.47 + 1.42 + 1.44 + 1.53 + 1.48 + 1.40 + 1.59}{10}$$

$$= \frac{14.61}{10} = 1.461 \text{ mm } \textbf{Ans.}$$

(*ii*) Average deviation

We know that the Average deviation,

$$d_1 = x_1 - \bar{x} = 1.34 - 1.461 = -0.121$$

$$d_2 = x_2 - \bar{x} = 1.38 - 1.461 = -0.081$$

$$d_3 = x_3 - \bar{x} = 1.56 - 1.461 = +0.099$$

$$d_4 = x_4 - \bar{x} = 1.47 - 1.461 = +0.009$$

$$d_5 = x_5 - \bar{x} = 1.42 - 1.461 = -0.041$$

$$d_6 = x_6 - \bar{x} = 1.44 - 1.461 = -0.021$$

$$d_7 = x_7 - \bar{x} = 1.53 - 1.461 = +0.069$$

$$d_8 = x_8 - \bar{x} = 1.48 - 1.461 = +0.019$$

$$d_9 = x_9 - \bar{x} = 1.40 - 1.461 = -0.061$$

$$d_{10} = x_{10} - \bar{x} = 1.59 - 1.461 = +0.129$$

$$D = \frac{|d_1| + |d_2| + |d_3| + |d_4| + |d_5| + |d_6| + |d_7| + |d_8| + |d_9| + |d_{10}|}{n}$$

$$= \frac{0.121 + 0.081 + 0.099 + 0.009 + 0.041 + 0.021 + 0.069 + 0.019 + 0.061 + 0.129}{10}$$

$$= 0.065$$

(*iii*) Standard deviation

We know that standard deviation of a finite number of data is,

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + d_4^2 + d_5^2 + d_6^2 + d_7^2 + d_8^2 + d_9^2 + d_{10}^2}{n-1}}$$

$$= \sqrt{\frac{(-0.121)^2 + (-0.081)^2 + (0.099)^2 + (0.091)^2 + (-0.041)^2 + (-0.021)^2 + (0.069)^2 + (0.019)^2 + (-0.121)^2 + (0.129)^2}{10-1}}$$

$$= \sqrt{\frac{0.05869}{9}} = 0.0807 \text{ mm } \textbf{Ans.}$$

(*iv*) Variance

We know that variance is the square of the standard deviation,

$$V = \sigma^2$$

$$= 0.0807^2 = 0.00651 \text{ mm}^2 \textbf{ Ans.}$$

SUMMARY

In this chapter you have learned that:

1. Measurement generally involves using an instrument as a physical means of determining a quantity or variable.

2. The gross errors are human mistakes like in reading, calculating and recordings etc.

3. The instrument error is generated due to instrument itself.

4. Environmental errors arise as a result of environmental effects on instrument.

5. Observational errors like parallax error occurs while reading a meter, wrong scale selection, the habits of individual observers etc.

6. Random error is due to friction in instrument movement, parallax errors between pointer and scale, mechanical vibrations, hysteresis in elastic members etc.

7. Absolute error may be defined as the difference between the measured value of the variable and the true value of the variable.

$$\delta A = A_m - A$$

8. The relative error is the ratio of absolute error to the true value of the quantity to be measured.

$$\text{Relative error } \varepsilon_r = \frac{\text{Absolute error}}{\text{true value}} = \frac{\delta A}{A}$$

9. The relative accuracy

$$\text{Relative Accuracy} = 1 - \left|\frac{A_m - A}{A_m}\right|$$

10. Accuracy is the degree to which instrument reading match the true or accepted values.

11. Precision is the degree to which successive measurements differ from one other.

12. The smallest increment in input which can be detected with certainty by an instrument is its resolution or discrimination.

13. Statistical analysis is about making sense of a set of data or a series of observations.

14. Arithmetic Mean

$$\bar{x} = \frac{x_1 + x_2 + x_3 + x_4 + ... + x_n}{n} = \frac{\sum x}{n}$$

15. The average deviation is the sum of the absolute values of the deviations divided by the number of readings.

$$D = \frac{|d_1| + |d_2| + |d_3| + ... + |d_n|}{n} = \frac{\sum |d|}{n}$$

16. Standard deviation is expressed as,

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n}} = \sqrt{\frac{\sum d_t^2}{n}}$$

17. The variance is the square of the standard deviation. It is denoted as V.

$$V = \sigma^2 = \frac{d_1^2 + d_2^2 + d_3^2 + ... + d_n^2}{n}$$

GLOSSARY

Absolute error: Absolute error is the difference between the measured value of the variable and the true value of the variable.

Accuracy: Accuracy is a closeness with which the instrument reading approaches the true value of the variable under measurement.

Arithmetic Mean: It's obtained by summing two or more numbers or variables and then dividing by the number of numbers or variables

Average Deviation: The average deviation is the sum of the absolute values of the deviations divided by the number of readings.

Deviation: It is the departure of a given reading from the arithmetic mean of the group of readings.

Environmental errors: This includes conditions in the area surrounding the instrument, such as the effects of changes in temperature, humidity, barometric pressure or of magnetic or electrostatic fields.

Gross Error: The gross error occurs due to the human mistakes in reading or using the instruments.

Instrumental errors: It is due to the inherent shortcomings in the instruments, misuse of the instruments, loading effects of instruments.

Observational errors: These errors occur due to carelessness of operators while taking the reading.

Precision: Precision is a measure of the reproducibility of the measurement.

Random Errors: These errors are due to unknown causes and occur even when all systematic errors have been accounted for.

Relative Error: The relative error is the ratio of absolute error to the true value of the quantity to be measured.

Resolution: The smallest increment in input which can be detected with certainty by an instrument is its resolution or discrimination.

Standard Deviation: It shows how much variation there is from the average (mean) value.

Statistical analysis: Statistical analysis is about making sense of a set of data or a series of observations.

Variance or mean square deviation: It describes how far values lie from the mean.

NUMERICAL PROBLEMS

1. A moving coil voltmeter has a uniform scale with 100 divisions, the full scale reading is 200 V and 1/10 of a scale division can be estimated with a fair degree of certainty. Determine the resolution of the instrument in volt.

   (**Ans.** 0.2 V)

2. Eight different students tuned in the circuit for resonance and the values of resonant frequency in kHz were recorded as:

   412, 428, 423, 415, 426, 411, 423, 416

Calculate the following:
(*i*) Arithmetic mean
(*ii*) Average deviation
(*iii*) Standard deviation
(*iv*) Variance.

(**Ans.** 419.25 kHz; 5.75 kHz; 6.54 kHz; 42.77 $(kHz)^2$)

DESCRIPTIVE QUESTIONS

1. What are the different type of the errors in the field of instrumentation and measurements?
2. What is the measurement of the error?
3. Explain the cause of Gross error?
4. Explain the cause of Systematic error?
5. Explain the following by suitable example
(*i*) Gross Errors
(*ii*) Systematic Errors
(*iii*) Random Errors *(GBTU, 2008-09)*
6. Explain the causes of random error? *(Nagpur University, Summer 2008)*
7. List the various steps to minimize errors.
8. What is the accuracy?
9. What is the Precision?
10. Explain the difference illustrate it between accuracy and precision. *(GBTU, 2008-09)*
11. Define the Accuracy and Precision within Application?
12. How the different statistical Analysis is Classify?
13. What are the Different statistical Analysis are occurred in the Measurement of Error?
14. What is the statistical Analysis? Explain briefly.
15. What are the different types of the statistical Analysis? Explain briefly.
16. Define the following terms
(*i*) Average value
(*ii*) Arithmetic mean
(*iii*) Deviation
(*iv*) Standard deviation
17. Enlist the main static characteristics of instruments. Explain any seven static characteristics. *(Nagpur University, Summer 2011)*
18. Explain dynamic characteristics of instruments in detail. *(Nagpur University, Summer, 2010)*
19. What are the different type of errors in the measurement and how will you minimize these errors? *(Nagpur University, Summer 2011)*
20. Define the following terms
(*i*) Linearity
(*ii*) Fidelity
(*iii*) Dead zone *(Nagpur University, Summer 2008, 2009)*
21. Explain the terms accuracy, sensitivity and resolution as under indicating instruments. *(GBTU/MTU, 2010-11)*
22. Define accuracy, precision, sensitivity, resolution and error with respect to the measurement. *(Nagpur University, Summer 2010)*
23. What do you mean by accuracy in instrument? Differentiate it with term Precision. *(GBTU/MTU, 2009-10)*

24. Explain different types of errors that may occur in measurements. *(GBTU/MTU, 2010-11)*

25. What is meant by arithmetic mean, average deviation and standard deviation. *(GBTU/MTU, 2010-11)*

26. Define the following:

(*a*) Accuracy
(*b*) Precision
(*c*) Repeatability
(*d*) Reproducibility
(*e*) Speed of response
(*f*) Response time

(*Nagpur University, Summer 2011, 2008, Winter 2008*)

MULTIPLE CHOICE QUESTIONS

1. The purpose of instrument is to

(*a*) Allow measurements to be made
(*b*) Transmit the information
(*c*) Change signals
(*d*) Any of the above

2. The measurement refers to which of the following

(*a*) Primary signal
(*b*) Measured variable
(*c*) Output
(*d*) All of the above

3. Which of the following errors can arise, as a result of mistake in reading, parallax improper instrument location and inadequate lighting?

(*a*) Construction errors
(*b*) Transmission errors
(*c*) Observation errors
(*d*) Translation errors

4. The use of electronic instrument becoming more extensive because they have

(*a*) A high sensitivity and reliability
(*b*) A fast response and compatibility with digital computers
(*c*) The capability to respond to signals from remote places
(*d*) All of the above

5. The arithmetic mean of given *n* numbers is given by the following expression

(*a*) $\bar{x} = \frac{\sum x}{n-1}$
(*b*) $\bar{x} = \frac{\sum x}{n}$
(*c*) $\bar{x} = \frac{\sum x^2}{n}$
(*d*) $\bar{x} = \frac{\sum x}{n^2}$

6. Relation between standard deviation and variance is

(*a*) $V = \sqrt{\sigma}$
(*b*) $V = \sigma^2$
(*c*) $V = 1 / \sigma$
(*d*) $V = 1/\sqrt{\sigma}$

ANSWERS

1. (*a*) **2.** (*c*) **3.** (*c*) **4.** (*d*) **5.** (*b*) **6.** (*b*)

Chapter 3

Measurements using Electrical Instruments

Outline

Objectives

After completing this chapter, you should be able to:

- Know the permanent-magnet moving-coil.
- Explain the construction and operation of PMMC instrument.
- Describe the galvanometer in details.
- Understand the working and construction of DC ammeter, shunt resistor and multirange ammeter.
- Discuss how DC voltmeter uses to measure the potential difference.
- Understand the working of series ohmmeter.
- Explain the wattmeter.
- Describe the instrumentation transformer.

3.1 Introduction

The electronic instruments generally have higher sensitivity, faster response and greater flexibility than mechanical or electrical instruments in indicating, recording and, where required, in controlling the measured quantity.

The deflection type instruments with a scale and movable pointer are called **analog** instruments. The deflection of the pointer is a function of (and, hence, analogous to) the value of the electrical quantity being measured.

In PMMC meter or (D'Arsonval) meter or galvanometer all are the same instruments, a coil of fine wire is suspended in a magnetic field produced by permanent magnet. According to the fundamental law of electromagnetic force, the coil will rotate in the magnetic field when it carries an electric current by electromagnetic (EM) torque effect.

A pointer is attached to the movable coil. This pointer will deflect according to the amount of current to be measured which is applied to the coil. The (EM) torque is counterbalanced by the mechanical torque of control spring attached to the movable coil also. When the torques are balanced, the moving coil will stop rotating and its angular deflection represent the amount of electrical current to be measured against a fixed reference, called a scale. If the permanent magnet field is uniform and the spring is linear, the pointer deflection will also be linear.

3.2 PMMC Meter

It is also called D' Arsonval meter movement or a permanent-magnet moving-coil (PMMC) meter movement. Since it is widely used in electronic instruments, it is worthwhile to discuss its construction and principle of operation.

The basic PMMC movement is often called the D'Arsonval movement, after its inventor. This design offers the largest magnet in a given space and is used when maximum flux in the air gap is required. It provides an instrument with very low power consumption and low current required for full-scale deflection. It can be used for D.C. measurements only.

1. Construction

As shown in Fig. 3.1, it consists of a permanent horse-shoe magnet with soft iron pole pieces attached to it. Between the two pole-pieces a cylinder-shaped soft iron core is situated. A coil of fine wire wound on a light metal frame moves around the cylinder-shaped soft iron core. The metal frame is mounted in jewel bearings so that it can rotate freely. A light pointer attached to the moving coil moves up-scale as the coil rotates when current is passed through it. The rotating coil is prevented from continuous rotation by a spring which provides restoring torque.

The moving coil movement described above is being increasingly replaced by tautband movement in which the moving coil and the pointer are suspended between bands of spring metal so that the restoring force is tensional. The bands perform two functions (*i*) to support the coil and (*ii*) to provide restoring torque thereby eliminating the pivots and jewels used with coil spring movement.

As compared to pivoted movement, the taut-band has the advantages of

1. Greater sensitivity i.e. small full-scale deflection current
2. Ruggedness,
3. Minimal friction,
4. Easy to manufacture.

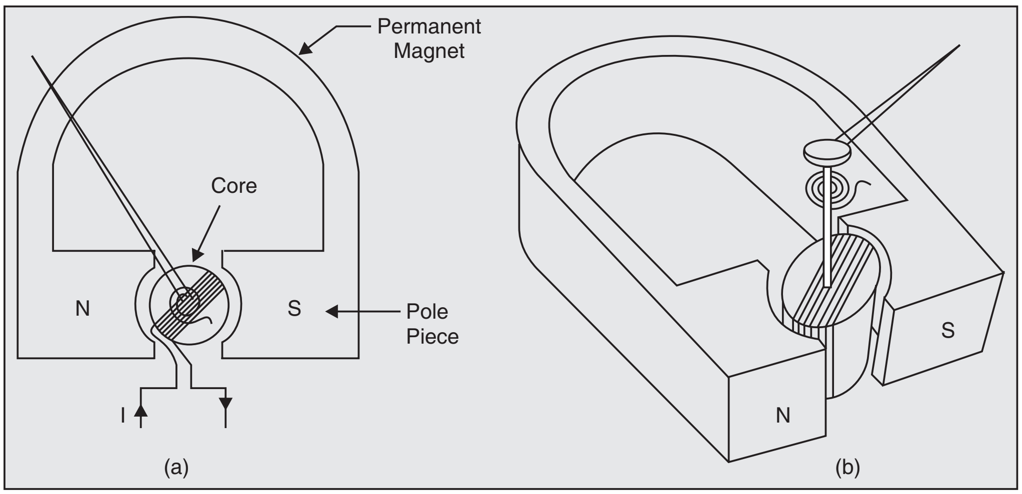


Fig. 3.1.

2. *Principle of Operation*

This meter movement works on the motor principle and is a current-responding device. The deflection of the pointer is directly proportional to the amount of current passing through the coil.

When direct current flows through the coil, the magnetic field so produced reacts with the field of the permanent magnet. The resultant force turns the coil alongwith its pointer. The amount of deflection is directly proportional to the amount of current in the coil. Hence, their scale is linear. With correct polarity, the pointer reads up-scale to the right whereas incorrect polarity forces the pointer off-scale to the left.

3. *Deflecting Torque*

If the coil is carrying a current of i A,

the force on a coil side = $BilN$

torque due to both coil sides = $(2r)(BilN)$

$= Gi$

$G = 2rBlN = NBA$

Where G = constant

$A = 2rl$ = area of the coil

N = no. of turns of the coil.

B = flux density in Wb/m^2.

l = length of the vertical side of the coil, m.

$2r$ = breadth of the coil, m

i = current in ampere.

4. Controlling Torque

The value of control torque depends on the mechanical design of the control device. For spiral springs and strip suspensions, the controlling torque is directly proportional to the angle of deflection of the coil.

$$\text{Control torque} = C\,\theta$$

Where, θ = deflection angle in radians

C = spring constant

3.3 Characteristics of Moving Coil Meter Movement

We will discuss the following three characteristics:

(*i*) full-scale deflection current (I_m),

(*ii*) internal resistance of the coil (R_m),

(*iii*) sensitivity (S).

1. Full-scale Deflection Current (I_m)

It is the current needed to deflect the pointer all the way to the right to the last mark on the calibrated scale. Typical values of Im for D' Arsonval movement vary from 2 µA to 30 mA.

It should be noted that for smaller currents, the number of turns in the moving coil has to be more so that the magnetic field produced by the coil is strong enough to react with the field of the permanent magnet for producing reasonable deflection of the pointer. Fine wire has to be used for reducing the weight of the moving coil but it increases its resistance. Heavy currents need thick wire but lesser number of turns so that resistance of the moving coil is comparatively less. The schematic symbol is shown in Fig. 3.2.

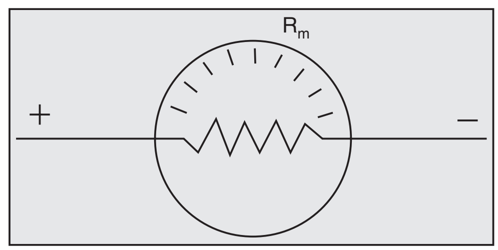


Fig. 3.2.

2. Internal Resistance (R_m)

It is the dc ohmic resistance of the wire of the moving coil. A movement with smaller I_m has higher R_m and *vice versa*. Typical values of R_m range from 1.2 W for a 30 mA movement to 2 kW for a 50 mA movement.

3. Sensitivity (S)

It is also known as **current sensitivity or sensitivity factor**. It is given by the reciprocal of full-scale deflection current I_m.

$$S = \frac{1}{I_m} \text{ ohm/volt.}$$

For example, the sensitivity of a 50-µA meter movement is

$$S = \frac{1}{50 \times 10^{-6}} \frac{\text{ohm}}{\text{volt}} = 20{,}000\ \Omega/\text{V} = 20\ \text{k}\Omega/\text{V}$$

The above figure shows that a full-scale deflection of 50 µA is produced whenever 20,000 W of resistance is present in the meter circuit for each volt of applied voltage. It also represents the ohms-per-volt rating of the meter. The sensitivity of a meter movement depends on the strength of the permanent magnet and number of turns in the coil. Larger the number of turns, smaller the amount of current required to produce full-scale deflection and, hence, higher the sensitivity. A high current sensitivity means a high quality meter movement. It also determines the lowest range that can be covered when the meter movement is modified as an ammeter or voltmeter.

3.4 Advantage of PMMC

Following are some of the advantages of PMMC which are important from the subject point of view:

1. It has uniform scale.
2. Operating current is small.
3. It has high sensitivity.
4. It consumes low power, of order of 25 W to 200 μW.
5. It has high accuracy.
6. Extension of instrument range is possible.
7. Not affected by eternal magnetic fields called stray magnetic fields.

3.5 Disadvantage of PMMC

PMMC has some disadvantages too. These are given below :

1. Used only for D.C measurements. The torque reverse if the current reverses. If the instrument is connected to A.C., the pointer cannot follow the reversals and the deflection corresponds to mean torque, which is zero, hence it cannot be used for A.C.
2. The cost of the instrument is high.

3.6 Galvanometer

A moving coil galvanometer is an instrument used for detection and measurement of small electric currents.

A **galvanometer** is a type of ammeter, an instrument for detecting and measuring electric current. It is an analog electromechanical transducer that produces a rotary deflection of some type of pointer in response to electric current flowing through its coil.

The Galvanometer is an electromechanical instrument which is used for the detection of electric currents or voltage through electric circuits. Being a sensitive instrument, Galvanometer cannot be used for the measurement of heavy currents.

However we can measure very small currents or voltages by using galvanometer but the primary purpose of galvanometer is the detection of electric current not the measurement of current.

The Galvanometer may be classified into three categories

1. DC Galvanometers

There are two types of galvanometer: (*i*) moving-magnet galvanometer and (*ii*) moving coil galvanometer.

(*i*) In ***moving-magnet galvanometer*** the magnet moves due to the magnetic field set up by the flow of current through a fixed coil. The damping in this galvanometer is poor but may be improved by using conducting plates near the moving magnets. Tangent galvanometer is the example of moving-magnet galvanometer.

(*ii*) In ***moving coil galvanometer*** a magnetic coil moves in the field of permanent magnet. The current to be detected is passes through the coil. ***D' Arsonval galvanometer*** is the example of ***moving coil galvanometer***.

2. AC Galvanometers

The AC Galvanometers is used for measuring the effective or rms value of small current or in most case null detectors in bridge and potentiometer circuits. There are two types of ac galvanometers: (*i*) phase sensitive and (*ii*) frequency sensitive galvanometer.

The phase sensitive is a dynamometer type galvanometer and the frequency sensitive is a tuned detector or vibration type galvanometer. It is important type of galvanometer for frequencies below 200 Hz.

3. Ballistic Galvanometers

It is used for the measurement of charge or quantity of electricity passed through it. This quantity of electricity in magnetic measurements is due to the induced emf or change in magnetic flux in the coil. It is used in almost all the dc magnetic measurements.

3.7 D' Arsonval or Moving Coil Galvanometer

Galvanometer is an instrument used to indicate the presence, direction, or strength of a small electric current. A typical Galvanometer is a sensitive instrument used in laboratory, mainly to detect and compare currents. It makes use of the fact that an electric current flowing through a wire sets up a magnetic field around the wire. This is based on the principle, discovered in 1820 by Hans Christian Oersted when he observed that a magnetic needle could be deflected by an electric current. The first galvanometer was made in 1820 by Johann Schweigger.

Fig. 3.3 shows the D'Arsonval galvanometer type. The description of the different parts is given below:

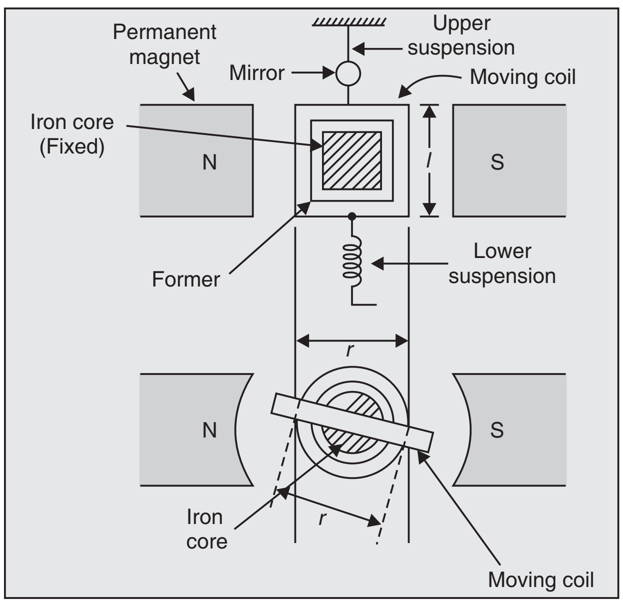


Fig. 3.3.

1. Moving Coil

The moving coil is the current carrying element. It is rectangular or circular in shape and consists of a number of turns of fine wire. It is arranged in a uniform, radial, horizontal magnetic field in the air gap between pole pieces of a permanent magnet and iron core. This coil is suspended so that it is free to turn about its vertical axis of symmetry.

2. Damping

The damping(or more precisely eddy current damping) is obtained by connecting a low resistance across the galvanometer terminals. Damping torque depends upon the resistance and we obtain critical damping by adjusting the values of resistance.

3. Suspension

The coil is supported by a flat ribbon suspension which also carries current to the coil. This is called the lower suspension and has a negligible torque.

The upper suspension consists of gold or copper wire of nearly 0.0125 or 0.025 mm diameter rolled into the form of a ribbon. This is mechanically not strong, so that galvanometer must be handled carefully without jerks. Sensitive galvanometer provided with coil clamps to take the strain from suspension.

4. Indication

The suspension carries a small mirror upon which a beam of light is cast. This beam of light is reflected on to a scale upon which the deflection is measured. This scale is usually about 1 meter away from the instrumentation.

5. Zero Setting

A torsion head is provided for adjusting the position of the coil and also for zero setting.

3.8 Torque Equation of Galvanometer

Galvanometer works on the principle of conversion of electrical energy into mechanical energy. When a current or voltage flows in a magnetic field it experiences a magnetic torque. If it is free to rotate under a controlling torque, it rotates through an angle proportional to the current flowing through it.

Fig. 3.4. shows the quantities that enter the torques equation of a galvanometer.

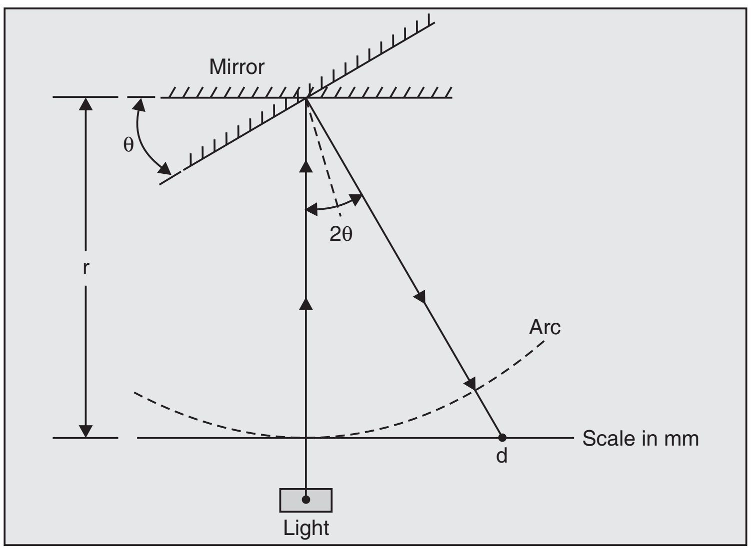


Fig. 3.4.

Where l, r = length of respectively vertical and horizontal side of coil

N = number of turns in the coil

B = flux density in the air gap

i = current through moving coil

K = spring constant of suspension

θ_F = final steady state deflection of moving coil

We know that the force on the coil is given by,

$$F = NBil \sin \alpha$$

where α = angle between direction of magnetic field and conductor.

When the field is radial, $\alpha = 90°$, then the force is given by

$$F = NBil$$

The deflecting torque is given by

$$T_d = \text{force} \times \text{distance} = NBilr$$
$$= NBAi$$

where $A = lr$ = area of coil

1. Deflection torque

$$T_d = Gi$$

where G is called the displacement constant of the galvanometer. It's value is given by

$$G = NBA = NBlr$$

2. Controlling torque

Controlling torque exerted by the suspension at deflection θF

$$T_c = K\theta_F$$

In steady state deflection

$$T_c = T_d$$
$$K\theta_F = G_i$$
$$\theta_F = \frac{Gi}{K}$$

For small deflection, the radius of arc and angle of turning, decide the deflection. If the mirror is turned through θ_F the angle through which the beam gets reflected is $2\theta_F$.

$$d \text{ in mm} = 2\ \theta_F \times r$$
$$d = \frac{2\ Gir}{K} \text{ mm}$$

where r = 1m = 1000 mm for the galvanometer.

3.9 Use of Galvanometer

There are many uses of galvanometer. Some of the important ones are as given below :

1. Galvanometer instrument used to determine the presence, direction, and strength of an electric current in a conductor.
2. A major early use for galvanometers was for finding faults in telecommunications cables. They were superseded late in the 20th century by time-domain reflectometers.
3. Used in positioning and control systems.
4. Mirror galvanometer systems are used as beam positioning elements in laser optical systems.
5. An automatic exposure unit from an 8 mm movie camera, based on a galvanometer mechanism (center) and a CdS photoresistor in the opening at left.

3.10 Variations of Basic Meter Movement

The basic moving-coil system can be converted into an instrument to measure dc as well as ac quantities like current, voltage and resistance etc. Without any modification, it can carry a maximum current of Im can withstand a maximum dc voltage $v = I_m R_m$.

DC instruments

(*a*) it can be made into a dc ammeter, milliammeter or micrommeter by adding a suitable shunt resistor R_{sh} in parallel with it as shown in Fig. 3.5(*a*),

(*b*) it can be changed into a dc voltmeter by connecting a multiplier resistor Rmult in series with it as shown in Fig. 3.5(*b*), (*c*) it can be converted into an ohmmeter with the help of a battery and series resistor *R* as shown in Fig. 3.5(*c*).

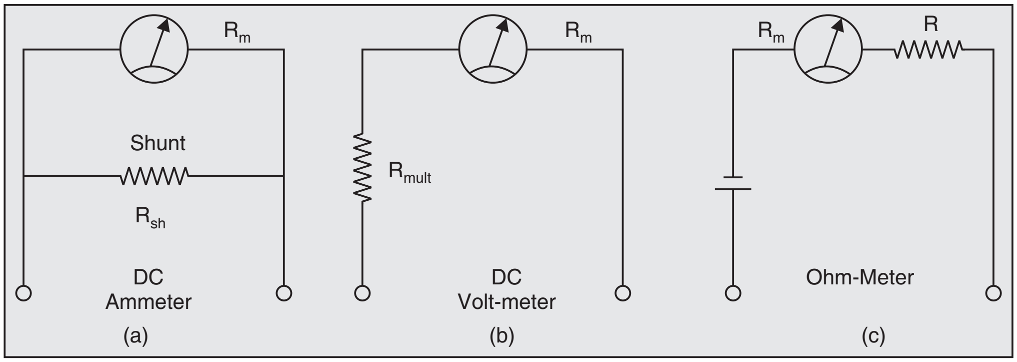


Fig. 3.5.

D.C. Instruments

(*a*) D.C. ammeter: by using a shunt resistor.

(*b*) D.C. voltmeter: by using series multiplier resistor.

(*c*) Ohmmeter: by using battery and series resistor.

3.11 D.C. Ammeter

The D'Arsonval galvanometer is a **moving coil** ammeter. It uses magnetic deflection, where current passing through a coil causes the coil to move in a magnetic field. The voltage drop across the coil is kept to a minimum to minimize resistance across the ammeter in any circuit into which it is inserted.

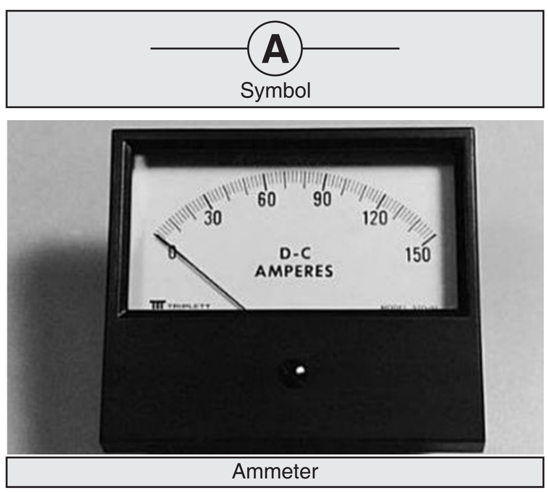


Fig. 3.6.

Ammeter Shunt Resistor

The basic movement of a dc ammeter is a PMMC D'Arsonval galvanometer. The coil winding of a basic movement is very small and light it can carry very small value of currents. When the large currents are to be measured it is necessary to bypass the major part of the current through a low resistance called shunt resistor. The shunt resistor is connected parallel with D'Arsonval movement. The ammeter is always connected in series with the load in the circuit.

The dc ammeter is shown in Fig. 3.7. The resistance of the shunt can be calculated by circuit analysis.

Where R_m = internal resistance of the movement coil

R_{sh} = resistance of the shunt

I_m = I_{fsd} = full scale deflection current of the movement

I_{sh} = shunt current

I = current to be measured

Since the shunt resistance is in parallel with the meter movement, the voltage drop across the shunt and movement is the same.

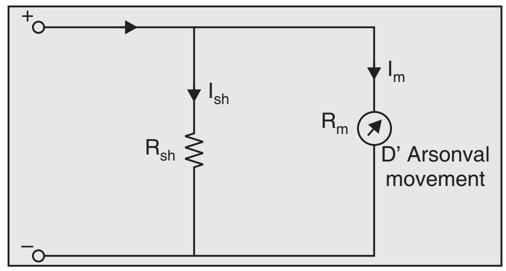


Fig. 3.7. DC Ammeter

$$V_{\text{shunt}} = V_{\text{movement}}$$

$$I_{sh} R_{sh} = I_m R_m$$

and

$$R_{sh} = \frac{I_m R_m}{I_{sh}}$$

We know that $I_{sh} = I - I_m$, so we can write

$$R_{sh} = \frac{I_m R_m}{I - I_m}$$

Rearranging the above equation we get,

$$\frac{I}{I_m} = 1 + \frac{R_m}{R_{sh}}$$

The ratio of total current to the movement current is known as multiplying power of shunt.

$$m = \frac{I}{I_m} = 1 + \frac{R_m}{R_{sh}}$$

$$R_{sh} = \frac{R_m}{(m-1)}$$

3.12 Properties of shunt resistor

Main properties of shunt resistor are given below:

1. Resistance of the shunt should not vary with time.
2. Temperature co-efficient of shunt and instrument should be low and should be same.

Example 1. *A 1 mA meter movement with an internal resistance of 100 Ω is to be converted into 0–100 mA. Calculate the value of shunt resistance required.*

Solution. Given: $R_m = 100\ \Omega$, $I_m = 1$ mA and $I = 100$ mA

We know that the value of shunt resistance,

$$R_{sh} = \frac{I_m R_m}{I - I_m}$$

$$= \frac{1\text{ mA} \times 100\ \Omega}{100\text{ mA} - 1\text{ mA}} = \frac{100\text{ mA }\Omega}{99\text{ mA}} = 1.01\ \Omega \textbf{ Ans.}$$

3.13 Multi-range Ammeter

The current range of the dc ammeter is further extended by a number of shunts, selected by a range switch. This type of meter is called a multi-range ammeter.

Fig. 3.8 shows the multi-range ammeter and circuit diagram is shown in Fig. 3.9. It has four shunts (R_{sh1}, R_{sh2}, R_{sh3}, R_{sh4}) parallel with the meter movement and gives four different current ranges (I_1, I_2, I_3, I_4).

Fig. 3.8. Multi-range Ammeter

If m_1, m_2, m_3 and m_4 be the shunt multiplying powers for currents I_1, I_2, I_3 and I_4 then,

$$R_{sh1} = \frac{R_m}{(m_1 - 1)}$$

$$R_{sh2} = \frac{R_m}{(m_2 - 1)}$$

$$R_{sh3} = \frac{R_m}{(m_3 - 1)}$$

and

$$R_{sh4} = \frac{R_m}{(m_4 - 1)}$$

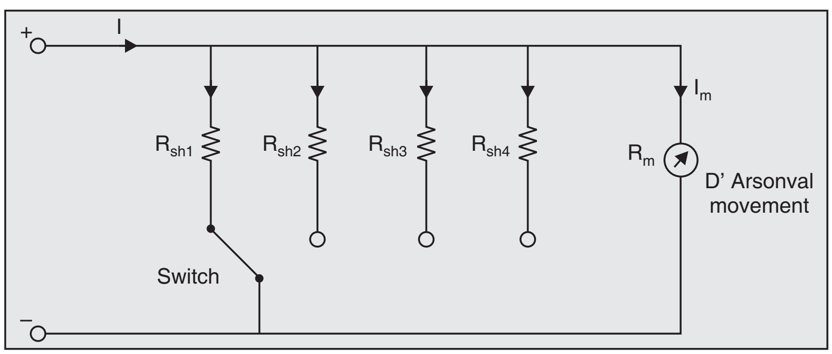


Fig. 3.9. Multi-range Ammeter

Ammeter uses a multiposition make-before-break switch. This type of switch is essential in order that the meter movement is not damaged when it change from one resistor to other resistor. If we used ordinary switch the meter remain without shunt when we change from one resistor to other resistor, this may damage the ammeter.

This ammeter used for ranges 1 – 50 A. While using the multi-range ammeter we use the highest current range first then decrease the current range.

Example 3.2. *Design a multi-range DC milli-ammeter with a basic meter having a resistance 75 Ω and full scale deflection for the current of 2 mA. The required ranges are 0-10 mA, 0-50 mA and 0-100 mA.*

Solution. Given: I_m = 10 mA; R_m = 75 Ω; I_1 = 10 mA; I_2 = 50 mA and I_3 = 100 mA.

For current range 0-10 mA

We know that for multi-range DC ammeter,

$$R_1 = \frac{I_m R_m}{(I_1 - I_m)}$$

$$= \frac{2 \times 75}{(10 - 2)} = 18.75\ \Omega$$

For current range 0-50 mA

We know that for multi-range DC ammeter,

$$R_2 = \frac{I_m R_m}{(I_2 - I_m)}$$

$$= \frac{2 \times 75}{(50 - 2)} = 3.125\ \Omega$$

For current range 0-100 mA

We know that for multi-range DC ammeter,

$$R_3 = \frac{I_m R_m}{(I_3 - I_m)}$$

$$= \frac{2 \times 75}{(100 - 2)} = 1.53\ \ \Omega$$

The design of multi-range ammeter is shown in Fig. 3.10.

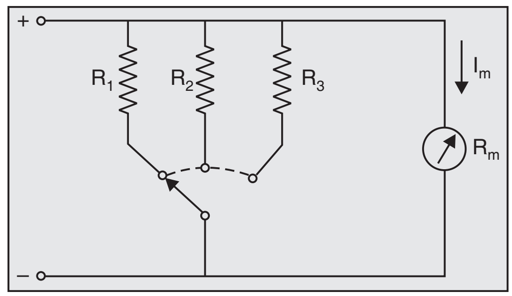


Fig. 3.10

3.14 Universal or Ayrton Shunt

We can use universal shunt in the multi-range ammeter. Fig. 3.11 shows the multi-range ammeter with universal shunt. The advantage of using universal shunt is that it eliminates the possibility of meter being in the circuit without shunt.

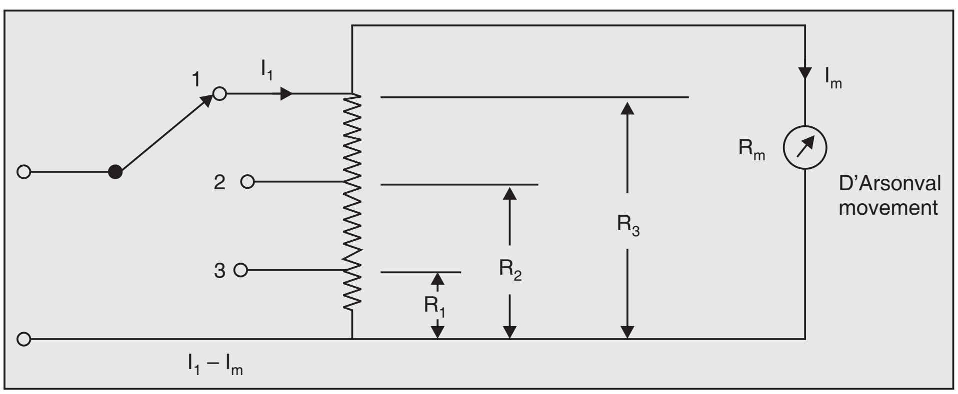


Fig. 3.11. Ammeter with universal shunt

When the switch is in position 1 then

$$I_m\ R_m = (I_1 - I_m)R_1$$

In position 2, then,

$$I_m\ (R_1 - R_2 + R_m) = (I_2 - I_m)R_2$$

In position 3, then,

$$I_m\ (R_1 - R_3 + R_m) = (I_3 - I_m)R_3$$

Precautions when using ammeter in measurement work,

1. Never connect an ammeter across a source of EMF. Because of its low resistance it draws damaging high currents and destroys the delicate movement. It is always connected in series with a load.

2. Always connect in right polarity. Reverse polarity may damage the pointer
3. When using the multi-range meter, first use the highest current range; then decrease the current range until substantial deflection is obtained.

3.15 DC Voltmeter

Voltmeter is used for measuring voltage or the potential difference. Fig. 3.12 shows the instrument and symbol of voltmeter.

Fig. 3.12. Voltmeter

Fig. 3.13 shows the circuit diagram of dc voltmeter. The high resistor is connected in series with the D' Arsonval movement. This resistor is called multiplier. The multiplier limits the current so that it does not exceed the full-scale deflection current. The voltmeter is always connected across the source of emf or a circuit.

where R_m = internal resistance of the movement coil

R_s = multiplier resistance

$I_m = I_{fsd}$ = full scale deflection current of the movement

V = full range voltage of the instrument

From the circuit shown in Fig 3.13,

$$V = I_m (R_s + R_m)$$

Rearranging the above equation,

$$R_s = \frac{V - I_m R_m}{I_m}$$

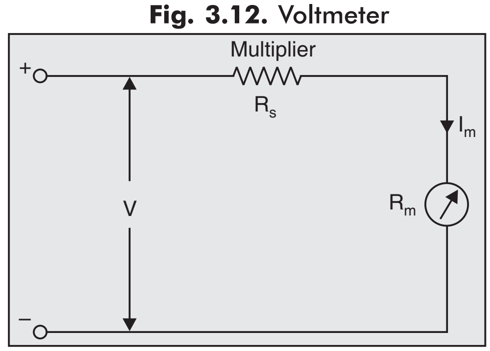


Fig. 3.13. DC Voltmeter

Example 3.3. *Calculate the value of multiplier resistance on the 50 V range of a dc voltmeter that uses a 200 μA meter movement with an internal resistance of 100 Ω*

Solution. Given: I_{fsd} = 200 μA, R_m = 100 Ω and V = 50 V.

We know that sensitivity,

$$\text{Sensitivity} = \frac{1}{I_{fsd}} = \frac{1}{200\ \mu\text{A}} = 5000\ \Omega/\text{V}$$

We also know that the relation between sensitivity and multiplier resistance,

$$S = \frac{R_s + R_m}{V}$$

or $$R_s = S \times V - R_m = [(5000 \times 50) - 100\ \Omega] = 249.9\ \text{k}\Omega$$ **Ans.**

Example 3.4. *A basic D'Arsonval movement with a full deflection of 50 μA and internal resistance of 500 Ω is used as a voltmeter. Determine the value of the multiplier resistance needed to measure a voltage range of 0–10 V.*

Solution. Given: I_m = 50 μA; R_m = 500 Ω and V = 10 V.

We know that the multiplier resistance for voltmeter is given by,

$$R_s = \frac{V - I_m R_m}{I_m}$$

$$= \frac{10 - 50\ \mu A \times 500\ \Omega}{50\ \mu A} = 0.2 \times 10^6 - 500$$

$$= 199.5\ k\Omega\ \textbf{Ans.}$$

3.16 Multi-range Voltmeter

Fig. 3.14 shows the multi-range voltmeter. The range of dc voltmeter is extended by using number of multipliers and a selector switch.

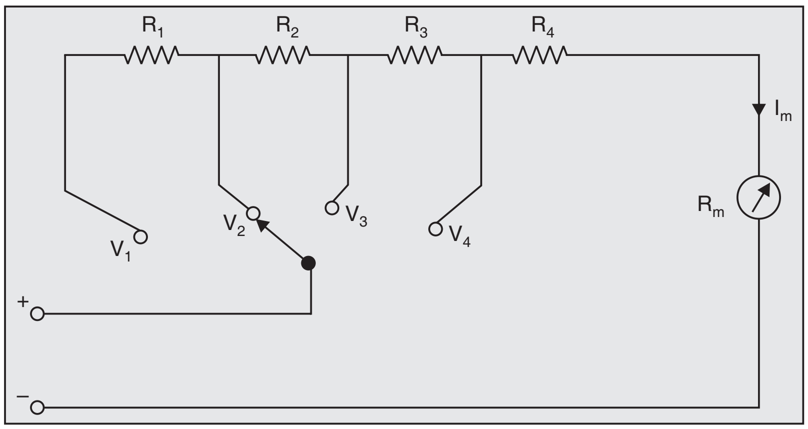


Fig. 3.14. Multi-range Voltmeter

A multi-range voltmeter using four position switch and four multipliers, R_1, R_2, R_3 and R_4, for the voltage ranges V_1, V_2, V_3 and V_4 respectively.

Precautions when using voltmeter in measurement work

1. Place the voltmeter across the circuit or component whose voltage is to be measured.
2. When using a multi-range voltmeter, always use the highest voltage range and then decrease the range until a good up-scale reading is obtained.
3. Always be aware of the loading effect.

Example 3.5. *Calculate the value of multiplier resistance for the multiple range dc voltmeter circuit shown in Fig 3.15.*

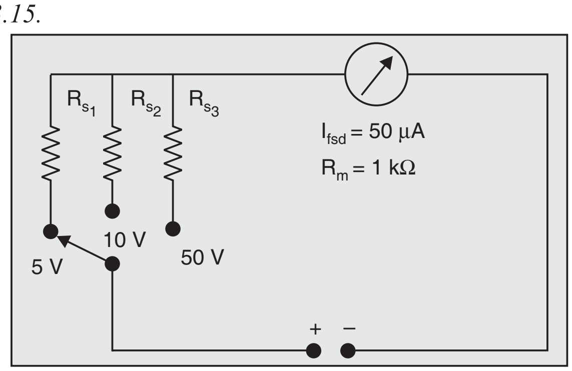


Fig. 3.15.

Solution. Given: $I_{fsd} = 50\ \mu A$ and $R_m = 1\ k\Omega$.

We know that the sensitivity of the meter movement,

$$\text{Sensitivity} = \frac{1}{I_{fsd}} = \frac{1}{50\ \mu A} = 20\ k\Omega/V$$

We know that the value of multiplier resistance for 5 V range,

$$R_{s_1} = S \times V - R_m$$
$$= (20 \text{ k} \times 5) - 1 \text{ k}\Omega = 100 \text{ k} - 1 \text{ k}\Omega$$
$$= 99 \text{ k}\Omega \textbf{ Ans.}$$

We know that the value of multiplier resistance for 10 V range,

$$R_{s_2} = S \times V - R_m$$
$$= 20 \text{ k} \times 10 - 1 \text{ k}\Omega = 200 \text{ k} - 1 \text{ k}\Omega$$
$$= 199 \text{ k}\Omega \textbf{ Ans.}$$

We know that the value of multiplier resistance for 50 V range,

$$R_{s_3} = S \times V - R_m$$
$$= 20 \text{ k} \times 50 - 1 \text{ k}\Omega = 1000 \text{ k} - 1 \text{ k}\Omega$$
$$= 999 \text{ k}\Omega \textbf{ Ans.}$$

Example 3.6. *A basic D'arsonval movement with internal resistance, R_m = 100 Ω, and full-scale current, I_{fsd} = 1 mA, is to be converted into a multirange dc voltmeter with voltage ranges of 0-10 V, 0-50 V, 0-250 V, and 0-500 V. The circuit arrangement is shown in Fig 3.16.*

Solution. Given: R_m = 100 Ω; I_{fsd} = 1 mA and voltage ranges = 0-10 V, 0-50 V, 0-250 V, and 0-500 V.

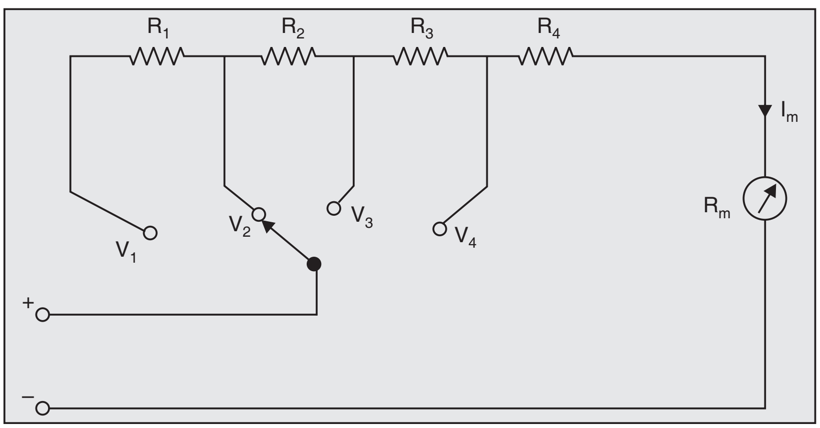


Fig. 3.16.

For the 10-V range, switch is on position V_4

We know that value of total resistance,

$$R_T = \frac{10 \text{ V}}{1\, m\text{A}} = 10 \text{ k}\Omega$$

Then the value of resistance R_4,

$$R_4 = R_T - R_m$$
$$= 10000 \ \Omega - 100 \ \Omega = 9{,}900 \ \Omega = 9.9 \text{ k}\Omega \textbf{ Ans.}$$

For the 50-V range, switch is on position V_3

We know that value of total resistance,

$$R_T = \frac{50 \text{ V}}{1\, m\text{A}} = 50 \text{ k}\Omega$$

Then the value of resistance R_3,

$$R_3 = R_T - (R_4 + R_m)$$

$$= 50\ \text{k}\Omega - (9.9\ \text{k}\Omega + 0.1\ \text{k}\Omega)$$
$$= 40\ \text{k}\Omega\ \textbf{Ans.}$$

For the 250-V range, switch is on position V_2

We know that value of total resistance,

$$R_T = \frac{250\ \text{V}}{1\ m\text{A}} = 250\ \text{k}\Omega$$

Then the value of resistance R_2,

$$R_2 = R_T - (R_3 + R_4 + R_m)$$
$$= 250\ \text{k}\Omega - (40\ \text{k}\Omega + 9.9\ \text{k}\Omega + 0.1\ \text{k}\Omega) = 200\ \text{k}\Omega\ \textbf{Ans.}$$

For the 500-V range, switch is on position V_1

We know that value of total resistance,

$$R_T = \frac{500\ V}{1\ mA} = 500\ \text{k}\Omega$$

Then the value of resistance R_1,

$$R_1 = R_T - (R_2 + R_3 + R_4 + R_m)$$
$$= 500\ \text{k}\Omega - (200\ \text{k}\Omega + 40\ \text{k}\Omega + 9.9\ \text{k}\Omega + 0.1\ \text{k}\Omega)$$
$$= 250\ \text{k}\Omega\ \textbf{Ans.}$$

3.17 Sensitivity

The sensitivity of a voltmeter is given in ohms per voltage. It is the reciprocal of the full-scale deflection current.

$$\text{Sensitivity} = \frac{\text{ohms}}{\text{Volt}} = \frac{1}{I_{fsd}}$$

The sensitivity of the dc voltmeter is given by

$$\text{Sensitivity} = \frac{1}{I_{fsd}}$$

$$S = \frac{R_s + R_m}{V}$$

$$R_s = S \times V - R_m$$

The sensitivity of the dc ammeter is given by

$$\text{Sensitivity } (S) = \frac{1}{I_{fsd}} = \frac{R_m}{I_{sh} R_{sh}}$$

Example 3.7. *Calculate the sensitivity of a 200 μA meter movement which is to be used as a dc voltmeter.*

Solution. Given: $I_{fsd} = 200\ \mu\text{A}$

We know that the sensitivity,

$$\text{Sensitivity} = \frac{1}{I_{fsd}}$$

$$= \frac{1}{200\ \mu\text{A}} = 5\ \text{k}\Omega/\text{V}\ \textbf{Ans.}$$

Example 3.8. *In the circuit shown in Fig. 3.17, the voltage across the resistor of value 25 kΩ is to be measured by using a voltmeter of sensitivity of 1 kΩ.V. Calculate the reading of the voltmeter in each case and the % error in the measurement.*

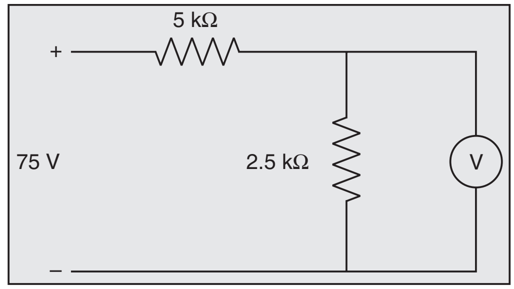


Fig. 3.17.

Solution. Given: S = 1 kΩ V

True value of the voltage across 2.5 kΩ = 75 × 2.5k / (5k + 2.5k) = 25 V.

Voltmeter resistance in 25 V range = 25 × 1 kΩ = 25 kΩ

We know that the voltage measured by the voltmeter

$$= \frac{2.5\,k\Omega \,||\, 25\,k\Omega}{5.0\,k\Omega + (2.5\,k\Omega \,||\, 25\,k\Omega)} \times 75 = 23.44 \text{ V } \textbf{Ans.}$$

We also know that the % error in the measurement.

$$\%\text{ error} = \frac{25 - 23.44}{25} \times 100 = 6.24\ \% \textbf{ Ans.}$$

Example 3.9. *A milli-ammeter of 2.5 ohms resistance reads upto 100 milli-amperes. Calculate the resistance which is necessary to enable it to use as:*

(i) *A voltmeter reading upto 10 V*

(ii) *An ammeter reading upto 10 A*

Solution. Given: I_m = 100 mA and R_m = 2.5 Ω.

A voltmeter reading upto 10 V

We know that the value of resistance is given by,

$$R_s = \frac{V - I_m R_m}{I_m} = \frac{10 - 0.1 \times 2.5}{0.1} = 97.5\ \Omega \textbf{ Ans.}$$

Current to be measured is 10 A

We know that the value of resistance for ammeter,

$$R_{sh} = \frac{I_m R_m}{I - I_m} = \frac{0.1 \times 2.5}{10 - 0.1} = 0.02525\ \Omega \textbf{ Ans.}$$

3.18 Loading Effect

When the voltmeter resistance is not high as compared to the resistance of the circuit across which it is connected, the measured voltage becomes less. The decrease in voltage may be negligible or it may be appreciable depending on the sensitivity (ohms-per-volt rating) and input resistance of the voltmeter. It is called voltmeter loading effect because the voltmeter loads down the circuit across which it is connected. Since input resistance of electronic voltmeter is very high (10 MW or more), loading is not a problem in their case.

When selecting a meter for a certain voltage measurement, it is important to consider the sensitivity of a dc voltmeter. A low sensitivity meter may give a correctly reading when measuring voltages in a low resistance circuit, but it is certain to produce unreliable readings in a high resistance circuit. A voltmeter when connected across two points in a highly resistive circuits, acts as shunt for that portion of the circuit, reducing the total equivalent resistance of that portion. The meter then indicates a lower reading than what existed before the meter was connected. This is caused mainly by low sensitivity instruments.

Example 3.10. *Fig. 3.18 shows a simple series circuit of R_1 and R_2 connected to a 100 V dc source. If the voltage across R_2 is to be measured by voltmeter having*

(a) *A sensitivity of 1000 Ω/V, and*

(b) *A sensitivity of 20,000 Ω/V,*

Find which voltmeter will read the accurate value of voltage across R_2. Both meters are used on the 50 V range.

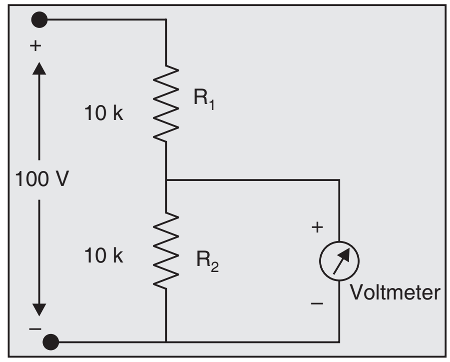


Fig. 3.18.

Solution. Given: R_1 = 10 kΩ; R_2 = 10 kΩ and V = 100 V.

We know that the voltage across R_2 resistance is

$$= \frac{10\text{ k}}{10\text{ k} + 10\text{ k}} \times 100 = 50\text{ V}$$

True voltage of resistance R_2 is 50 V

(*a*) *Voltmeter with sensitivity of 1000 Ω/V*

It has resistance of 1000 × 50 = 50 kΩ on its 50 V range

Voltmeter is connected across R_2, then equivalent parallel resistance is given by

$$R_{eq} = \frac{10\text{ k} \times 50\text{ k}}{10\text{ k} + 50\text{ k}}$$

$$= 8.33\text{ k}\Omega$$

We know that the voltage across total combination,

$$V_1 = \frac{R_{eq}}{R_1 + R_{eq}}$$

$$= \frac{8.33\text{ k}}{10\text{ k} + 8.33\text{ k}} \times 100\text{ V} = 45.43\text{ V}$$

Thus the voltmeter with sensitivity of 1000 Ω/V will indicate 45.43 V.

(*b*) *Voltmeter with sensitivity of 20,000 Ω/V*

It has resistance of 20,000 × 50 = 1000 MΩ on its 50 V range

Voltmeter is connected across R_2, then equivalent parallel resistance is given by

$$R_{eq} = \frac{10\text{ k} \times 1\text{ M}}{10\text{ k} + 1\text{ M}} = 9.9\text{ k}\Omega$$

Voltage across total combination,

$$V_2 = \frac{R_{eq}}{R_1 + R_{eq}}$$

$$= \frac{9.9\text{ k}}{10\text{ k} + 9.9\text{ k}} \times 100\text{ V} = 49.74\text{ V}$$

Thus the voltmeter with sensitivity of 20000 Ω/V will indicate 49.74 V.

The reading 49.74 V is near to 50 V. Thus the reading of high sensitivity voltmeter is near to the true voltage of resistance R_2.

3.19 Ohmmeter

The basic meter movement can be used to measure resistance if it is combined with a battery and current-limiting resistance as shown in Fig. 3.19 (*a*). In that case, it is known as an ohmmeter.

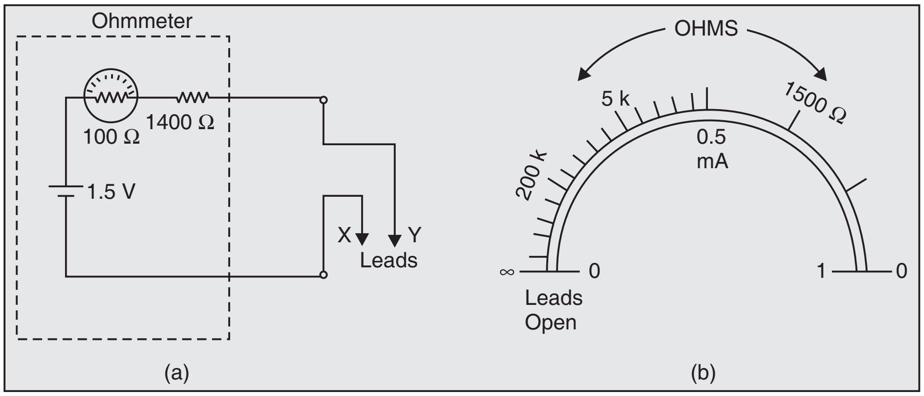


Fig. 3.19.

For measuring resistance, the ohm-meter leads X-Y are connected across the unknown resistance after switching off the power in the circuit under test. Only in that case, the ohmmeter battery can provide current for the meter movement. Since the amount of current depends on the amount of external resistance, the meter scale can be calibrated in ohms (instead of mA).

When the leads X-Y are shorted, meter current is 1.5V/(100 + 1400) W = 1 mA. The meter shows full-scale deflection to the right. The ohmmeter reading corresponds to 0 W because external resistance is zero. When leads X-Y are open i.e. do not touch each other, meter current is zero. Hence, it corresponds to infinite resistance on the ohmmeter scale.

Following points about the ohmmeter are worthnoting :

1. The resistance scale is non-linear i.e. it is expanded at the right near zero ohm and crowded at the left near infinite ohm. This nonlinearity is due to the reciprocal function $I = V/R$.
2. The ohmmeter reads up-scale regardless of the polarity of the leads because direction of current is determined by the internal battery;
3. At half-scale deflection, external resistance equals the internal resistance of the ohmmeter.
4. The test leads should be shorted and 'ZERO OHMS' control adjusted to bring the pointer to zero on each range.

3.20 Series Ohmmeter

This instrument essentially consists of a sensitive dc instrument connected in series with a resistance and a battery to a pair of terminals to which the resistance under test is connected. So that indication of the instrument depends on the magnitude of current flowing through the meter which ultimately depends on the value of resistance under test, provided the instrument is properly calibrated.

Circuit diagram of a simple series type ohmmeter is shown in Fig. 3.20. When terminals A and B are shorted together and the value of shunt resistor R_{sh} is adjusted so that the instrument indicates the full-scale reading on the scale then this position of the pointer corresponding to zero resistance. When terminals A and B are left open no current flows through the meter and it does not give any movement on the scale and the position of pointer corresponds to ∞ resistance.

A convenient quantity to use to design of a series type ohmmeter is the value of R_x which causes half-full scale deflection of the instrument. At this position the resistance across terminals A and B is defined as the half-scale position resistance R_h. IF full-scale deflection current of the meter, f_m, internal resistance of the meter, R_m, the battery emf E and the half-scale resistance R_h are given then the circuit can be analyzed and the values of R_{se} and R_{sh} can be determined.

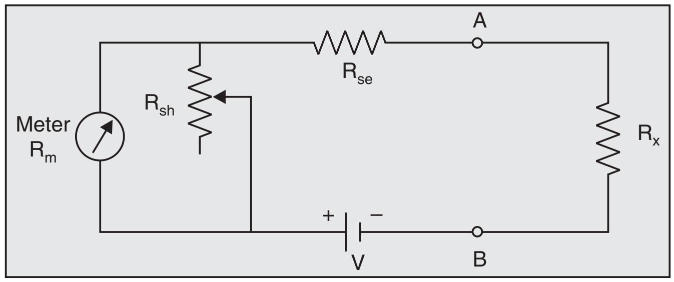


Fig. 3.20.

When the terminal A and B is shorted

When the terminal *A* and *B* is shorted (unknown resistor R_x = 0), the maximum current is flows in the circuit. In this condition the shunt resistor is adjust until the movement indicates full-scale current (I_{fsd}). The full scale current position of the pointer is marked "0 Ω" on the scale.

When the terminal A and B is opened

When the terminal *A* and *B* is opened (unknown resistor $R_x = \infty$), the current in the circuit drops to zero and the movement indicates zero current, which is then marked "∞ Ω" on the scale.

By connecting different known resistance across the terminals *A B*, intermediate marking can be done on scale. The accuracy of the instrument can be checked by measuring different values of the standard resistance.

The current is inversely proportional to the resistance, the scale is marked from ∞ to 0 as shown in Fig 3.21.

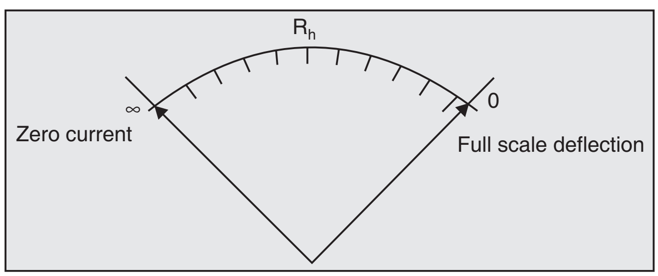


Fig. 3.21.

values of R_{se} ~~R_1~~ and R_{sh} ~~R_2~~ can be determined from the value of R_x.

A convenient quantity to use in design of a series type ohmmeter is the value if R_x which causes half-scale deflection of the meter. At this position, the resistance across terminals *A* and *B* is defined as the half-scale position resistance R_h. Its value is equal to the total resistance R_1 in series with parallel combination of R_m and R_{sh}.

$$R_h = R_{se} + \frac{R_{sh} R_m}{R_{sh} + R_m} \qquad \ldots(i)$$

The total resistance presented to the battery then equals $2R_h$, and the battery current needed to supply the half-scale deflection is

$$I_h = \frac{E}{2R_h}$$

for full scale deflection, the battery current must be doubled

$$I_f = 2I_h = \frac{E}{R_h}$$

shunt current through R_{sh} ~~R_2~~ is

$$I_{sh} = I_f - I_{fm} \qquad \ldots(ii)$$

$$I_2 = I_t - I_{fsd} \qquad \ldots(ii)$$

voltage across the shunt (E_{sh}) is equal to the voltage across the movement

$$E_{sh} = E_m$$

$$I_{sh} R_{sh} = I_{fm} R_m$$

$$R_{sh} = \frac{I_{fm} R_m}{I_{sh}}$$

substituting eq (*ii*) in above equation we get

$$R_{sh} = \frac{I_m R_m}{I_f - I_{fm}} = \frac{I_{fm} R_m R_h}{E - I_{fm} R_h} \qquad \ldots(iii)$$

solving equation (*i*) using above equation

$$R_{se} = R_h - \frac{I_{fm} R_m R_h}{E} \qquad \ldots(iv)$$

The value of resistance R_{se} ~~R_1~~ and R_{sh} ~~R_2~~ determined by equation (*iii*) and (*iv*).

Example 3.11. *A 50 Ω basic movement requiring a full scale current of 1 mA is to be used as series ohmmeter. The internal battery voltage is 3 V. A half scale deflection marking desired is 1000 Ω. Calculate*

(i) *Values of R_{se} and R_{sh}*

(ii) *Maximum value of R_{sh} ~~R_2~~ to compensate for a 5 % drop in battery voltage*

Solution. Given: $R_h = 1000\ \Omega$; $R_m = 50\ \Omega$; $V = 3$ V and $I_{fm} = 1$ *m*A.

Values of R_{se} and R_{sh}

We know that the value of R_{se} resistance in ohmmeter,

$$R_{se} = R_h - \frac{I_{fm} R_m R_h}{E}$$

$$= 1000 - \frac{1\times10^{-3}\times50\times1000}{3}$$

$$= 983.33\ \Omega \ \textbf{Ans.}$$

we also know that the value of R_{sh},

$$R_{sh} = \frac{I_{fm} R_m R_h}{E - I_{fm} R_h}$$

$$= \frac{1\times10^{-3}\times50\times1000}{3-1\times10^{-3}\times1000} = 25\ \Omega\ \textbf{Ans.}$$

Maximum value of R_2 to compensate for a 5 % drop in battery voltage

Due to 5 % drop in battery voltage, then the voltage become

$$V = 3 - 0.05 \times 3 = 2.85 \text{ V}$$

We know that the value of R_{sh}

$$R_{sh} = \frac{I_{fm} R_m R_h}{E - I_{fm} R_h}$$

$$= \frac{1 \times 10^{-3} \times 50 \times 1000}{2.85 - 1 \times 10^{-3} \times 1000} = 27.027 \ \Omega \ \textbf{Ans.}$$

3.21 Shunt Type Ohmmeter

Fig. 3.22 Show the shunt type ohmmeter. It consists of a battery in series with an adjustable resistance R_{se} and a D'Arsonval movement. The known resistance is connected in parallel with the meter. The switch disconnects the battery when the instrument is not in use.

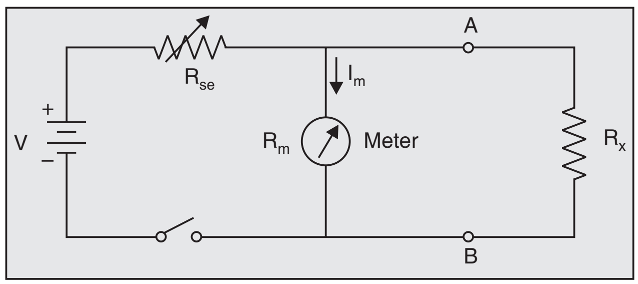


Fig. 3.22.

When the terminal A and B is shorted:

When the terminal A and B is short than the entire current flows through the short circuit and the meter current is zero. This pointer position is marked as zero and the corresponding $R_X = 0$ as terminals AB are shorted.

When the terminals A and B are open:

When the terminals A and B are open, then the entire current flows through the meter and pointer deflects to maximum. The resistance R_{se} is then adjusted such that current through the meter is full scale deflection current. This position of pointer is marked as ∞.

The scale is marked as 0 to ∞ as shown in Fig. 3.23.

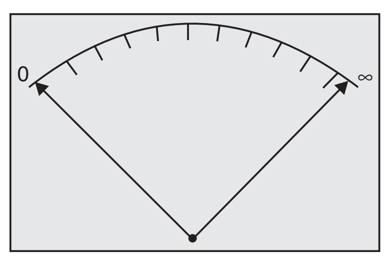


Fig. 3.23.

When the terminals A and B open-circuited, the current flowing through the meter

$$I_{fm} = \frac{V}{R_{se} + R_m}$$

with terminals A and B connected across resistance under test, R_x

$$\text{Battery Current, } I_B = \frac{V}{R_{se} + \dfrac{R_m R_x}{R_m + R_x}}$$

and current flowing through the meter, I_m

$$I_m = \frac{V}{R_{se} + \dfrac{R_m R_x}{R_m + R_x}} \times \frac{R_x}{R_m + R_x}$$

The meter current expressed as a fraction of the full-scale deflection current,

$$S = \frac{I_m}{I_{fm}} = \frac{R_x(R_{se} + R_m)}{R_{se}(R_m + R_x) + R_m R_x}$$

$$= \frac{R_x}{R_x + \dfrac{R_{se}R_m}{(R_{se} + R_m)}} = \frac{R_x}{R_x + R_p}$$

where,
$$R_p = \frac{R_{se}R_m}{(R_{se} + R_m)}$$

From the above expression for S it is obvious that the half-way mark on the scale occurs when $R_x = R_p$. The distribution of scale marking is almost linear in the lower part i.e. for $R_x << R_p$ and it becomes progressively more crowded as R_x increases.

So half-full scale reading will be when,

$$R_h = \frac{R_{se}R_m}{R_{se} + R_m}$$

This type of ohmmeter is particularly suited for the measurement of low value resistors.

3.22 Wattmeter

Power is defined as the rate at which energy is transformed or made available. The power is a circuit at any instant is equal to the [product of the current in the circuit and the voltage across its terminal at that instant. The power in a dc circuit is best measured by separately measuring quantities V and I and by computing power by formula $P = VI$. In the case of ac circuit the instantaneous power varies continuously as the current and voltage of though a cycle of values. If the voltage and current are both sinusoidal the average power over cycle is given by the expression $P = VI \cos \phi$ watts where V and I are the *r.m.s.* values of voltage and current.

A wattmeter is a device used to measure how much electrical power a circuit is producing, expressed in watts. It uses resistance to move a piece of metal, which is carefully calibrated along a display with wattage numbers on it, the higher the wattage, the more the piece of metal will move.

The wattmeter is an instrument for measuring the electric power in watts of any given circuit. Wattmeter is the combination of both ammeter and voltammeter. It consists of two coil current coil and pressure coil. The current coil is inserted in series with the line carrying current to be measured and the pressure coil in series with a high non-inductive resistance R is connected across the load or supply terminal. There are different types of wattmeter and they are given below:

3.23 Dynamometer Type Wattmeter

A dynamometer is a device for measuring force, moment of force (torque), or power. For example, the power produced by an engine, motor or other rotating prime mover can be calculated by simultaneously measuring torque and rotational speed.

A dynamometer can also be used to determine the torque and power required to operate a driven machine such as a pump. In that case, motoring or driving dynamometer is used. A dynamometer that is designed to be driven is called an

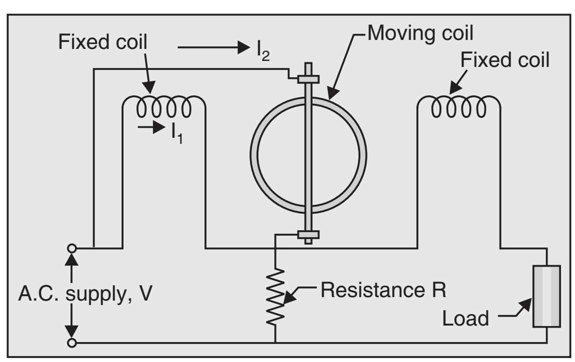


Fig. 3.24.

absorption or passive dynamometer. A dynamometer that can either drive or absorb is called a universal or active dynamometer.

Figure 3.24 show the dynamometer. The fixed coil (current coil) which is divided into two equal portion in order to provide uniform field. It is designed to handle the full load current. The moving coil is used as a pressure coil. The fixed coil carry the current through the circuit and the moving coil carries the current proportional to the voltage across the circuit. A high non-inductive resistance is connected in series with the moving coil in order to limit the current in the circuit. Since one flux is proportional to load current and the other is proportional to load voltage, the torque on the pointer or the moving coil is proportional to the power. The magnetic field of the fixed and moving coils reacts on one other causing the moving coil to turn about its axis.

The moving coil is carried on a pivoted spindle and the movement is spring controlled. The moving system carries a pointer and a damping vane, the latter moving in a sector-shaped box. The current coils are usually laminated when heavy current are to be carried. Damping is provided by light aluminum vanes moving in air dash pot.

Let I_1 = main circuit current flowing through the fixed coil

I_2 = current proportional to the supply voltage

B = flux density

V = supply voltage

$$B \propto I_1$$

and

$$B = K_1 I_1$$

Where K_1 is a constant.

also

$$I_2 \propto V$$

$$I_2 = K_2 V$$

Where K_2 is another constant. The deflecting torque is given by,

$$T_d \propto BI_2 \propto I_1 V$$

$$T_d = KVI_1 = K \times \text{Power}$$

Where K is a constant. In dc circuit the power is given by the product of the voltage and current. Hence the torque is directly proportional to power. In ac circuit the mean deflecting torque T_m is given by,

$$T_m \propto VI \cos \theta \propto \text{True Power}$$

Advantages

Some of the main advantages are given below:

1. It gives a very degree of accuracy.
2. Scale is not uniform
3. It can be used on both ac and dc supply.

Disadvantages

Some of the disadvantages are given below:

1. Errors due to voltage drop in the circuit.
2. Errors due to the current taken by the voltage coil.

3.24 Induction Type Wattemeter

Figure 3.25 shows an induction type wattmeter. It consists of two laminated electromagnets. One of them is excited by the load current of main circuit, series or current magnets and its exciting coil (current coil) is connected in series with circuit. The other is excited by a current proportional to the voltage of the circuit called shunt magnet. Its exciting coil known as voltage of pressure coil is connected in parallel with the circuit. A thin aluminum disc is mounted of such a way that is cuts the fluxes of both magnets, and the deflecting torque is produced by the interaction between these fluxes and the eddy current which they induce in the disc.

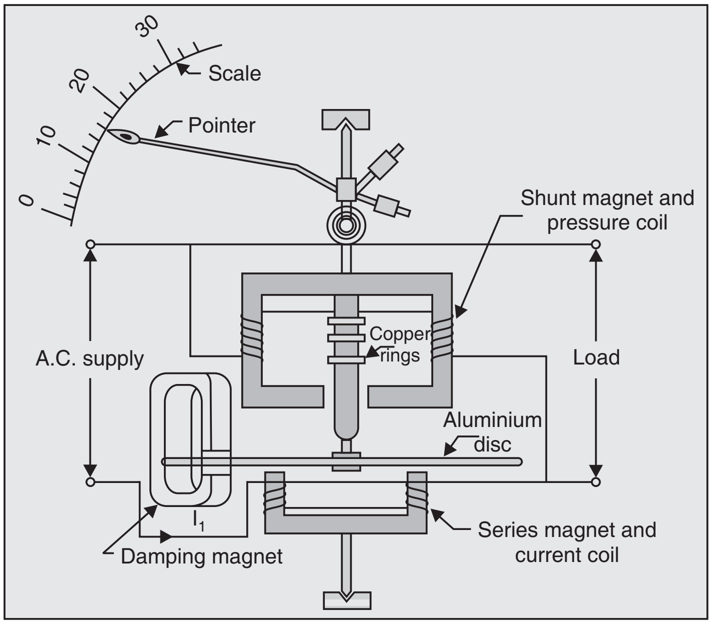


Fig. 3.25.

The two or three copper rings are fitted on the central limb of the shunt magnet and can be adjust to make the resultant flux in the shunt magnet lag behind the applied voltage by 90°. The two pressure coils are joined in series and are so wound that both send the flux through the central limb in the same direction. The series magnet also carries two coils joined in series and are so wound that they magnetize their respective magnetic cores in the same direction. Desired phase shift between the two magnets fluxes can be obtained by adjusting the position of the copper shading rings. The controlling torque in induction wattmeter is provided by a spring fitted to the spindle of the moving system which also carries the pointer. The damping in these instruments is provided by the eddy current induced in the aluminum disc due to the fluxes produced by a permanent magnet.

The current coil carries the line current I_1 so that the flux produced by it is directly proportional to the line current I_1 and is in phase with it.

$$\phi_1 \propto I_1$$

The pressure coil of the shunt magnet is made highly inductive, having an inductance L and negligible resistance. This is connected across the supply voltage V,

$$\phi_2 \propto I_2 \propto \frac{V}{\omega L}$$

Where $\omega = 2\pi f$

f = supply frequency

ϕ_2 lags behind the supply voltage by 90°. Now let the load current I_1 lag behind V by an angle ϕ. Therefore the phase angle between ϕ_1 and ϕ_2,

$$\alpha = (90° - \phi)$$

The Deflection torque acting on the aluminum disc is given by,

$$T_d = K\,\omega\,\phi_1\,\phi_2 \sin\alpha$$

Where K is the constant. Now substituting the value of ϕ_1 and ϕ_2 in above equation we get,

$$T_d = K\,\omega\,I_1\,\frac{V}{\omega L}\sin(90° - \phi)$$

$$T_d = K'\,VI_1 \cos\phi$$

Where K' is constant,

$$T_d \propto VI_1 \cos\phi \propto \text{Power}$$

The deflection torque is proportional to the power in the load circuit.

Advantages

Some of the advantages of the induction wattmeter are given below:

1. Have large scales
2. Can handle current upto 100 amperes.
3. Free from the effects of stray fields.
4. Practically free from frequency errors.

Disadvantages

Some of the disadvantages are given below:

1. Scale is not uniform.
2. Temperature errors.
3. Used only when the frequency and the supply voltage are constant.

3.25 Measurement of Power in Three Phase Circuit

In the three phase circuit the quantity may be of two types phase quantity and line quantity. The voltage and current both phase and line values are *rms* values.

The voltage may be measured between either two phases or one phase and one neutral and similarly current may be flow between either two phases or one phase and one neutral. When the quantity is being measured phase to phase is called line quantity. When the quantity is being measured phase to neutral called phase quantity.

Let three phase are R, Y and B and neutral N them phase voltage for R phase Y phase and B phase can be represented as V_{RN}, V_{YN} and V_{BN} respectively or simply can also be represented as V_R, V_Y and V_B respectively. Line voltage V_{RY} means the voltage between the phase R and phase Y keeping in mind that R is the forward path and Y is the reverse path here in this way the line voltage can be taken for any two phases.

3.26 Power in Three Phase Circuit with Balanced Load

The power input to a single phase ac circuit is $VI\cos\phi$. Thus the per phase in a 3-phase system is $V_P I_P \cos\phi$. Where V_P and I_P are the *rms* value of per phase voltage and current respectively and ϕ is the angle between the phase current and phase voltage caused by the load. Hence the total power fed to a three phase system with balanced load,

$$= 3 \text{ power per phase}$$

$$= 3V_P I_P \cos\phi$$

In the three phase system the voltages and current are given as line voltage normally. For a star connected three phase circuit,

$$I_P = I_L \text{ and } V_L = \sqrt{3}\,V_P$$

$$\text{Power} = 3V_P I_P \cos\phi$$
$$= \sqrt{3}\, V_L I_L \cos\phi$$

and for delta connected phase circuit,

$$V_P = V_L \text{ and } I_L = \sqrt{3} I_P$$
$$\text{Power} = 3V_P I_P \cos\phi$$
$$= \sqrt{3}\, V_L I_L \cos\phi$$

The power fed to the load through three phase circuit is independent of the connection of the circuit.

The power of single phase circuit can be measured by using the wattmeter. It is necessary to know how it operated for measurement of power which is the product of two Phasor quantity voltage and current. The wattmeter shown in Fig. 3.26 consists of two coils current coil and pressure coil.

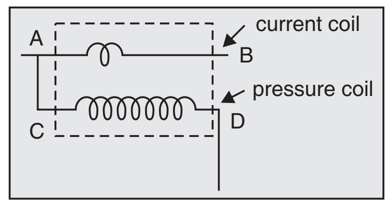


Fig. 3.26.

The wattmeter is such calibrated that the current coil responds to the current of the circuit and pressure coil responds to the voltage in circuit and the overall reading is equal to the $VI \cos\phi$. To measure the power in three phase circuit we can use three arrangements of wattmeter they are given below:

1. Three wattmeter method
2. Two wattmeter method
3. One wattmeter method

We will discuss each method one by one in the following pages.

3.27 Three Wattmeter Method

In this method three wattmeter are used. Each wattmeter is connected between a phase and neutral. This method is employed for measurement of power in 3- phase 4-wire circuit. Figure 3.27 shows the connection of three wattmeter method. As the neutral wire is common to the three phase each wattmeter reads power in its own phase and the total power of the load circuit is given by the sum of the reading of the three wattmeter.

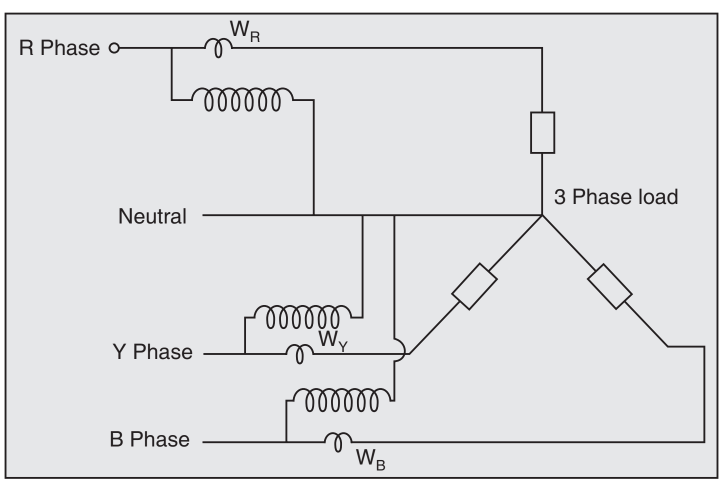


Fig. 3.27.

The total power of load circuit,

$$P = W_R + W_Y + W_B$$

In balanced condition,

$$\text{Total Power} = V_\phi I_\phi \cos\phi + V_\phi I_\phi \cos\phi + V_\phi I_\phi \cos\phi$$
$$= 3V_\phi I_\phi \cos\phi$$
$$= \sqrt{3}\, V_L I_L \cos\phi$$

3.28 Two-Wattmeter Method

In this power in a 3-phase three wire system having balanced or unbalanced load can be measured by using two wattmeter. The load mat be start or delta connected. The current coil of the two wattmeter are connected in any of the two phase wires and the pressure coil are connected between three phase wires.

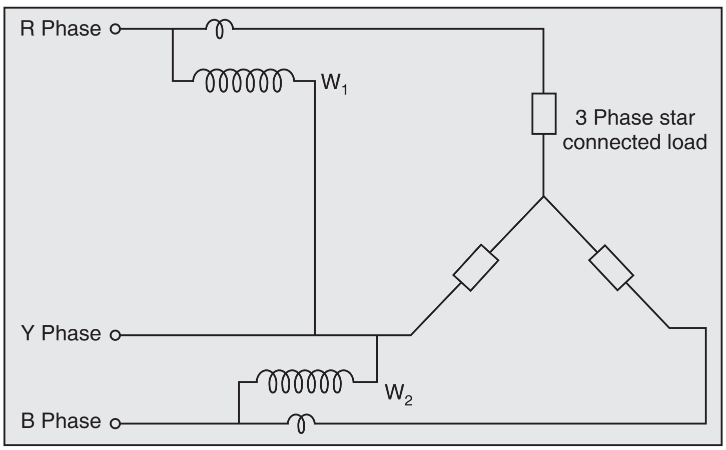


Fig. 3.28.

The first wattmeter is connected the phase R and Y. The current coil in R phase while the pressure coil is across the phase R and Y. So the value of the wattmeter,

$$W_1 = V_{RY}\, I_R \cos\phi_1$$

Where ϕ_1 is the angle between the vector V_{RY} and I_R

The second wattmeter is connected between the phase B and Y. The current coil in B phase while the pressure coil is across B and Y. So the value of the wattmeter,

$$W_2 = V_{BY}\, I_B \cos\phi_2$$

To find the value ϕ we have to draw the phasor diagram. The phasor for star connected system is shown in Fig. 3.29, it including the three phase currents I_R, I_Y and I_B. If the load power factor is cos ϕ lagging this means the phase current I_R, I_Y and I_B will lag by ϕ angle with their corresponding phase voltage V_R, V_Y and V_B respectively. Now we can find out the require angle ϕ_1 and ϕ_2. First we draw the phase voltages V_R,

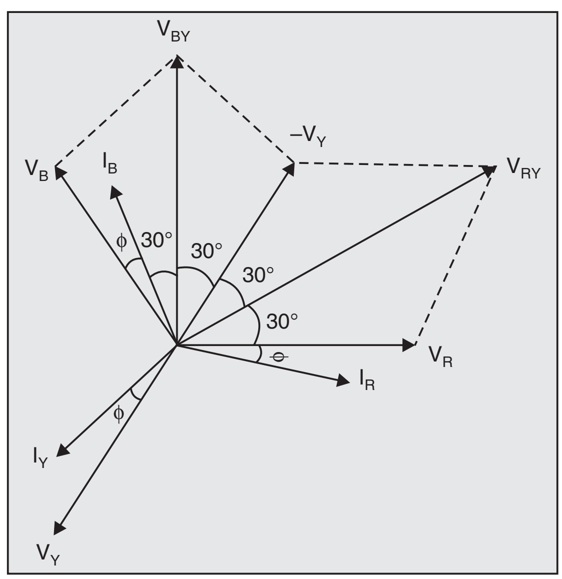


Fig. 3.29.

V_Y and V_B. Then the three phase current I_R, I_Y and I_B corresponding to phase voltage V_R, V_Y and V_B each current will lag by ϕ angle corresponding to its voltage. The angle ϕ_1 and ϕ_2 are,

$$\phi_1 = \angle V_{RY} \text{ and } I_R$$
$$= 30° + \phi$$

and

$$\phi_2 = \angle V_{BY} \text{ and } I_B$$
$$= 30° - \phi$$

for the star connected load,

$$I_P = I_L$$
$$W_1 = V_{RY} \cdot I_R \cos \phi_1$$
$$= V_L \cdot I_P \cos (30° + \phi)$$
$$W_2 = V_{BY} \cdot I_B \cos \phi_2$$
$$= V_L \cdot I_P \cos (30° - \phi)$$
$$W_1 = V_L \cdot I_L \cos (30° + \phi)$$
$$W_2 = V_L \cdot I_L \cos (30° - \phi)$$

and,

$$W_1 - W_2 = V_L \cdot I_L \sin \phi$$

On adding W_1 and W_2 we get,

$$W_1 + W_2 = V_L \cdot I_L [\cos (30° + \phi) + \cos (30° - \phi)]$$
$$W_1 + W_2 = \sqrt{3}\, V_L . I_L \cos \phi \qquad ...(i)$$

We can conclude that the sum of two wattmeter value will be equal to the resultant power of three phase circuit.

$$W_1 - W_2 = V_L . I_L [\cos (30° + \phi) - \cos (30° - \phi)] \qquad ...(ii)$$
$$W_1 + W_2 = V_L . I_L \sin \phi$$

Dividing the equation (*i*) and (*ii*) we get,

$$\tan \phi = \frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)}$$

For leading power factor,

$$\tan \phi = -\frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)}$$

3.29 One Wattmeter Method

This method is same as two wattmeter method except only one wattmeter is used with ON-OFF switches connection in pressure coil with rest two phase wires. The current coil of the wattmeter is connected in *R* phase. The pressure coil of the wattmeter can be connected in the phase *Y* or phase *B* with the help of ON-OFF switches S_1 and S_2. If the switch S_i is ON, the wattmeter reads the power between phase *R* and *Y*.

$$W = V_{RY} . I_R \cos \phi_1$$

If the switch S_2 is ON the wattmeter reads the power between *R* and *B*,

$$W = V_{RB} . I_B \cos \phi_2$$

The total power of three phase circuit can be calculated by adding these two wattmeter reading same as in two wattmeter methods.

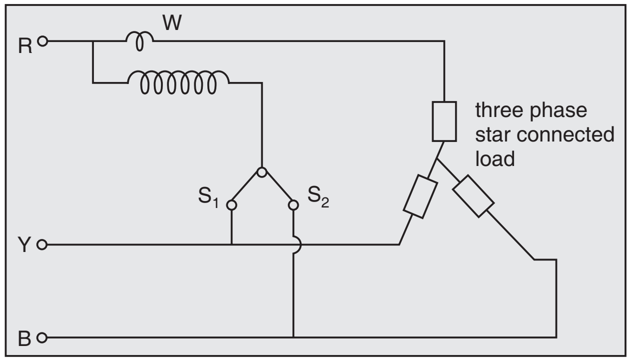


Fig. 3.30.

3.30 Blondel's Theorem

Blondel's theorem state that in a system of *N* electrical conductors, *N*-1 electrical meter or wattmeter elements, when properly connected, will measure the electrical power or energy taken.

In an *N*-wire circuit, the total power supplied is given by the algebraic sum of the readings of *N* wattmeters, so arranged that a current coil of a wattmeter is in each wire and the corresponding potential coil is connected between that wire and a common point on the system.

3.31 Instrument Transformer

Instrument transformers are designed to transform voltage or current from the high values in the transmission and distribution systems to the low values that can be utilized by low voltage metering devices. Instrument transformer isolate measurement, protection and control circuitry from the high currents or voltages present on the circuits being measured or controlled. There are two type of instrument transformers, they are given below:

1. Current Transformer
2. Potential Transformer

Current transformer (CT) together with potential transformer (PT), are known as instrument transformers. We will discussed each transformer one by one in the following pages.

3.32 Current Transformer

The current transformer (CT) is used for measurement of electric currents. When current in a circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring and recording instruments. It used in conjunction with current measuring devices, its primary winding is designed to be connected in series with the line. It is necessary that the impedance of the primary winding be made as small as possible. The secondary winding consists of more turns than the primary winding. The ratio of primary to the secondary current is inversely proportional to the ratio of primary to secondary turns. This transformer is usually step-up transformer in terms of primary to secondary turn ratio.

In current transformer the load impedance or burden on the secondary is very small, so the current transformer operates on short-circuit conditions. The current through the secondary winding depends upon the current flowing in the primary winding. A current transformer also isolates the measuring instruments from what may be very high voltage in the monitored circuit. Current transformer are commonly used in metering and protective relays in the electrical power industry.

Figure 3.31 show the circuit of current transformer. As seen from the figure the primary winding of the transformer is connected in series with the line carrying high current. The secondary of the transformer is made up of a large number of turns of fine wire having small cross-section area. This is connected to the coil of normal range ammeter.

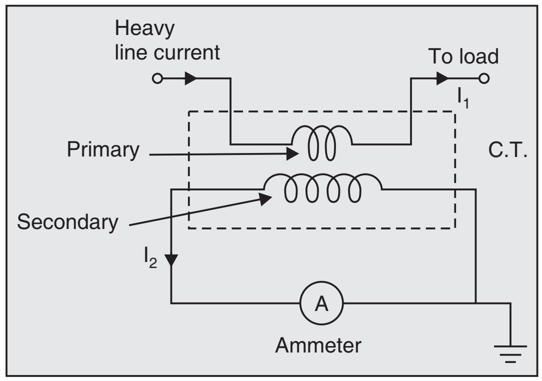


Fig. 3.31.

This transformer is basically step-up transformer, its step-up a voltage from primary to secondary. Thus it reduce current from primary to secondary. From the current point of view it is step-down transformer.

Lets N_1 is the number of turns in primary winding and N_2 is the number of turns in secondary. Primary current is I_1 and secondary current is I_2 in the current transformer, then

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

N_2 is high as compare to N_1, the ratio of I_1 to I_2 is also high for current transformer. For example consider 200 : 5 ranges. Its indicate that the current transformer step-down the current from primary to secondary by a ratio 100 to 5.

In wound type construction the primary is wound for more than one full turn, on the core. In a low voltage wound type current transformer, the secondary winding is wound on a backelite former. The heavy primary winding is directly wound on the top of the secondary winding with a suitable insulation in between the two. Otherwise the primary is wound completely separately and then tapped with suitable insulating material and assembled with the secondary on the core.

In bar type construction the primary winding is a bar of suitable size. It passes through the centre of a hollow metal core. The bar may be of rectangular or circular cross-section. The secondary winding is wound on this core.

3.33 Secondary Side of Current Transformer should not be Open

The secondary side of current transformer should not be kept open. Either it should be shorted or must be connected in series with a low resistance coil such as current coils of wattmeter, coil of ammeter etc. If it is left open, then current through secondary becomes zero hence the ampere turns produced by secondary which generally oppose primary ampere turns becomes zero. As there is no counter magnetomotive force (MMF) to unopposed primary MMF (ampere turns), its produce high flux in the core. This produces excessive core losses, heating the core beyond limits. Similarly heavy electromotive force will be induced on the primary and secondary side. This may damage the insulation of the winding. It is usual to ground the current transformer on the secondary side to avoid a danger of sock to the operator.

Hence never open the secondary winding circuit of a current transformer while its primary winding is energised. Thus most of the current transformer have a short circuit link or a switch at secondary terminals. When the primary is to be energised, the short circuit link must be closed so that there is no danger of open circuit secondary.

3.34 Phasor Diagram For a Current Transformer

Figure 3.32 show the phasor diagram of current transformer the magnitude of magnetising component I_m and iron-less component I_e of the exciting current I_o are exaggerated for convenience in drawing. Taking flux ϕ as reference phasor, the induced emfs in the primary and secondary winding. E_P and E_s lagging behind the flux ϕ by 90°.

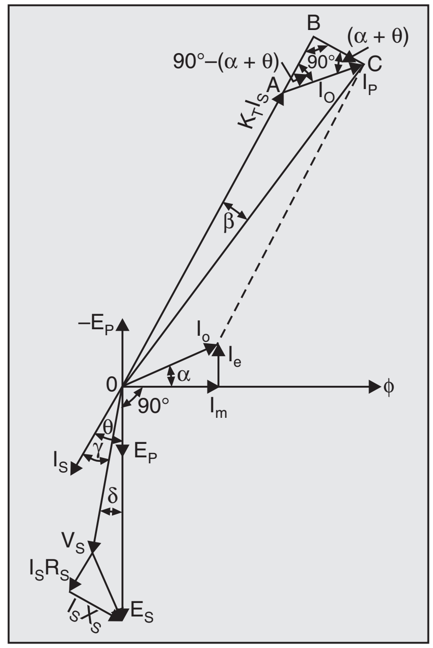


Fig. 3.32. Phasor diagram for CT

The excitation current I_o drawn by the primary is constituted by two components I_m and I_e. The secondary current I_s lags behind the secondary induced emf by an angle θ, where θ is the sum of angle δ, the angle produced by the secondary winding resistance R_s and reactance X_s and angle γ.

The secondary current is now transferred to the primary side by receiving secondary current phasor I_s and multiplying by the turn ratio K_T. The resultant primary current I_P is the phasor sum of $K_T I_s$ and no-load current I_o.

The primary current I_P

$$I_P = OC \simeq OB$$
$$= OA + AB$$
$$= K_T I_s + I_o \sin(\alpha + \theta)$$

If θ is very small, then primary current,

$$I_P = K_T I_s + I_o \sin \alpha$$
$$= K_T I_s + I_e$$

Thus the actual current ratio,

$$K_C = \frac{\text{Primary Winding Current}}{\text{Secondary Windin Current}}$$

$$= \frac{K_T I_s + I_e}{I_s}$$

$$= K_T + \frac{I_e}{I_s}$$

The actual current ratio is also known as transformation ratio R. From the phasor diagram

$$\tan \beta = \frac{BC}{OB} = \frac{I_o \cos(\alpha + \theta)}{K_T I_s + I_o \sin(\alpha + \theta)}$$

I_o is very small as compared to $K_T I_s$, hence I_o sin (α + θ) can be neglected and β is very small,

$$\beta = \frac{I_o \cos(\alpha + \theta)}{K_T I_s}$$

If the secondary phase angle θ is very small then,

$$\text{Phase angle } (\beta) = \frac{I_o \cos\alpha}{K_T I_s}$$

$$= \frac{I_m}{K_T I_s} \text{ radians.}$$

3.35 Error in Current Transformer

The error in current transformer are discussed below.

Ratio Error. It is given by,

$$\text{Ratio Error} = \frac{\text{Nominal Ratio} - \text{Actual Ratio}}{\text{Actual Ratio}}$$

$$= \frac{K_n - K_c}{K_c}$$

Where K_n is the nominal ratio and given by,

$$K_n = \frac{\text{Rated primary current}}{\text{Rated secondary current}}$$

Nominal ratio K_n is normally equal to turn-ratio K_T of current transformer.

$$K_n = K_T = \frac{\text{Number of turns on secondary winding}}{\text{Number of turns on primary winding}}$$

The actual ratio K_c is defined as the ratio of actual primary current to secondary current,

$$K_c = \frac{\text{Actual Primary Current}}{\text{Actual Secondary Current}}$$

$$= \frac{K_T I_s + I_o \sin(\alpha + \theta)}{I_s}$$

$$= \frac{K_T I_s + I_m \sin\theta + I_e \cos\theta}{I_s} \quad ...(i)$$

So ratio error

$$= \frac{K_m - K_c}{K_c}$$

$$= \frac{K_T - K_c}{K_c}$$

Substituting the value of K_c in above equation, we get,

$$= \frac{K_T I_s - (K_T I_s + I_m \sin\theta + I_c \cos\theta)}{K_T I_s + I_m \sin\theta + I_e \cos\theta}$$

The ratio error is small than denominator is very nearly equal to K_T I_s and the ratio error is given by,

$$\text{Ratio Error} = \frac{-I_m \sin\theta - I_e \cos\theta}{K_T I_s}$$

Ratio error is taken as positive when actual ratio of CT is less than nominal ratio. In above expression of ratio error negative sign indicates that the actual ratio of CT is more than nominal ratio.

Phase Angle Error. The angular phase displacement β between I_P and I_s reversed is called the phase angle error of the CT.

$$\beta = \frac{I_o \cos(\alpha + \theta)}{K_T I_s}$$

$$= \frac{I_o \cos\alpha \cos\theta + I_o \sin\alpha \sin\theta}{K_T I_s}$$

$$= \frac{I_m \cos\theta - I_c \sin\theta}{K_T I_s} \text{ radians}$$

Thus in power measurement owing to use CT are two types of errors are introduced one due to actual transformation ratio being different from the turn-ratio and other due to secondary winding current not being 180° out of phase with the primary winding current.

The angle θ, sum of two small angled δ and γ is very small. Hence $\cos\theta \simeq 1$ and $\sin\theta \simeq 0$, then the ratio error and phase angle error,

$$\text{Ratio error} = \frac{-I_e}{K_T I_s}$$

$$\beta = \frac{I_m}{K_T I_s} \text{ radian.}$$

3.36 Characteristics of Current Transformers

The performance variation with load conditions are given below:

1. **Effect of change in Primary Winding Current.** At low load-current values, exciting current I_o is a greater proportion of primary current I_P owing to the curvature of the *B-H* curve of the core material at low flux densities. Thus the ratio error is made more negative and phase angle is made more positive normally. This means increased errors. When the primary winding current I_P increase, there is increase in secondary winding current I_s and there is decrease in ratio error and phase angle with secondary.
2. **Effect of change in Power Factor of Secondary Burden.** Reduction of the power factor of the secondary burden increases the angle γ and hence θ and thus brings the phasor K_T, I_s and I_o more nearly into phase with one another. Thus primary current I_P is increased and again the ratio error is made more negative. The phase angle error is obviously reduced with reduction of power factor, since $K_T\ I_s$ move more near into phase with I_o. For burdens which are sufficiently capacitor I_s leads E_s and so angle θ is negative and actual transformation ratio decreases, become less than the turn-ratio for values of θ approaching – 90°.
3. **Effect of change in Frequency.** The effect of frequency variation is less important than that of variation of load and load power factor. The variation of magnetizing and iron-less magnetizing force, with variation of frequency is comparatively small if the frequency variation does not exceed 10-20 kHz, so that an approximation, they may be considered independent of frequency.

Example 3.12. *A current transducer with a bar has 300 turns in its secondary winding. The resistance and reactance of the secondary circuit are 1.5 Ω and 1.0 Ω respectively including the* *transformer winding with a 5 A flowing in the secondary winding, the magnetising mmf is 100 amperes and the iron loss is 1.2 watts. Determine the ratio and phase errors.*

(GBTU, 2004-05)

Solution. Given $N_s = 300$; $I_s = 5$ A; *mmf* = 100 A and iron loss = 1.2 W

We know that the turn ratio,

$$K_T = \frac{N_2}{N_1} = \frac{300}{1} = 300$$

and secondary impedance,

$$Z_S = (1.5 + 1.0\,j) = 1.8 \angle 33.7^\circ\ \Omega$$

and secondary voltage,

$$E_2 = I_2 Z_2 = 5.0 \times (1.5 + 1.0\,j) = 9\text{V}$$

and,

$$I_m = \frac{mmf}{N_1} = \frac{100}{1} = 100 \text{ A}$$

We know that the energy component of exciting current on secondary side,

$$\frac{\text{Iron Loss}}{E_2} = \frac{1.2}{9} = 0.13 \text{ A}$$

We also know that the energy component of exciting current on primary side,

$$I_e = N_2 \times \text{energy component of exciting current on secondary side}$$
$$= 300 \times 0.133 = 40 \text{ A}$$

and exciting current in primary side,

$$I_o = (I_m + jI_e) = 100 + j\,40 = 107.7 \angle 21.8^\circ\text{A}$$

We know that actual current ratio,

$$K_C = K_T + \frac{I_o \sin(\theta + \alpha)}{I_2} = 300 + \frac{107.7 \sin(33.7^\circ + 21.8^\circ)}{5} = 317.6$$

We know that the percentage ratio error,

$$= \frac{K_N - K_C}{K_C} \times 100 = \frac{300 - 317.6}{317.6} \times 100 \qquad ...(K_N = K_T)$$

$= -\ 5.54\%$ **Ans.**

We also know that the phase angle is given by,

$$\beta = \frac{I_o \cos(\theta + \alpha)}{K_T I_2} = \frac{107.7 \cos(33.7^\circ + 21.8^\circ)}{300 \times 5} \text{ radians} = 2.33^\circ \text{ radians}$$ **Ans.**

Example 3.13. *At its rated load, 25 VA, a 100/5 ampere current transformer has an iron loss of 0.2 W and a magnetizing current of 1.5 A. Calculate its error and phase angle when supplying rated output to a meter having a ratio resistances to reactance as 6.0.*

(GBTU, 2001-02)

Solution. Given: $K_T = 100/5 = 20$; $I_s = 5$ A; rated burden = 25 VA; $I_m = 1.5$ A and iron loss = 0.2 W.

We know that secondary voltage,

$$E_S = \frac{\text{Rated burden}}{I_S} = \frac{25}{5} = 5 \text{ V}$$

and total secondary impedance,

$$Z_S = \frac{E_S}{I_S} = \frac{5}{5} = 1\ \Omega$$

and ratio,

$$\text{Ratio} = \frac{R_S}{X_S} = 6$$

and,

$$\theta = \tan^{-1}\frac{X_S}{R_S} = \tan^{-1}\frac{1}{6} = 9.46°$$

We know that the energy component of exciting current on secondary side,

$$\frac{\text{Iron Loss}}{E_S} = \frac{0.2}{5} = 0.04\ \text{A}$$

We also know that the energy component of exciting current on primary side,

$I_e = N_S \times$ energy component of exciting current on secondary side

$= 20 \times 0.04 = 0.8\ A$

We know that the percentage ratio error,

$$= -\frac{I_m \sin\theta + I_e \cos\theta}{K_T I_S + I_e \cos\theta + I_m \sin\theta} \times 100$$

$$= -\frac{(1.5 \times \sin 9.46°) + (0.8 \times \cos 9.46°)}{(20 \times 5) + (0.8 \times \cos 9.46°) + (1.5 \times \sin 9.46°)} \times 100 = -1\%\ \textbf{Ans.}$$

We also know that the phase angle error,

$$\beta = \frac{180}{\pi} \times \frac{I_m \cos\theta - I_e \sin\theta}{K_T I_S} = \frac{180}{\pi} \times \frac{1.5 \cos 9.46° - 0.8 \sin 9.46°}{20 \times 5}$$

$= 0.7724°$ **Ans.**

Example 3.14. *A CT with turn-ratio of 1:201 is rated as 100/5 A, 25 VA. The core loss and magnetizing components of primary are 3A and 7A under rated conditions. Find the ratio and phase angle errors for full burden at 0.8 pg leading. Secondary winding and leakage may be neglected.*

(GBTU, 2002-03)

Solution. Given: $K_T = 201$; $K_N = 100/5$; $I_e = 3$ A; $I_m = 7$ A and $I_S = 5$ A.

We know that the angle α,

$$\text{angle } \alpha = \tan^{-1}\frac{I_e}{I_m} = \tan^{-1}\frac{3}{7} = 23.2°$$

We also know that the angle θ,

$$\text{angle } \theta = \delta + \gamma = 0 + \cos^{-1} 0.8 = -36.8°$$

and the current ratio,

$$K_C = K_T + \frac{I_e \cos\theta + I_m \sin\theta}{I_S} = 201 + \frac{(3 \times 0.8) + 7 \times (-0.6)}{5} = 200.64$$

We know that the ratio error,

$$= \frac{K_N - K_C}{K_C} \times 100 = \frac{200 - 200.64}{200.64} \times 100 = -0.319\%\ \textbf{Ans.}$$

We also know that the phase angle error,

$$\beta = \frac{180}{\pi} \times \frac{I_m \cos\theta - I_e \sin\theta}{K_T I_S} = \frac{180}{\pi} \times \frac{7 \times 0.8 - 3 \times (-0.6)}{201 \times 5} = 0.422° \textbf{ Ans.}$$

3.37 Potential Transformer

It's also called Voltage Transformer (VT). The potential transformer is used for measurement of high voltages by means of low range voltmeter. Both the primary and secondary windings are wound on a high grade steel, low voltage winding kept next to the earth core and the high voltage winding is on the outside. They reduce the voltage to a reasonable operating value. Primary winding consists of large numbers of turns while the secondary has less number of turns. The primary is connected across the high voltage line while secondary is connected to the low range voltmeter coil. The connection of potential transformer is shown in Fig. 3.33. The potential transformer are always step-down transformer.

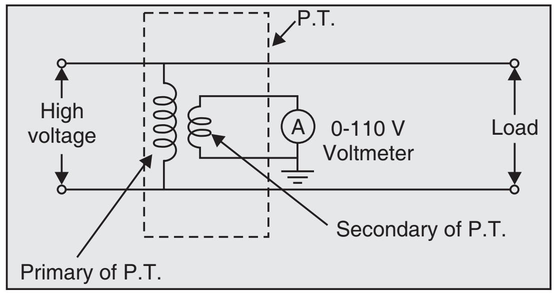


Fig. 3.33.

As shown in Figure the voltage being measured connect across the primary winding which has large number of turns and connected across the circuit. The secondary winding, which has much smaller number of turns, is coupled magnetically through the magnetic circuit to the primary winding. The turn ratio is adjusted that secondary voltage is 110V when full-rated primary voltage is applied to the primary.

3.38 Phasor Diagram for a Potential Transformer

Figure 3.34 show the phasor diagram of potential transformer (PT). In phasor diagram E_S is the secondary induced emf and V_S is the secondary terminal voltage which is obtained by subtracting vectorially the resistive and reactive drops from secondary emf E_S. I_S is the secondary current lagging behind the secondary terminal voltage V_S by ϕ.

The primary induced emf E_P which is in opposition to the secondary induced emf E_S is obtained by subtracting the resistive and reactive drops caused by primary current from primary voltage applied V_P.

The phase angle of the transformer is the angle β between the reversed secondary voltage $K_T V_S$ and the primary voltage V_P and is taken as positive when the reversed secondary voltage is in advance of the primary voltage phasor.

Along the $K_T V_S$ axis we get,

$$V_P \cos\beta = K_T V_S + K_T I_S R_S \cos\phi + K_T I_S X_S \sin\phi + I_P R_P \cos\theta + I_P X_P \sin\theta \quad ...(i)$$

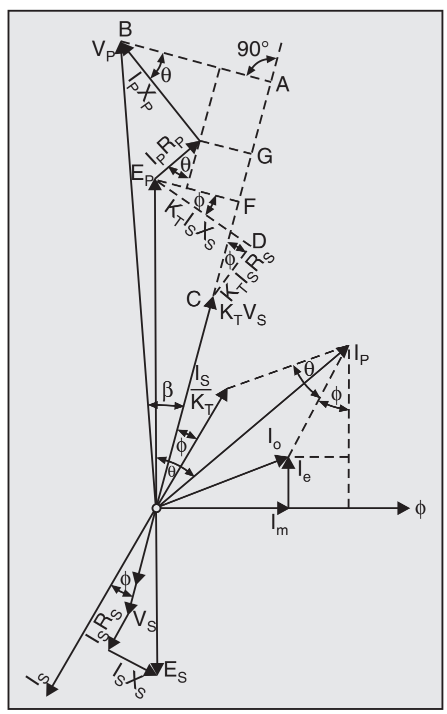


Fig. 3.34. Phasor Diagram for PT

Since β is very small, $\cos\beta \cong L$

$$I_p \cos\theta = I_e + \frac{I_s}{K_T}\cos\phi$$

$$I_p \sin\theta = I_m + \frac{I_s}{K_T}\sin\phi$$

Substituting the value of $I_p \cos\theta$ and $I_p \sin\theta$, we get,

$$V_p \cong K_T V_s + K_T I_s R_s \cos\phi + K_T I_s X_s \sin\phi + \left(I_e + \frac{I_s}{K_T}\cos\phi\right)R_p + \left(I_m + \frac{I_s}{K_T}\sin\theta\right)X_p$$

$$= K_T V_s + \frac{I_s}{K_T}\cos\phi\,(R_p + K_T^2 R_s) + \frac{I_s}{K_T}\sin\phi\,(X_p + K_T^2 X_s) + I_e R_p + I_m X_p$$

$$= K_T V_s + \frac{I_s}{K_T} R'_p \cos\phi + \frac{I_s}{K_T} X'_p \sin\phi + I_e R_p + I_m X_p$$

where R'_p and X'_p are the equivalent total resistance and total reactance respectively referred to the primary winding.

Actual voltage ratio, $$R = \frac{V_p}{V_s}$$

$$= K_T + \frac{{}^{I_s}\!/_{K_T}(R'_p\cos\phi + X'_p\sin\phi) + I_e R_p + I_m X_p}{V_s}$$

and,

$$\tan\beta = \frac{AB}{OA} = \frac{K_T I_s X_s \cos\phi - K_T I_s R_s \sin\phi + I_p X_p \cos\theta - I_p R_p \sin\theta}{K_T V_s + K_T I_s R_s \cos\phi + K_T I_s X_s \sin\phi + I_p R_p \cos\theta + I_p X_p \sin\theta}$$

$$= \frac{K_T I_s X_s \cos\phi - K_T I_s R_s \sin\phi + I_p X_p \cos\theta - I_p R_p \sin\theta}{K_T V_s}$$

All other terms in the denominator are very small in comparison with $K_T V_s$ and so can be neglected, since β is very small, $\tan\beta = \beta$. Substituting $\tan\beta = \beta$, $I_\beta \cos\theta = I_e + \frac{I_s}{K_T}\cos\phi$ and $I_p \sin\theta = I_m + \frac{I_s}{K_T}\sin\theta$ in above equation we get,

$$\beta = \frac{K_T I_s X_s \cos\phi - K_T I_s R_s \sin\phi + I_e X_p + \frac{X_p I_s}{K_T}\cos\phi - I_m R_p - \frac{I_s R_p}{K_T}\sin\phi}{K_T V_s}$$

$$-\beta = \frac{\frac{I_s}{K_T}(X'_p\cos\phi - R'_p\sin\phi) + I_e X_p - I_m R_p}{K_T V_s} \text{ radians}$$

β determined above will be negative, since in the phasor diagram $K_T V_s$ is drawn lagging behind the phasor V_p. For β to be positive,

$$\beta = \frac{\frac{I_s}{K_T}(R'_p \sin\phi - X'_p \cos\phi) - I_e X_p + I_m R_p}{K_T V_s}$$

3.39 Characteristics of Potential Transformers

The main characteristics of Potential Transformers are given below:

1. Effect of change in Secondary Burden. When the load is increased on the secondary side of potential transformer, then the secondary current and the primary current also increase. This causes increase in resistance and reactance drops in both primary and secondary windings.

2. Effect of change in Power Factor of Secondary Burden. When the power factor of secondary burden is reduced from unity to lagging, angle ϕ is increased, primary current I_P becomes more nearly in phase with I_o. The voltage V_P and V_S move more nearly into phase with E_P and E_S respectively. The voltage drops in windings for a given load are very little influenced by power factor of the loads. So the result is an increase in V_P relative to E_P and a reduction of V_S relative to E_S.

The ratio error of potential transformers increases with the fall in power factor of secondary burden. Since V_S is advanced in phase and V_P retarded in phase, the phase angle of the transformer reduced. A change from unity to a lagging of secondary burden tends to increase the ratio error but to decrease the phase angle.

3. Effect of change in Frequency. The reduction of frequency results in an increase in the core flux, with a corresponding increase in the exciting current I_o and reduction in reactance volt drops.

4. Effect of Primary Voltage. Variation of errors due to change in primary voltage are of no importance, as supply system of voltages do not vary widely.

3.40 Error in Potentiometer Transformer

There are two types of error in potentiometer transformer, they are given below:

1. Ratio Error or Percentages Ratio Error: The actual ratio of transformation varies with operating conditions and the error in secondary voltage may be defined as,

$$\text{Percentage Ratio Error} = \frac{K_N V_S - V_P}{V_P} \times 100$$

$$\text{Where } K_N = \text{Normal Ratio} = \frac{\text{Rated Primary Voltage}}{\text{Rated Secondary Voltage}}$$

2. Phase Angle Error. In an ideal potential transformer there should not be any phase difference between primary winding voltage and the secondary winding voltage. However, practically it is not possible.

The phase error has importance in voltage measurement while the phase angle error has importance when power is measured.

3.41 Design Feature of Potentiometer Transformer to Reduce Errors

There two types of error in potentiometer transformer, ratio error and phase angle error in voltage measurement. These errors can be compensated upto a limit while taking some precaution during the design of a potential transformer.

1. **Core.** These error partly depend upon the energy and magnetization components of no-load current. The errors controlled by reducing the no-load current. To keep the no-load current minimum possible the reluctance of the otz core is made small as possible and

flux density in the core is kept comparatively low. High quality of material is used to reduce core losses.

2. **Windings.** Errors also occur due to Potential transformer winding resistance and leakage reactance. The primary winding is wound over the secondary winding on the same limbs to reduce the leakage to the minimum. The primary and secondary windings must be kept as close as possible. Potential transformer winding resistance is reduced by keeping the mean length of the turns smallest and by using thick copper wire.
3. **Turn-Compensation.** It can be seen than the transformation ratio $\left(\frac{V_P}{V_S}\right)$ is more than the turn-ratio, K_T and it increases with the increase in the load connected on the secondary side. Hence the ratio error can be eliminated by making the turn ratio K_T less than the transformation ratio, which can be accomplished conveniently either by reducing the number of turns on primary or by increasing the number of turns on the secondary winding.

3.42 Capacitor Potential Transformer

For the voltage above 100 kV the conventional type of potential transformer becomes extremely expensive. For voltage above 100 kV a capacitor potential transformer is used. It is a combination of a capacitor potential divider and a magnetic potential transformer of relatively small ratio is used. Magnet potential transformer is also known as intermediate transformer.

Figure 3.35 shows the capacitor potential transformer. A slack of high voltage capacitors from the potential divider, the capacitor of the two sections be C_1 and C_2 respectively.

The voltage is applied to the primary of the intermediate transformer *T*. Both the potential divider and the intermediate transformer will have ratios and insulation requirements which are suitable for economical construction. The intermediate transformer must be of very small ratio error and phase angle to give satisfactory performance of the complete unit.

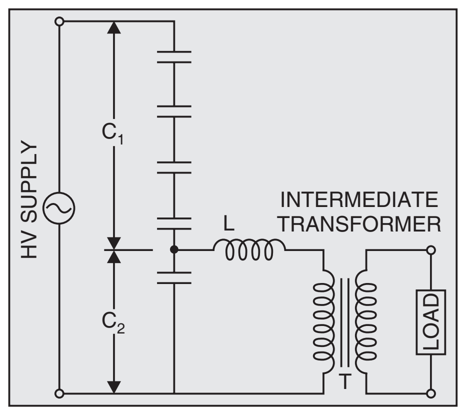


Fig. 3.35. Capacitor Potential Transformer

Intermediate transformer sometimes also known as auxilliary transformer consists of an inductance *L* which may consist wholly or partly of leakage inductance of the windings of the intermediate transformer. The value of the inductance *L* may be adjusted equal to $\frac{1}{\omega^2(C_1 + C_2)}$ so that the voltage drop due to current drained from the divider is largely compensated. Thus the overall voltage transformation ratio is independented of burden. The overall ratio is the product of the divider and transformer ratios.

3.43 Testing of Potential Transformer

For determine the ratio and phase angle errors, following two tests are conducted:

1. Absolute Method
2. Comparison Method

We will discuss each tests one by one in the following pages.

3.44 Absolute Method for Testing Potential Transformers

Figure 3.36 shows the circuit arrangement for absolute test method the burden (z) is connected across the secondary winding. The normal primary voltage at normal frequency is applied to the primary winding. The one end of the secondary winding is connected to the other end of the primary winding. A potential divider of non-inductive and non-capacitive is connected across the primary winding.

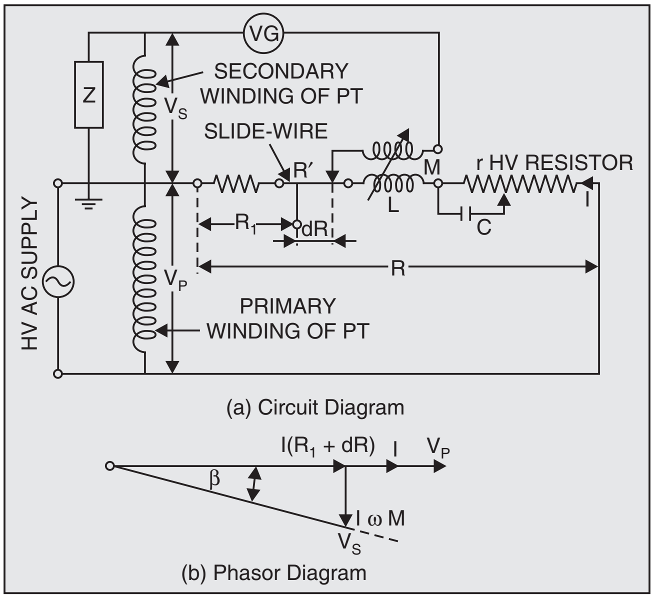


Fig. 3.36. Absolute Method of PT testing.

The principle of this test is to balance the secondary winding against a fraction of the primary voltage obtained from potential divider and the errors are measured in terms of the circuit constants.

The impedance of the divider

$$Z = \mathrm{R} - r + j\omega L + \frac{r}{1 + j\omega C_r}$$

The potential divider consists of a fixed resistance R_1 in series with slid-wire R'. This divider is connected to the high voltage resistance r in series with a primary coil of a variable mutual inductor M. The galvanometer (G) gives zero indication on adjustment of variable mutual inductor M and slid-wire R'. The resistances R and R_1 are chosen so that the ratio R/R_1 is equal to the nominal ratio of potential transformers under test.

Lets L = self inductance of the primary coil mutual inductor

C = shunts capacitor of potential divider

The impedance of the potential divider,

$$Z = R - r + j\omega L + \frac{r}{1 + j\omega C_r}$$

$$= R - r + j\omega L + \frac{r(1 - j\omega Cr)}{(1 + j\omega Cr)\,(1 - j\omega Cr)}$$

$$= R - r + \frac{r}{1 + \omega^2 C^2 r^2} + j\omega\left(L - \frac{Cr^2}{1 + \omega^2 C^2 r^2}\right)$$

The value of c and r as so chosen so that the term $\dfrac{Cr^2}{1+\omega^2C^2r^2}$ is equal to the self inductance of the primary coil of mutual inductor (L) at operating frequency. Thus,

$$Z = R - r + \frac{r}{1+\omega^2C^2r^2}$$

Above equation shows that the divider is non-reactive at the operating frequency. The term $w^2c^2r^2$ is normally very small in comparison to unity, so it can be neglected.

$$Z = R - r + \frac{r}{1}$$

$$Z = R$$

The impedance of the divider is equal to R. The phasor diagram for the balanced condition is shown in Fig. 3.36.

The current in the potential divider,

$$I = \frac{V_p}{R}$$

Lets, dR is the inserted resistance of slid-wire and M be the mutual inductor to have zero deflection in galvanometer. In the balanced condition secondary voltage is balanced by the voltage across resistance (R_1 + dR) and voltage induced in the secondary coil of mutual inductor M.

$$V_S = I\,(R_1 + dR) - jI_w\, M$$

The phase angle (β) of the transformer is very small, so we neglect it.

$$V_S = I\,(R_1 + dR)$$

$$= \frac{V_p}{R}\,(R_1 + dR)$$

thus, the transformer-ratios,

$$\frac{V_p}{V_S} = \frac{R}{R_1 + dR}$$

and,

$$\text{Ratio error} = \frac{\text{Nominal ratio} - \text{Actual ratio}}{\text{Actual ratio}}$$

$$= \frac{\dfrac{R}{R_1} - \dfrac{R}{(R_1 + dR_1)}}{\dfrac{R}{(R_1 + dR)}}$$

$$= \frac{dR}{R_1}$$

R_1 is the fixed value of the circuit. From the above equation we see that the ratio error is obtained directly from the slid-wire calibrated in values of ratio error.

From the phasor diagram value of tan β

$$\tan\beta = \frac{\omega M}{R_1 + dR}$$

Since dR is very small in comparison to R_1 and so it can be neglected and β being very small tan β can be taken equal to β. Thus the phase angle error of potential transformer,

$$\beta = \frac{\omega M}{R_1}$$

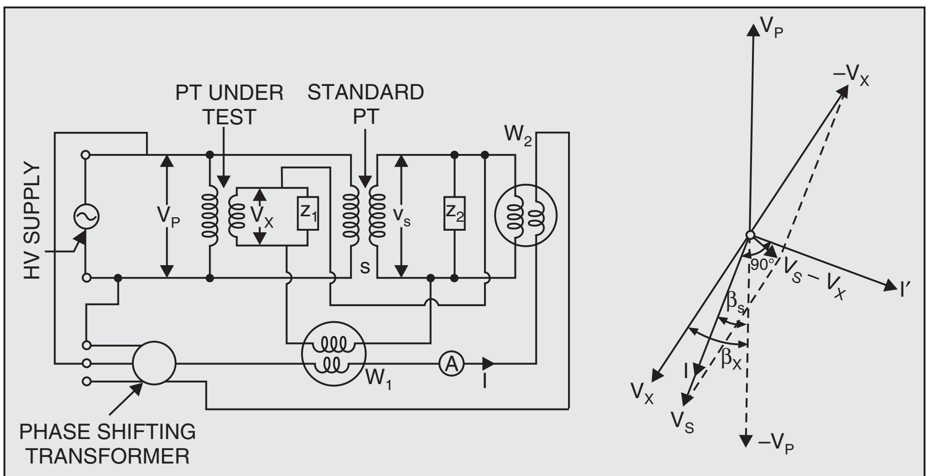
The mutual inductor M can be calibrated directly in terms of phase angle error.

3.45 Comparison Method for Testing Potential Transformer

In this method we compare the potential transformer under test with the standard potential transformer whose errors are small and known.

Figure 3.37 shows the circuit arrangement of comparison method. The primary winding of the both potential transformers are connected in parallel. The secondary winding are so connected that the voltage acting across the potential coil of wattmeter W_1 is the phasor difference of the two secondary voltage V_S and V_X. The potential coil of wattmeter W_2 is directly connected across the secondary of the standard potential transformer. The current coils of both wattmeters are connected in series so as to carry the same current and are supplied from a phase shifting transformer.

The impedance Z_1 and Z_2 are adjusted to the required values. Wattmeter indicates the phase and voltage at which the transformers are tested.



(a) Circuit Diagram (b) Phaser Diagram

Fig. 3.37. Comparison Method of PT Testing

Figure 3.37 shows the phase diagram. The phase shifting transformer is adjust to give the maximum value, so the current I will be in phase with the secondary voltage of standard transformer, the reading of wattmeter,

$$W_2 = V_S I$$

$$V_S = \frac{W_2}{I}$$

The reading of wattmeter W_1 for this setting is equal to the product of current I and the component of voltage which is in phase with this current.

$$W_1 = I\,[(V_S - V_X)\cos(\beta_X - \beta_S)]$$

$$\simeq I\,(V_S - V_X) \qquad (\because\ \beta_X - \beta_S \text{ is very small})$$

$$V_S - V_X \approx \frac{W_1}{I} \qquad ...(i)$$

R_S and R_X are the true voltage transformation ratios of the standard and under test potential transformer respectively then,

$$R_S = \frac{V_p}{V_s}$$

$$R_X = \frac{V_p}{V_x}$$

Substituting the value of V_S and V_X to the Eq. (*i*), we get

$$\frac{V_p}{R_s} - \frac{V_p}{R_x} = \frac{W_1}{I}$$

$$\frac{1}{R_s} - \frac{1}{R_x} = \frac{W_1}{I} \cdot \frac{1}{V_p}$$

$$R_X = \frac{V_s R_s}{V_s - \frac{W_1}{I}}$$

From above equation we see that the ratio error of the potential transformer under test is determined if the ratio error of the standard potential transformer is known.

Let the phase of the current I is advanced until wattmeter W_2 reads zero and reading of wattmeter W_1' is noted. In this position current I' is in quadrature with V_S, new reading of wattmeter W_1'.

$$W_1' = I' V_X \cos [90° - (\beta_X - \beta_S)]$$
$$= I' V_X \sin (\beta_X - \beta_S)$$

$$\sin (\beta_X - \beta_S) = \frac{W_1'}{I' V_x}$$

Since $V_X = V_S$ and $\beta_X - \beta_S$ is very small, $\sin (\beta_X - \beta_S) = \beta_X - \beta_S$

$$\beta_X - \beta_S = \frac{W_1'}{I' V_s}$$

From the above equation we see that the phase angle of potential transformer under test is determined if the phase angle of the standard potential transformer is known.

3.46 Testing of Current Transformer

Figure 3.38 shows the circuit diagram of CT under test. The primary of the CT under test in series with a rheostat and a standard low resistance. *S* connected across low voltage supply. The circuit of the secondary is completed by a variable resistance *R*, the primary of the mutual inductance *M*, and *Z* which may include an ammeter and which is adjusted so that the total burden has the required value. The value of *S* and *R* are chosen so that *R*/*S* is approximately equal to the nomial ratio of the CT. Actually *S* is suitable chosen to carry the full primary current and *R* is adjusted as required to render the voltage drop across them equal. Compensation for phase difference is affected by adjustment of mutual inductance *M*. In operation *R* and *M* are adjusted alternately until the vibration galvanometer indicates zero deflection. The condition is represented by the diagram.

$$\tan \beta = \frac{e}{I_s R} = \frac{\omega M I_s}{I_s R} = \frac{\omega M}{R}$$

$$\cos\beta = \frac{I_s K}{I_p S}$$

$$\frac{I_p}{I_s} = \frac{R}{S\cos\beta}$$

actual current ratio, $$K_C = \frac{I_p}{I_s} = \frac{R}{S\cos\beta} = \frac{R}{S}$$

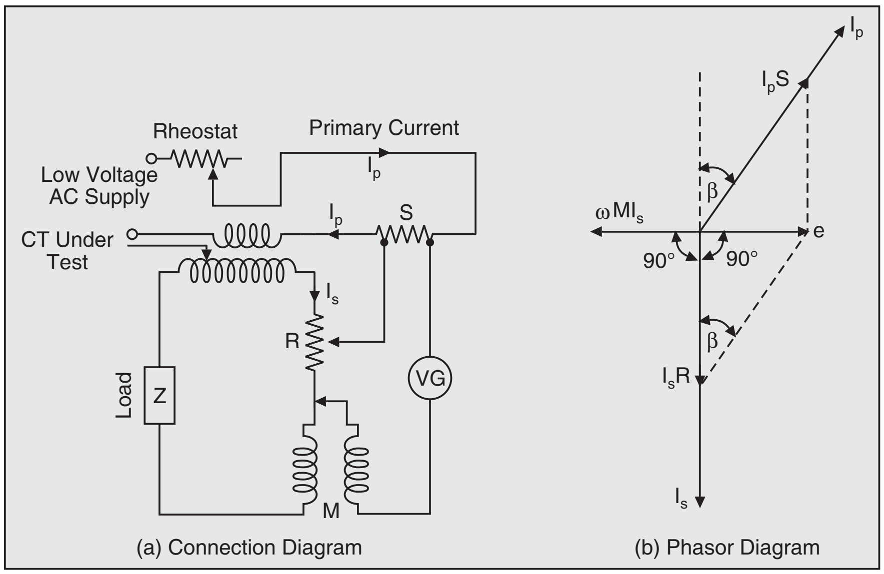


Fig. 3.38.

3.47 Difference Between Current and Potentiometer Transformers

Main difference between current and potentiometer transformers are shown in Table 3.1.

Table 3.1

S. No.	*Current Transformer*	*Potentiometer Transformer*
1.	It is step-up transformer	It is step down transformer
2.	The winding carried full-line current	The winding is impressed with full voltage
3.	Primary constant is independent of the conditions of secondary circuit	Primary current is dependent on the conditions of the secondary circuit
4.	The secondary winding must never be opened. It must always be short circuit	The secondary winding is nearly under open circuit conditions.

3.48 Advantages and Disadvantages of Instrument Transformers

Advantages

Some of the main advantages of instrument transformer are given below:

1. Voltmeter and ammeter can be used along with these transformers to measure high voltage and currents.
2. The rating of low range can be fixed irrespective of the value of high voltage or current to be measured.

3. When the instruments are used in conjunction with instrumental transformer, their reading don't depend upon their constants (R, L, C).
4. These can be used for operating many types of protecting devices such as relays.
5. These transformer isolate the measurement form high voltage and current circuits. This ensures safety of the operator and makes the handling of the equipments very easy and safe.

Disadvantages

The only disadvantage of these instrument transformers is that they can be used only for a.c. circuits and not for d.c. circuits.

Applications of Instrument Transformers

There are three primary applications for which are used for metering (for energy billing and transaction purposes), protection control (for system protection and protective relaying purposes) and load survey (for economic management of industrial loads).

SUMMARY

1. A moving coil galvanometer is an instrument used for detection and measurement of small electric currents.
2. Galvanometer is an instrument used to indicate the presence, direction, or strength of a small electric current.
3. The basic movement of a dc ammeter is a PMMC D'Arsonval galvanometer.
4. Voltmeter is used for measuring voltage or the potential difference.
5. The sensitivity of an instrument is given in ohms per volt. It is the reciprocal of the full-scale deflection current.

$$\text{Sensitivity} = \frac{\text{ohms}}{\text{Volt}}$$

$$\text{Sensitivity} = \frac{1}{I_{fsd}}$$

6. An ohmmeter is an electrical instrument that measures electrical resistance.

GLOSSARY

Basic Galvanometer: A moving coil instrument consists of a permanent horse shoe type magnet, rectangular coil of N turns, a pointer which rotates and shows the deflection of the coil on the scale.

DC Ammeter: The D'Arsonval galvanometer is a moving coil ammeter. It uses magnetic deflection, where current passing through a coil causes the coil to move in a magnetic field.

DC Voltmeter: In DC voltmeter the high resistor is connected in series with the D'Arsonval movement.

Series Type Ohmmeter: The known resistance is connected in series with the D'Arsonval movement.

Shunt Type Ohmmeter: The known resistance is connected in parallel with the D'Arsonval movement.

NUMERICAL PROBLEMS

1. Determine the resistor value required to use a 0-1 mA meter with an internal resistance of 125 Ω for a 0-1 V meter

(**Ans.** 875 Ω)

2. The coil of a moving iron ammeter has a resistance of 6.25 Ω and full-scale reading of 0.012 A. What would be the full-scale reading of the instruments if used as a voltmeter?

(**Ans.** 0.075 V)

3. It is desired to convert a 0-1000 μA meter movement, with an internal resistance of 100 Ω into a 0-100 mA meter. Calculate the required value of shunt resistance

(**Ans.** 1Ω)

4. A moving coil ammeter has fixed shunt of 0.01 Ω. With a coil resistance of 750 Ω and a voltage drop of 400 mV across it, the full scale deflection is obtained. Calculate the current through shunt.

(**Ans.** 40 A)

5. A 1 mA meter movement with an internal resistance of 50 Ω is to be used in a 0-1 V, 0-10 V, 0-50 V, and 0-100 V range in the arrangement shown in Fig. 3.22. Find the value of the multiplier resistances. (**Ans.** 950 Ω, 9 Ω, 40 Ω, 50 Ω)

6. In the circuit shown in Fig. 3.39. the voltage across the resistor of value 25 kΩ is to be measured first by using a voltmeter of sensitivity of 1 kΩ.V, and then with a voltmeter of sensitivity of 20 kΩ/V. Calculate the reading of the voltmeter in each case and the % error in the measurement.

(**Ans.** 15 V, 40 % , 24.2 V and 3.2 %)

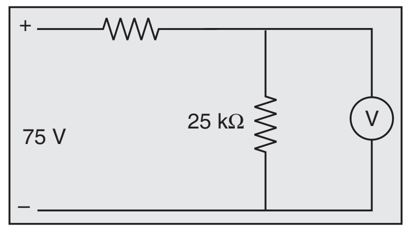


Fig. 3.39.

7. A moving coil instrument has a resistance of 10 Ω and takes 40 mA to produce full-scale deflection. The shunt resistance required to convert this instrument for use as an ammeter of range 0 to 2 A is ohm resistance. If the coil resistance of the meter is 1000 Ω, a potential difference of 500 mV is required across it for full-scale deflection. Under this condition, the current in the shunt would be.

(**Ans.** 25 A)

8. A moving coil instrument having a resistor of 10 ohms gives full scale deflection when a current of 5 mA passed through it. Explain how this instrument can be used for measurement of

(*i*) Current upto 1 A.

(*ii*) Voltage upto 5 V.

(**Ans.** 0.05025 Ω and 990 Ω)

DESCRIPTIVE QUESTIONS

1. Describe the working of PMMC meter.

2. State the advantages and disadvantages of moving iron instrument.

3. Describe the construction details and principle of operation of a D'Arsonval galvanometer.

4. What is the torque equation of galvanometer.

5. Which type of meter movement is most widely used in ac instruments for current and voltage measurements?

6. What type of movement is used for an ammeter?

7. What are the advantage of an Aryton shunt ammeter over a multirange ammeter

8. What are the requirements of shunt?

9. What precautions are to be observed when using an Ammeter?

10. Compare the multi-range voltmeter with the Aryton shunt voltmeter.

11. How an ammeter can be changed into a voltmeter?

12. Ammeter and voltmeter are connected in series and parallel respectively. Why?

13. Discuss in detail the principle of operation of electronics voltmeter with the help of a circuit diagram.

(GBTU/MTU, 2004-05)

14. How the range of DC ammeter and DC voltmeter can be extended? Derive the expression to calculate shunt resistance and multiplier resistance.

15. What is loading effect?
16. What is the sensitivity of voltmeters and ammeter.
17. Describe the working of series type ohmmeter in detail.
18. Differentiate between a series type ohmmeter and a shunt type ohmmeter.
19. Describe the working of an Instrument Transformer. *(PTU, Dec. 2004)*
20. Compare the feature of various transducers. *(PTU, Dec. 2004)*
21. What is phase angle error? *(PTU, Dec. 2004)*
22. Distinguish between current and potential transformers. *(PTU, May 2004)*
23. Explain the instrument transformer. *(PTU, May 2004)*
24. Name the testing methods of CT and PT. *(PTU, May 2006)*
25. Why secondary of CT is never kept open? *(PTU, Dec. 2006)*
26. What is phase angle error. *(PTU, Dec. 2006)*
27. Describe the design and constructional features used in potential transformer for reduction of ratio and phase angle error. *(PTU, Dec. 2006)*
28. What are the instrument transformers? How do they differ from power transformer. *(PTU, May 2007)*
29. Why ratio and phase angle errors are important in case of a current transformer. *(PTU, May 2007)*
30. Derive the expression of ratio error and phase angle error of potential transformer. *(PTU, May 2007)*
31. Why CT and PT are called instrument transformers. *(PTU, Dec. 2008)*
32. Explain the working principle of current transformer. What will happen if the secondary circuit of the CT is open circuited while primary carries current. *(PTU, Dec. 2008)*
33. With the help of schematic introduce a typical telemetering system and present functioning each element block. *(PTU, Dec. 2008)*
34. For what application can CT and PT be used? *(PTU, May 2009)*
35. Explain the principle of operation of current transformer and give for the ratio and phae angle error. *(PTU, May 2009)*
36. Describe the difference between bounded and inbounded strain gauge. *(PTU, May 2011)*
37. How errors can be reduced in instrument transformers. *(PTU, May 2011)*
38. Give the difference between current and potential transformers. *(PTU, Dec. 2010)*
39. Define transformation ratio of current transformer. *(PTU, Dec. 2009)*
40. Write advantages of instrument transformers. *(PTU, Dec. 2009)*
41. Discuss characteristics of current transformers. *(PTU, Dec. 2009)*
42. Describe an Induction type watt-hour meter. Show that in such instruments disc revolutions are proportional to the electric current supplied through the meter. *(Nagpur University, Summer 2011)*
43. Explain with neat sketch the single-phase electrodynamometer type of meter. Draw the phasor diagram. *(Nagpur University, Summer 2011)*
44. Differentiate between CT and PT. *(Nagpur University, Summer 2010)*
45. Explain the method of turns compensation used in current transformers to reduce the ratio error. Explain with suitable example. *(Nagpur University, Summer 2010)*

46. Explain the term "loading" in voltmeter and give the method to remove the adverse effect of loading. *(GBTU/MTU, 2009-10)*

47. Describe the principle of operation and use of Galvanometer. *(GBTU/MTU, 2010-11)*

48. Describe the principle of operation and application of PMMC instruments. *(GBTU/MTU, 2010-11)*

49. Explain the operation of series ohmmeter. *(GBTU/MTU, 2009-10)*

50. Describe the construction and working of a PMMC type of instrument. Derive the expression for deflection of a PMMC ammeter. Comment on the shape of the scale. *(Nagpur University, Summer 2010)*

51. Explain construction and operating principle of PMMC galvanometer. Enlist the advantages and disadvantages of PMMC meters. *(Nagpur University, Summer 2010)*

52. Explain the basic ammeter circuit using PMMC meter. *(Nagpur University, Summer 2010)*

53. Explain the basic voltmeter circuit using PMMC instruments. *(Nagpur University, Summer 2010)*

54. Write the merits and demerits of PMMC instruments. *(GBTU/MTU, 2009-10)*

55. Explain the working of basic DC ammeter. *(GBTU/MTU, 2009-10)*

MULTIPLE CHOICE QUESTIONS

1. The current sensitivity of a meter is expressed in

(*a*) ampere (*b*) ohm/ampere (*c*) ohm/volt (*d*) ampere/division.

2. The basic meter movement can be converted into an ohmmeter by connecting a .....with it.

(*a*) high resistance in series (*b*) low resistance in parallel

(*c*) battery in series (*d*) battery and a variable resistance in series

3. A 0-1 mA meter has a sensitivity of

(*a*) 1 k W/V (*b*) 1 mA (*c*) 1 k W (*d*) 1000 A.

4. Loading effect is principally caused---by instrument

(*a*) high resistance (*b*) low-sensitivity

(*c*) high-sensitivity (*d*) high-range

5. A multimeter is used to measure

(*a*) resistance (*b*) current

(*c*) voltage (*d*) all of the above

6. Moving iron instruments can be used as,

(*a*) Standard instruments for calibration of other instruments.

(*b*) Transfer type instruments.

(*c*) Indicator type instruments as on panels

(*d*) All of the above.

7. In series type ohmmeter,

(*a*) 0 marking is on the left hand side of scale while ∞ marking is on the right hand side

(*b*) 0 marking is on the right hand side of scale and ∞ infinity marking on the left hand side.

(*c*) Any of the above two marking can be on left or right side of the scale.

(*d*) 0 marking is in the middle of scale.

8. A make break switch is provided to disconnect the battery when the meter is not in use in,

(*a*) both series and shunt type ohmmeters.

(*b*) Only in series type ohmmeters.

(*c*) Only in shunt type ohmmeters.

(*d*) None of the above.

9. In D'Arsonval galvanometer, an iron core is usually used between the permanent magnet pole faces. This is used so that,

(*a*) Flux density in the air gap becomes high thereby a large deflecting torque is produced.

(*b*) The effect of stray magnetic fields is reduced

(*c*) Moment of inertia of moving parts becomes smaller.

(*d*) None of the above.

10. Sometimes, the D'Arsonval galvanometers, do not use ferromagnetic cores between poles of the permanent magnetic. In this case

(*a*) The flux density becomes smaller resulting in low deflecting torques

(*b*) The dimension of the moving coil can be made smaller thereby reducing the moment of interia

(*c*) The magnetic field may not br radial resulting in a non-uniform scale even if spring control is used

(*d*) All of the above.

11. A1 mA D'Arsonval movement has a resistance of 100 Ω. It is to be converted to a 10 V voltmeter. The value of multiplier resistance is

(*a*) 999 Ω (*b*) 9999 Ω (*c*) 9900 Ω (*d*) 990 Ω

12. A D'Arsonval movement is rated at 20 μA. Its sensitivity is

(*a*) 20000 Ω/V (*b*) 200000 Ω/V

(*c*) 200 Ω/V (*d*) Cannot be determined.

ANSWERS

1. (*c*)	**2.** (*d*)	**3.** (*a*)	**4.** (*b*)	**5.** (*d*)	**6.** (*c*)
7. (*b*)	**8.** (*c*)	**9.** (*a*)	**10.** (*d*)	**11.** (*c*)	**12.** (*a*)

Chapter 4

Precise Resistance Measurement

Outline

Objectives

After completing this chapter, you should be able to:

- Describe the construction and operation of bridge circuit.
- Understand how to measure the different values of resistances using different methods.
- Explain the measurement of resistance with Ammeter-voltmeter method
- Describe the Potentiometer Method.
- Explain in detail the working of Wheatstone, Kelvin and Megaohm Bridges
- Understand the Carey-Foster slide-wire bridge method
- Explain the working of Megger

4.1 Introduction

A resistor is an electrical component, which has been manufactured with specific amount of resistance. In electronic circuit, the resistor plays one of the most important part. The resistors are used mainly for two purposes, namely controlling the flow of electric current and providing desired amounts of voltage in electric or electronic circuits.

There are different methods available for measuring the resistance. The precision measurements of component values have been made by using various forms of bridges and instruments. There are different types of resistor according to their resistance value. So we use different instrument to measure their resistance value.

4.2 Bridge Circuit

Fig. 4.1 shows the circuit diagram of a simple bridge circuit. A **bridge circuit** is a type of electrical circuit in which two circuit branches (usually in parallel with each other) are connected (bridged) by a third branch between the first two branches at some intermediate point along them. Bridge circuits are used in many applications, both linear and non-linear, including instrumentation, filtering and power conversion.

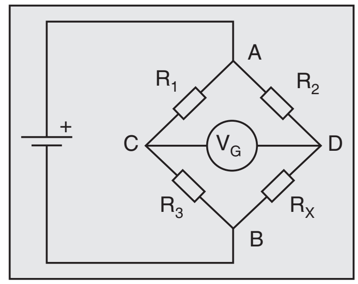


Fig. 4.1.

The bridge circuit constructed from single or combination of passive circuit elements (resistors, inductors, capacitors). Let us consider that the bridge circuit construct from the resistors element, one of which has an unknown value (R_x), and known resistance R_1, R_2 and R_3, where R_3 is the variable resistance. The two opposite corners of the square are connected to a source of electric current, such as battery, while the galvanometer is connected across the other two opposite corners. The current through the galvanometer depends on the potential difference between the two point *C* and *D*. To find the value of unknown resistor we have to first balance the bridge circuit. The bridge is balanced when there is no current flow through the galvanometer. The potential difference across the galvanometer is zero.

The variable resistor is adjusted until the galvanometer reads zero. Then the ratio between the variable resistor and its neighbor is equal to the ratio between the unknown resistor and its neighbour, and this enables the value of the unknown resistor to be calculated.

$$\frac{R_1}{R_2} = \frac{R_2}{R_X}$$

The simplest form of bridge is for the purpose of measuring resistance and is called Wheatstone bridge.

4.3 Advantages of Bridge Circuits

Although there are several advantages of bridge circuits, yet the following one s are important from the subject point of view:

1. Accuracy in high measurements.
2. Accuracy is independent of null detector characteristics.
3. It can be used in control circuits.

4.4 Types of Bridge Circuit

The bridge circuits are of two types DC Bridge and AC Bridge. In DC bridge circuit, a DC source battery and a galvanometer are used. While in the AC bridge circuit, an AC source and a detector sensitive to AC voltage are used. Further the bridges are classified in many types. The classification of bridge depend on the resistance value, element of unknown branches, *Q* value etc. The bridge circuit may be broadly classified into the following categories:

1. D.C. Bridge Circuits

Different types of DC bridge circuits are given below :

(*a*) Wheatstone Bridge Circuit
(*b*) Kelvin Bridge Circuit
(*c*) Double Kelvin Bridge Circuit

2. A.C Bridge Circuits

Difference types of AC bridge circuits are given below :

(*a*) Maxwell Bridge Circuit
(*b*) Hay's Bridge Circuit
(*c*) Anderson's Bridge Circuit
(*d*) Owen's Bridge Circuit
(*e*) De Sauty's Bridge Circuit
(*f*) Schering Bridge Circuit
(*g*) Wien Bridge Circuit
(*h*) Resonance Bridge Circuit

The DC Bridge is covered in this chapter while the AC Bridge, in the next chapter.

4.5 Classification of Resistances

Based upon the value, the resistances can be classified into the following three categories:

1. **Low resistance.** The resistance with values less than or equal to 1 Ω are called low resistance. Armatures winding of machines, ammeter shunts, cables, contacts etc. all have a low resistance value.
2. **Medium resistance.** The resistance with values ranging from 1 Ω to 100 kΩ are called medium resistance. The resistors employed in electronic circuits usually are of medium resistance type.
3. **High resistance.** The resistance with values above 100 kΩ are high resistances. Some of the electrical and electronic circuits do employ resistors with high resistance values.

4.6 Measurement of Resistance

There are several methods used for the measurement of resistance. Fig. 4.2 shows the methods that are used for the measurement the low-, medium- and high-resistance values.

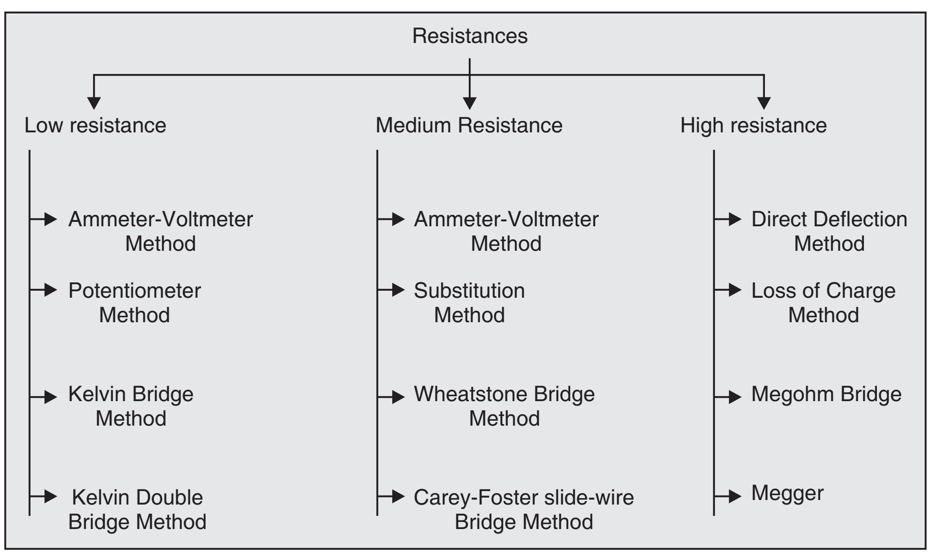


Fig. 4.2.

4.7 Measurements of Low Resistance

There are several methods for the measurement of low resistance value. But the following ones are important from the subject point of view :

1. Ammeter-Voltmeter Method
2. Potentiometer Method
3. Kelvin Bridge Method
4. Kelvin Double Bridge Method

We shall now discuss all the above mentioned methods one by one in the following pages.

4.8 Ammeter-Voltmeter Method

This method is used for measuring low resistance value when accuracy of the order of 1 % is sufficient. The ammeter-voltmeter method employs the simple ohm's law to determine the value of an unknown resistance.

Fig. 4.3 shows the circuit arrangement of ammeter-voltmeter method. The current through the unknown resistor (R_X) and potential drop across it are measured simultaneously. The readings are obtained by ammeter and voltmeter respectively. The required range of instrument to be used and the voltage of the supply required will depend on the size and rating of the resistance under test. A high-value resistor will require high-voltage source, a high-range voltmeter and a low-range ammeter whereas, a low-value resistor will require in most cases, a low–voltage, high-current source, a low-range voltmeter and a high-range ammeter. The exact requirement will, of course, depend also on the rating of the resistor, as well as the instruments available. There are two ways to connect the voltmeter as discussed below.

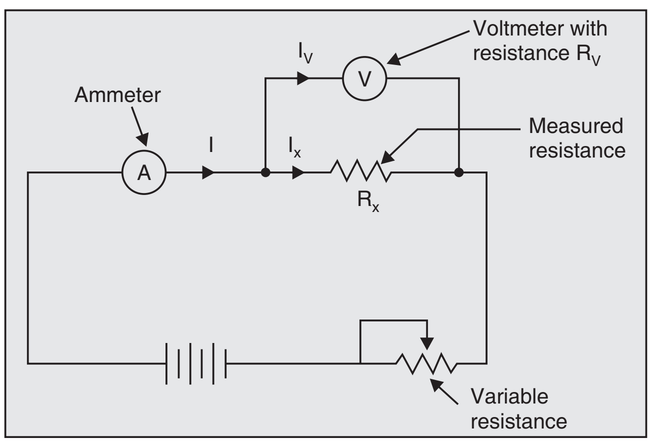


Fig. 4.3.

1. Voltmeter is connected directly across the resistor only

When the voltmeter is connected directly across the resistor, the ammeter measures the current flowing through the unknown resistance R_X and the voltmeter.

Current through ammeter

= Current through unknown resistance (X) + Current through voltmeter

$$I = I_X + I_V$$

$$I_X = I - I_V$$

the value of unknown resistance,

$$R_X = \frac{V}{I_X} = \frac{V}{I - I_V} = \frac{V}{I - V/R_V}$$

$$= \frac{V}{I\left(1 - \frac{V}{IR_V}\right)} \qquad \ldots(i)$$

where V = voltmeter reading

R_V = resistance of the voltmeter

I = current indicated by ammeter

The value of unknown resistance is determined by equation (*i*).

Substituting the value, $V/I = R_m$ in the equation (*i*) we get,

$$R_X = R_m\left(\frac{1}{1 - \frac{R_m}{R_V}}\right)$$

From the above equation we see that the true value of unknown resistance is equal to measured value of unknown resistance provided that voltmeter is of infinite resistance. However if the voltmeter is of very large resistance as compared to the resistance under measurement then,

i.e. $R_V >> R_m$

$$R_X = \ 1 + \frac{R_m}{R_V}$$

Thus the measured value of unknown resistance, R_m is lesser than its true value.

2. *Voltmeter is connected directly across the ammeter and resistor:*

Figure 4.4 shows the voltmeter connected directly across the ammeter and unknown resistance, R_X, the voltmeter measures the voltage drop across the ammeter and unknown resistance. The ammeter is connected so that it indicates only the current flowing through the unknown resistance.

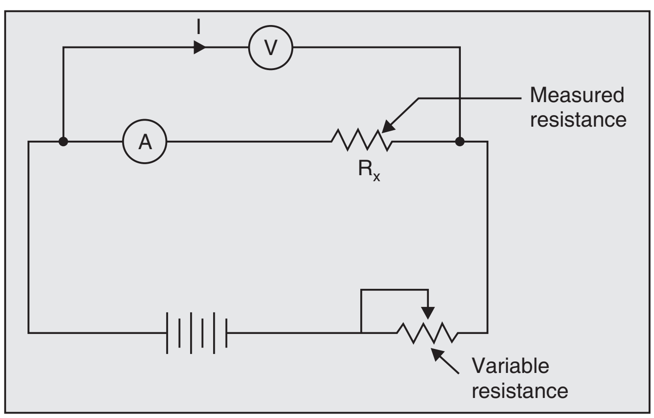


Fig. 4.4.

$$V = IR_A + IR_X = I(R_A + R_X)$$

$$R_X = \frac{V}{I} - R_A \qquad \ldots(ii)$$

where R_A is the resistance of the ammeter. The value of unknown resistance is determined by the equation (*ii*).The ammeter-voltmeter method of measuring resistance is capable of fair accuracy, depending on care in taking the reading and on the accuracy and range of the instruments used for measurement of voltage and current. This method is useful in some laboratory work in which high accuracy is not required.

4.9 Advantages and Disadvantages of Ammeter-Voltmeter Method

Advantages

Some of the main advantages of ammeter-voltmeter method are given below :

1. It does not require skilled operation.
2. Accuracy of the order ± 1 % can be achieved.

Disadvantages

Some of the main disadvantages of ammeter-voltmeter are given below :

1. A correction factor needs to apply on the measured value to obtain the true value of the resistance.
2. The low values of resistances invariably have a high percentage of error.

Example 4.1. *The ammeter-voltmeter method is used to measure the of an aircraft instrument resistance. With the voltmeter connected across the resistance, the readings on the ammeter and voltmeter are 0.3 A and 2.4 V respectively. The resistance of the voltmeter is 450 Ω. Calculate (i) the true value of resistance and (ii) percentage error in the value of resistance, if the voltmeter current is ignored.*

Solution. Given: $V = 2.4$ V; $I = 0.3$ A and $R_V = 450\ \Omega$

(*i*) ***True value of resistance.***

We know that the value of unknown resistance,

$$R_X = \frac{V}{I\left(1 - \dfrac{V}{I R_V}\right)} = \frac{2.4}{0.3\left(1 - \dfrac{2.4}{0.3 \times 450}\right)} = 8.14\ \Omega \ \textbf{Ans.}$$

(*ii*) ***Percentage error in the value of resistance, if the voltmeter current is ignored.***

If current through the voltmeter is ignored then,

$$R = \frac{V}{I} = \frac{2.4}{0.3} = 8\ \Omega$$

the percentage error is given by the equation,

$$\%\ \text{Error} = \frac{R - R_X}{R_X} \times 100 = \frac{8 - 8.14}{8.14} \times 100$$

$$= -1.72\ \%\ \textbf{Ans.}$$

4.10 Potentiometer Method

In potentiometer method the unknown resistance is compared with a standard resistance of the same order of magnitude. Fig. 4.5 shows the circuit diagram of potentiometer method. As seen from the diagram, the unknown resistance R_X, ammeter A, a rheostat R (to limit the current) and a standard resistance are connected in series with low voltage high current supply source. The value of standard resistance should be known.

The current through the circuit is adjusted by a rheostat so that a potential difference across the resistor is about 1V. The voltage drop across the potentiometer and the standard resistor is measured by a potentiometer. The ratio of the two potentiometer reading gives the ratio of R_X to S.

$$\frac{R_X}{S} = \frac{\text{Potentiometer reading across } R_X}{\text{Potentiometer reading across } S} = \frac{V_X}{V_S}$$

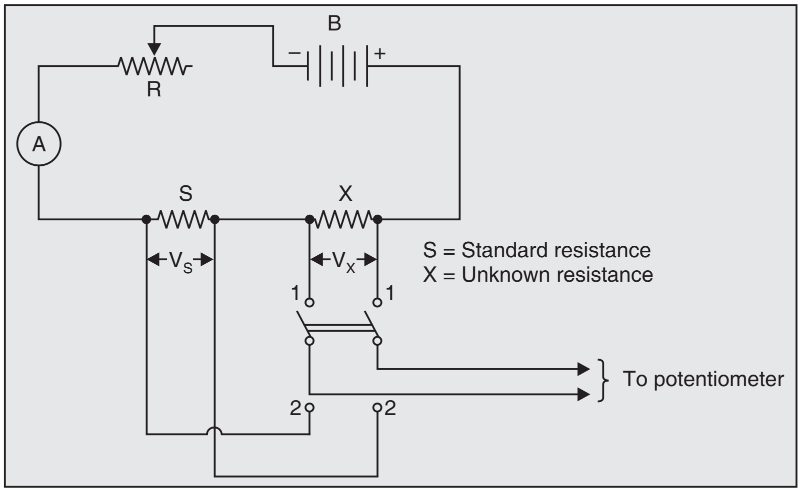


Fig. 4.5.

The accuracy of this method depends upon there being no change in current between the two readings. The source to supply current through the circuit should be extremely stable.

4.11 Advantages and Disadvantages of Potentiometer Method

Advantages of Potentiometer Method

Though there are numerous advantages of potentiometer method, yet some of the important are given below:

1. Inexpensive
2. Simple to handle
3. Useful for the measurement of large amplitudes of displacement
4. Electrical efficiency is very high.

Disadvantages of Potentiometer Method

Though the potentiometer method has a number of disadvantages, yet some of them are given below:

1. Force is required to move the sliding contacts.
2. Sliding contacts can wear out, become misaligned and generate noise.

Example 4.2. *In a measurement of resistance by potentiometer, the voltage drops across a resistor under test and across 0.025 Ω standard resistors were found to be 0.882 V and 1.2 V respectively. Determine the value of resistor under test.*

Solution. Given: $S = 0.025\ \Omega$; $V_X = 0.882$ and $V_S = 1.2$ V.

We know that,

$$\frac{R_X}{S} = \frac{\text{Potentiometer reading across } R_X}{\text{Potentiometer reading across } S} = \frac{V_X}{V_S}$$

$$\frac{R_X}{0.025} = \frac{0.882}{1.2}$$

$$R_X = \frac{0.882}{1.2} \times 0.025 = \frac{0.882}{1.2} \times 0.025 = 0.0183 \textbf{ Ans.}$$

4.12 Kelvin Bridge

Fig. 4.6 shows the circuit diagram of a Kelvin Bridge. This circuit provides great accuracy in the measurement of low value resistance generally below 1 Ω. It is used for measuring resistance values ranging from microohms to 1 ohm.

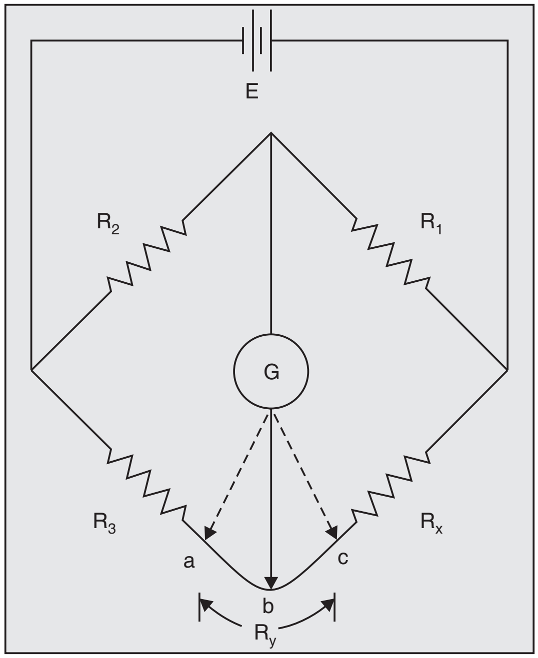


Fig. 4.6. Kelvin Bridge

The resistance R_y represents the resistance of the conducting lead from R_3 to R_x. The resistance R_x is the unknown resistance to be measured. The galvanometer can be connected either to point '*c*' or to point '*a*'. When it is connected to point '*a*', the resistance R_y of the connecting lead is added to the unknown resistance R_x. The measurement value of the resistance is too high than the actual value.

When the galvanometer is connected to the point '*c*', the resistance R_y of the connecting lead is added to the known resistance R_3. The actual value of R_3 is higher than the normal value by the resistance R_y and the resulting measurement of R_x is lower than the actual value.

If the galvanometer is connected to point '*b*', in between points '*c*' and '*a*', in such a way that the ratio of the resistance from '*c*' to '*b*' and that from '*a*' to '*b*' equals the ratio of resistance R_1 and R_2 then,

$$\frac{R_{cb}}{R_{ab}} = \frac{R_1}{R_2}$$

Balance equation for the bridge is given by relation,

$$\frac{R_x + R_{cb}}{R_3 + R_{ab}} = \frac{R_1}{R_2}$$

$$(R_x + R_{cb}) = \frac{R_1}{R_2}(R_3 + R_{ab}) \quad \ldots(i)$$

We know that

$$R_{ac} + R_{bc} = R_y$$

and $$\frac{R_{bc}}{R_{ac}} = \frac{R_1}{R_2} \qquad \ldots(ii)$$

Adding 1 on the both side of equation (*ii*) we get

$$\frac{R_{bc}}{R_{ac}} + 1 = \frac{R_1}{R_2} + 1$$

$$\frac{R_{bc} + R_{ac}}{R_{ac}} = \frac{R_1 + R_2}{R_2}$$

$$\frac{R_y}{R_{ac}} = \frac{R_1 + R_2}{R_2} \qquad \ldots(\because R_{ac} + R_{bc} = R_y)$$

$$R_{ac} = \frac{R_2\, R_y}{R_1 + R_2} \qquad \ldots(iii)$$

$$R_{bc} = R_y - R_{ac}$$

$$= R_y - \frac{R_2\, R_y}{R_1 + R_2}$$

$$= \frac{R_1\, R_y}{R_1 + R_2} \qquad \ldots(iv)$$

Substituting the equation (*iii*) and (*iv*) in equation (*i*),

$$R_x + \frac{R_1\, R_y}{R_1 + R_2} = \frac{R_1}{R_2}\left(R_3 + \frac{R_2\, R_y}{R_1 + R_2}\right)$$

$$R_x = \frac{R_1\, R_3}{R_2}$$

This is the standard equation of the bridge balance. The equation does not depend on the resistance of connecting lead from R_3 to R_x. The effect of lead and contact resistances is completely eliminated by connecting the galvanometer to the intermediate position '*b*'.

4.13 Double Kelvin Bridge

Fig. 4.7 shows the circuit diagram of Kelvin double bridge. This bridge contains another set of ratio arms hence called double bridge. The second set of arms labeled '*l*' and '*m*'. The galvanometer is connected to point '*f*'. The ratio of the resistances of arms '*l*' and '*m*' is same as the ratio of R_1 and R_2.

The galvanometer indicates "zero" when the potential at '*a*' equals the potential at '*f*', i.e.,

$$E_{ab} = E_{bcf}$$

According to the *Voltage Divider Rule* the voltage across the '*ab*',

$$E_{ab} = \frac{R_2}{R_1 + R_2} \times E \qquad \ldots(i)$$

The value of *E* is given by,

$$E = I\,[R_3 + R_x + (l + m) \,||\, R_y]$$

$$E = I\left[R_3 + R_x + \frac{(l + m)\, R_y}{(l + m) + R_y}\right]$$

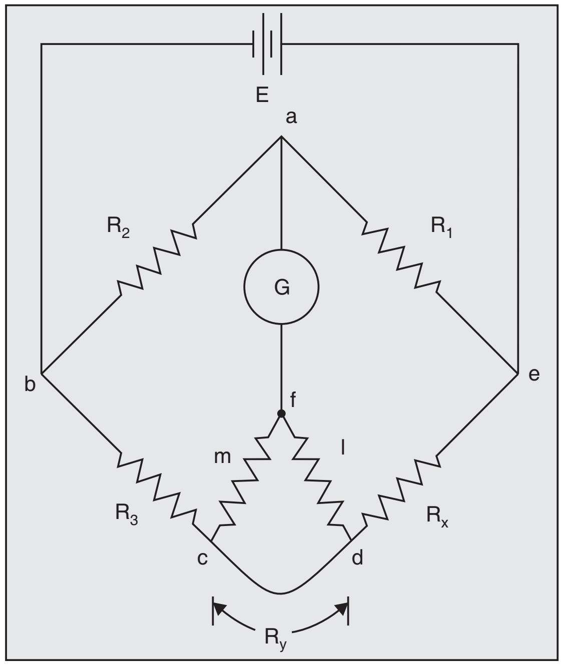


Fig. 4.7. Double Kelvin Bridge

Substituting the value of E in equation (*i*) we get,

$$E_{ab} = \frac{R_2}{R_1 + R_2} \times I \left[R_3 + R_x + \frac{(l+m)\,R_y}{(l+m)+R_y} \right]$$

Similarly,

$$E_{bcf} = I \left[R_3 + \frac{m}{l+m} \left\{ \frac{(l+m)\,R_y}{(l+m)+R_y} \right\} \right]$$

but,

$$E_{ab} = E_{bcf} = \frac{R_2}{R_1 + R_2} \times I \left[R_3 + R_x + \frac{(l+m)\,R_y}{(l+m)+R_y} \right]$$

Rearranging the above equation we get,

$$R_x = \frac{R_1\,R_3}{R_2} + \frac{m\,R_1\,R_y}{R_2\,(a+b+R_y)} - \frac{l\,R_y}{l+m+R_y}$$

$$R_x = \frac{R_1\,R_3}{R_2} + \frac{m\,R_y}{l+m+R_y}\left(\frac{R_1}{R_2} - \frac{l}{m} \right) \qquad \ldots(ii)$$

The ratio of the resistances of arms 'l' and 'm' is same as the ratio of R_1 and R_2, i.e.,

$$\frac{R_1}{R_2} = \frac{l}{m} \qquad \ldots(iv)$$

From equation (*iv*) and (*iii*) we get the value of R_x,

$$R_x = \frac{R_1\,R_3}{R_2}$$

This is the equation for Kelvin Bridge. It indicates that the resistance of the connecting lead R_y, has no effect on the measurement, provided that the ratios of the resistances of the two sets of ratio arms are equal. Fig. 4.8 shows the Kelvin double bridge. This bridge is mostly used for industrial and laboratory purpose.

Fig. 4.8. Kelvin double bridge used in industry

Example 4.3. *In a Kelvin double bridge, there is error due to mismatch between the ratio of outer and inner arm resistances. The following data relates to this bridge,*

Standard resistance = 100.03 μΩ

Inner arms = 100.31 Ω *and 200* Ω

Outer arms = 100.24 Ω *and 200* Ω

The resistance of connecting leads from standard to unknown resistance is 680 μΩ. *Determine the value of unknown resistance.*

Solution. Given: $R_3 = 100.03\ \mu\Omega = 100.03 \times 10^{-6}\ \Omega$; $l = 100.31\ \Omega$; $m = 200\ \Omega$; $R_1 = 100.24\ \Omega$; $R_2 = 200\ \Omega$ and $R_y = 680\ \mu\Omega = 680 \times 10^{-6}\ \Omega$.

We know that the value of unknown resistance

$$R_x = \frac{R_1 R_3}{R_2} + \frac{m R_y}{l + m + R_y}\left(\frac{R_1}{R_2} - \frac{l}{m}\right)$$

$$= \frac{100.24 \times (100.03 \times 10^{-6})}{200} + \frac{200 \times (680 \times 10^{-6})}{100.31 + 200 + (680 \times 10^{-6})}\left(\frac{100.24}{200} - \frac{100.31}{200}\right)$$

$$= (50.135 \times 10^{-6}) + (4.528 \times 10^{-4}) \times (-3.5 \times 10^{-4})$$

$$= 49.97 \times 10^{-6}\ \Omega = 49.97\ \mu\Omega \textbf{ Ans.}$$

4.14 Measurement of Medium Resistance Values

There are several methods for the measurement of medium resistance values. Some of the important methods different types of method are as given below.

1. Ammeter-voltmeter Method
2. Substitution Method
3. Wheatstone Bridge
4. Carey-Foster slide-wire Bridge Method

We shall know discuss all the above mentioned methods one by one in detail in the following pages. We have already discussed the ammeter-voltmeter method for the measurement of low resistance values. This method is same for measurement of medium resistance values.

4.15 Substitution Method

In substation method, the unknown resistor is substituted by the known variable resistance R in the circuit. Then we compare voltage or current in both circuits to find the value of unknown resistance. There is different way to find the value of unknown resistance R_X in the substitution method. The method is discussed below:

1. Substitution by Variable resistance R.

The unknown resistance R_X is connected in the circuit as shown in Fig. 4.9 and the value of current is recorded. Then the unknown resistance R_X is removed and it is substituted by a known variable R as shown in Fig. 4.10. The value of resistance is varied to make the current same in both cases. Then the value of known resistance R_X is equal to known resistance,

$$R_X = R$$

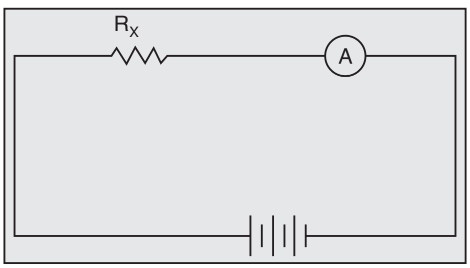


Fig. 4.9. With unknown resistance R_X.

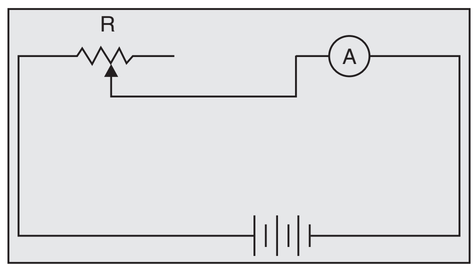


Fig. 4.10. With known resistance R_X.

2. Substitution by fixed resistance R.

If we are using the fixed resistance R then the following reading should be taken to find the value of unknown resistance.

Case (a): Fig. 4.11 shows the resistance R_X and R in series, the reading of ammeter is given by,

$$I_1 = \frac{V}{R + R_X} \qquad \ldots(i)$$

Case (b): Fig. 4.12 shows when resistance R_X is removed, the reading of ammeter is given by,

$$I_2 = \frac{V}{R} \qquad \ldots(ii)$$

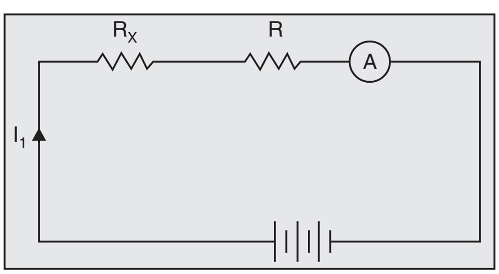


Fig. 4.11. R_X and R in series.

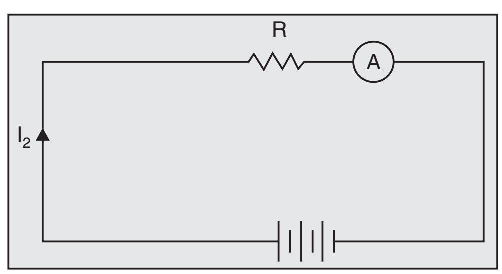


Fig. 4.12. R_X is removed.

Dividing equation (*ii*) by (*i*) we get,

$$\frac{I_2}{I_1} = \frac{R + R_X}{R} = 1 + \frac{R_X}{R}$$

$$\frac{R_X}{R} = \frac{I_2}{I_1} - 1$$

$$R_X = R\left(\frac{I_2 - I_1}{I_1}\right) \quad \ldots(iii)$$

The value of unknown resistance is calculated by equation (*iii*).

3. Two-Way Switch Method.

In this method Fig. 4.13 shows on the unknown resistance R_X and the known resistance R are connected in parallel through a two-way switch is used. The switch is connected to the unknown resistance first and the value of current, I_1 is recorded. Then the switch is connected to the known resistance R and the value of current I_2 is recorded.

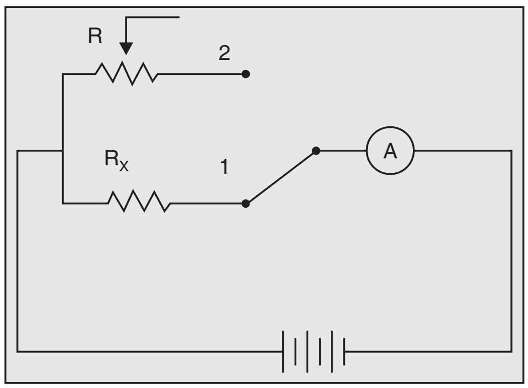


Fig. 4.13.

When the switch is connected to the unknown resistance R_X, the value of circuit current,

$$I_1 = \frac{V}{R_X} \quad \ldots(i)$$

When the switch is connected to the known resistance R, the value of circuit current,

$$I_2 = \frac{V}{R} \quad \ldots(ii)$$

Dividing the equation (*ii*) with (*i*), we get,

$$\frac{I_2}{I_1} = \frac{R_X}{R}$$

or

$$R_X = R \times \frac{I_2}{I_1} \quad \ldots(iii)$$

Using the above equation, we can find the value of unknown resistance.

4.16 Wheatstone Bridge

The Wheatstone bridge circuit is used to compare an unknown resistance with a known resistance. The bridge is commonly used in control circuits. Wheatstone bridge is the most accurate method available for measuring resistance and is popular for laboratory use.

Fig. 4.14 shows the Wheatstone bridge circuit. The bridge has four resistive arms, together with a source of e.m.f and a null detector. The source of e.m.f and a switch is connected to '*A*' and '*B*', while a current indicating meter,"galvanometer" is connected between '*C*' and '*D*'. When there is no current through the galvanometer, the pointer shows zero. The current in one direction cause the pointer to deflect on one side and current in the opposite direction cause the pointer to deflect to the other side.

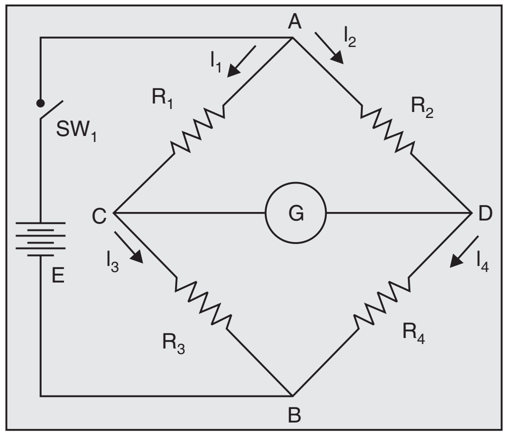


Fig. 4.14 Wheatstone Bridge.

The bridge is said to be balanced when the potential difference across the galvanometer is '0V' so that there is no current through the galvanometer. This condition occurs when the voltage from point '*C*' to point '*A*' is equal to the voltage from point '*D*' to point '*A*'. By referring the other battery terminal, the bridge is balanced when the voltage from point '*C*' to point '*B*' equals the voltage from point '*D*' to point '*B*'. Thus when the bridge is balanced,

$$I_1 R_1 = I_2 R_2 \qquad \ldots(i)$$

Applying Kirchhoff's Voltage Law in loop *ABC* when the galvanometer current is zero, we get,

$$I_1 R_1 + I_3 R_3 - E = 0$$

But since current $I_1 = I_3$, we get,

$$I_1 = I_3 = \frac{E}{R_1 + R_3} \qquad \ldots(ii)$$

Similarly, in loop *ADB* we get,

$$I_2 = I_4 = \frac{E}{R_2 + R_4} \qquad \ldots(iii)$$

Using equation (*i*) (*ii*) and (*iii*), we get

$$\frac{R_1}{R_1 + R_3} = \frac{R_2}{R_2 + R_4}$$

or

$$R_1 R_4 = R_2 R_3 \qquad \ldots(iv)$$

In balanced condition if three of the resistances have known values, then the value of fourth resistance is calculated from the equation (*iv*). If R_4 is unknown resistor R_x, then the value of R_x,

$$R_x = R_3 \frac{R_2}{R_1}$$

Resistor R_3 is called the standard arm of the bridge, and resistors R_2 and R_1 are called the ratio arms. The laboratory version of Wheatstone bridge instrument is shown in Fig. 4.15.

Fig. 4.15. Illustrating a portable Wheatstone bridge used in industry

4.17 Measurement Errors in Wheatstone Bridge

The Wheatstone bridge is widely used for precision measurement of resistance from approximately 1Ω to the low megaohm range. Measurement errors are given below:

1. The main source of measurement error is found in the limiting errors of three known resistors
2. Insufficient sensitivity of the null detector
3. Changes in resistance of the bridge arms due to the heating effect of the current through the resistors
4. Thermal e.m.fs in the bridge circuit or the galvanometer circuit can also cause problems when low-value resistors are being measured.

Example 4.4. *In a Wheatstone bridge resistance R_1 = 20 kΩ, R_2 = 30 kΩ and R_3 = 80 kΩ. Determine the unknown resistance R_X.*

Solution. Given: R_1 = 20 kΩ; R_2 = 30 kΩ and R_3 = 80 kΩ.

We know that the value of unknown resistance in Wheatstone bridge,

$$R_x = R_3 \frac{R_2}{R_1}$$

$$= \frac{30 \times 80}{20} = 120 \text{ k}\Omega \textbf{ Ans.}$$

Example 4.5. *Each of the ratio arms of a laboratory type Wheatstone bridge has guaranteed accuracy of ± 0.05 %, while the standard arm has a guaranteed accuracy of ± 0.1 %. The ratio arms are both set at 1000 Ω and bridge is balanced with standard arm adjusted to 3154 Ω.*

Determine the upper and lower limits of the unknown resistance, based upon the guaranteed accuracies of the unknown bridge arms.

Solution. Given: $R_1 = R_2$ = 1000 Ω and R_3 = 3154 Ω

We know that the value of unknown resistance in Wheatstone bridge,

$$R_x = R_3 \frac{R_2}{R_1} = \frac{3154 \times 1000}{1000} = 3154\ \Omega$$

The percentage error in determination of R_X

$$\frac{\delta R_X}{R_X} = \pm \frac{\delta R_1}{R_1} \pm \frac{\delta R_2}{R_2} \pm \frac{\delta R_3}{R_3}$$

$$= \pm\ 0.05 \pm 0.05 \pm 0.1 = \pm\ 0.2\ \%$$

Therefore, the limiting value of R_X is,

$$R_X = 3154 \pm 0.2\ \%$$

The value of unknown resistance is from 3147 to 3160 Ω **Ans.**

4.18 Unbalanced Wheatstone Bridge

To determine whether or not the galvanometer has the required sensitivity to detect an unbalance condition, it is necessary to calculate the galvanometer current. To determine the amount of deflection that would result for a particular degree of unbalance, we use Thevenin's theorem,

Fig. 4.16 shows the unbalanced Wheatstone bridge, since we are interested in the circuit through the galvanometer, the Thevenin equivalent circuit is determined by looking into galvanometer terminals '*c*' and '*d*'.

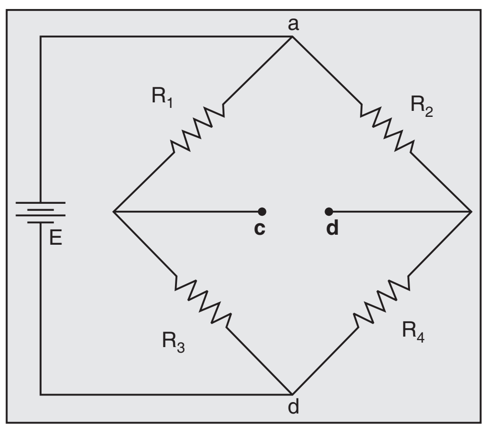


Fig. 4.16. Unbalanced Wheatstone Bridge.

The Thevenin or open-circuit voltage is given by,

$$E_{th} = E_{ac} - E_{ad} = I_1 R_1 - I_2 R_2$$

where

$$I_1 = \frac{E}{R_1 + R_3}$$

and

$$I_2 = \frac{E}{R_2 + R_4}$$

$$E_{th} = E\left(\frac{R_1}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right)$$

The resistance of the Thevenin equivalent circuit is found by looking back into terminals *c* and *d* and replacing the battery by its internal resistance. Thus Thevenin resistance looking into terminals *c* and *d*,

$$R_{th} = \frac{R_1 R_3}{R_1 + R_3} + \frac{R_2 R_4}{R_2 + R_4}$$

The galvanometer current is given by,

$$I_g = \frac{E_{th}}{R_{th} + R_g}$$

where I_g is the current through galvanometer and R_g is its resistance.

4.19 Carey-Foster Slide-Wire Bridge Method

Carey-Foster slide-wire bridge is an elaboration of the Wheatstone bridge. This bridge is mainly used for comparing two nearly equal resistances. Fig. 4.17 shows the circuit diagram where R_1 and R_2 are nominal ratio arms, R_X the resistance under test and R_3 the standard resistance.

A uniform slide-wire of length L is included between R_X and R_3. The balanced condition is obtained by adjustment of the sliding contact on the slide-wire.

The resistance R_1 and R_2 are first adjusted so that the ratio R_1/R_2 is approximately equal to the ratio R_X/R_3 by the sliding the contact on the slide-wire. Let L_1 be the distance of the sliding contact from the left hand end of the slide-wire.

$$\frac{R_1}{R_2} = \frac{R_X + l_1 r}{R_3 + (L - l_1) r} \qquad \ldots(i)$$

Where 'r' is the resistance per unit length of the slide-wire.

Then the resistance R_X and R_3 are interchanged and new balance is obtained. Let the distance of the sliding contact is L_2.

$$\frac{R_1}{R_2} = \frac{R_3 + l_2 r}{R_X + (L - l_2) r} \qquad \ldots(ii)$$

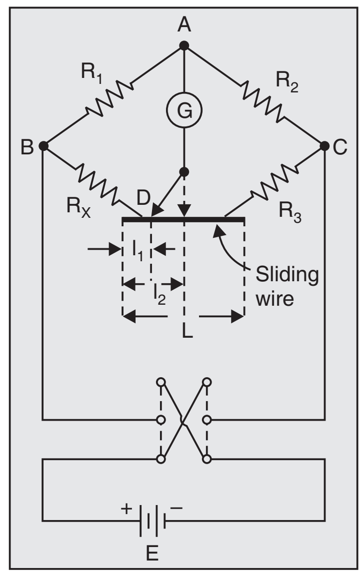


Fig. 4.17. Carey-Foster slide-wire Bridge

Now comparing the equation (i) and (ii) we get,

$$\frac{R_X + l_1 r}{R_3 + (L - l_1) r} = \frac{R_3 + l_2 r}{R_X + (L - l_2) r}$$

adding 1 the both side of the above equation we get,

$$\frac{R_X + l_1 r}{R_3 + (L - l_1) r} + 1 = \frac{R_3 + l_2 r}{R_X + (L - l_2) r} + 1$$

$$\frac{R_X + l_1 r + R_3 + Lr - l_1 r}{R_3 + (L - l_1) r} = \frac{R_3 + l_2 r + R_X + Lr - l_2 r}{R_X + (L - l_2) r}$$

$$\frac{R_X + R_3 + Lr}{R_3 + (L - l_1) r} = \frac{R_3 + R_X + Lr}{R_X + (L - l_2) r}$$

$$R_3 + (L - l_1) r = R_X + (L - l_2) r$$

$$R_3 + Lr - l_1 r = R_X + Lr - l_2 r$$

$$R_3 - R_X = r (l_1 - l_2) \qquad \ldots(iii)$$

The equation (iii) shows that the difference between the resistance R_X and R_3 is obtained from the resistance of the slide wire between the two point balance points.

The resistance 'r' of the slide wire is calibrated by shunting the resistance R_3 by a known high resistance. The effective value of the standard resistance R_3 reduces to R'_3. Now let the new balance points l'_1 and l'_2 are obtained. Repeating the whole procedure again we get,

$$R'_3 - R_X = r\,(l'_1 - l'_2) \qquad \ldots(iv)$$

Dividing the equation (*iii*) by (*iv*) we get,

$$\frac{R_3 - R_X}{R'_3 - R_X} = \frac{r\,(l_1 - l_2)}{r\,(l'_1 - l'_2)}$$

$$R_3\,(l'_1 - l'_2) - R_X\,(l'_1 - l'_2) = R'_3\,(l_1 - l_2) - R_X\,(l_1 - l_2)$$

$$R_X\,[(l'_1 - l'_2) - (l_1 - l_2)] = R_3\,[(l'_1 - l'_2) - (l_1 - l_2)]$$

$$R_X = \frac{R_3\,[(l'_1 - l'_2) - (l_1 - l_2)]}{(l'_1 - l'_2) - (l_1 - l_2)}$$

$$R_X = \frac{R_3\,[(l'_1 - l'_2) - R_3\,(l_1 - l_2)]}{l'_1 - l'_2 - l_1 - l_2} \qquad \ldots(v)$$

Equation (*v*) shows that this method compares R_X and R_3 directly in terms of the lengths only. The resistance R_1, R_2 and contact resistance are being eliminated.

All high accuracy bridges have errors because of thermo-electric e.m.f in the low resistance arms. To eliminate this type of error Carey-Foster bridge uses a switch which enables the connections to R_X and R_3 resistances to be interchanged without handling the coils.

4.20 Measurement of High Resistance Values

The value of high resistance is of the order of hundreds to thousands of megaohm. Some of the examples of high resistance values are in the following cases:

1. Insulation resistance of components
2. Resistance of the elements like in vacuum tube circuits.
3. Leakage resistance of capacitors

It may be carefully noted that the methods of resistance measurement described in the previous sections are not suitable for high resistance measurement. One of the main problems in high resistance measurements is the leakage that occurs over and around the component or specimen under test, or over the binding posts by which the component is attached to the instrument or within the instrument itself. The resistance of insulating materials, generally, falls rapidly with increasing temperature, so the change in temperature and operating temperature plays a very important role in the determination of the resistance. The value of insulation resistance should always be stated together with the temperature at which the test was carried out.

There are several methods to measure the high resistance values but the following ones are important from the subject point of view:

1. Direct deflection method
2. Loss of charge method
3. Megohm bridge
4. Megger

Now we shall discuss all the above mentioned methods one by one in detail in the following pages.

4.21 Direct Deflection Method

The direct deflection method is used for high resistance measurement. The sensitive moving coil galvanometer and high resistance(about 1 kΩ or more) is connected in series with the resistance to be measured along with supply voltage. The deflection of the galvanometer gives a measure of the insulation resistance. This method is for measuring insulation resistance of the cable. The cables are of two types: Cable with Sheath and Cable without Sheath.

(a) Direct deflection method for Cable with Sheath

Fig. 4.18 shows the direct deflection method for measuring the insulation resistance of a cable with sheath. The galvanometer measures the current I_X between the conductor and the metal sheath. The leakage current I_L over the insulating material is carried by the guard wire wound on the insulation and therefore does not flow through the galvanometer.

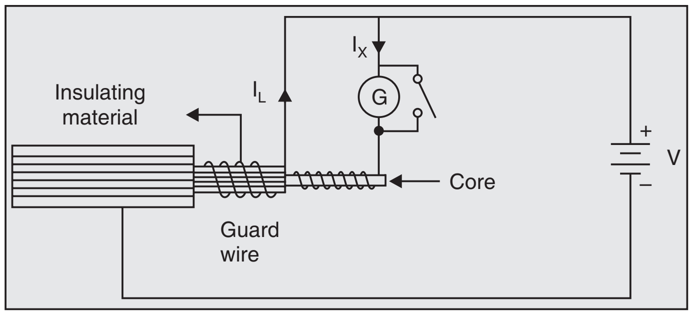


Fig. 4.18. Illustrating direct deflection method for Cable **with** sheath

(b) Cable without Sheath

Cables without metal sheaths can be tested in a similar way like in cable with sheath. The direct deflection method for measuring the insulation resistance is shown in Fig. 4.19. First the cable is immersed in slightly saline water for about 24 hours and the temperature is kept constant about 20°C. The water enters the pores of the cable and the temperature of the cable attains the temperature of the water. The water and tank then form the return path for the current.

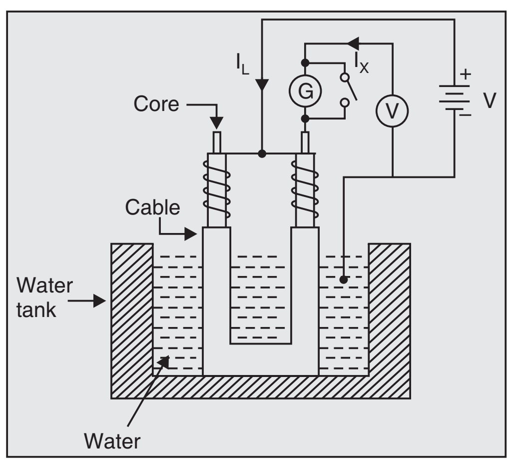


Fig. 4.19. Illustrating direct deflection method with Cable **without** Sheath

The galvanometer is properly shunted. It includes a series resistance of high value. The true value of insulation resistance can be determined by subtracting the value of series resistance from the observed resistance. The scale of the galvanometer is calibrated by replacing the insulation by a standard high resistance.

While conducting tests on cables the galvanometer should be short-circuited before applying the voltage. The short-circuiting connection is removed only after sufficient time has elapsed so that charging and absorption currents cease to flow.

The galvanometer should be very sensitive, high resistance and uniform scale. To prevent leakage currents, the galvanometer circuit switches and circuitry must be well insulated.

4.22 Measurement of Volume and Surface Resistivities

The insulation resistance material is available in sheet form. In such case volume and surface resistivity of the material are measured as discuss below:

1. Volume Resistivity

For measurement of volume resistivity,we measure and record the voltage applied and current through galvanometer. Leakage current over the edge of the specimen will flow between the ring and the lower electrode and hence will not introduce error into the measurement. The volume resistivity ρ can be calculated as follows,

Let, d_1 = diameter of upper electrode

t = thickness of the specimen sheet

V_1 = Voltmeter reading

I_1 = Current through galvanometer

Resistance of the specimen,

$$R = \frac{V_1}{I_1} \quad \ldots(i)$$

$$R = \frac{\rho t}{\frac{\pi}{4} d_1^2} = \frac{4\rho t}{\pi d_1^2} \quad \ldots(ii)$$

From equation (*i*) and (*ii*), volume resistivity of specimen is given by,

$$\rho = \frac{\pi d_1^2 V_1}{4t\, I_1} \quad \ldots(iii)$$

The resistance, R_t between two electrodes of the dielectric medium is given by,

$$\frac{1}{R_t} = \frac{1}{R_v} + \frac{1}{R_s}$$

where R_v = volume resistance and

R_s = Surface resistance

2. Surface Resistivity.

The surface resistivity is the resistance between opposite edges of a square area of the surface of the material. To measure the surface resistivity the galvanometer is placed as shown in Fig. 4.20. The galvanometer measures the leakage current. The current flowing between upper and lower electrodes will be eliminated from the measurement.

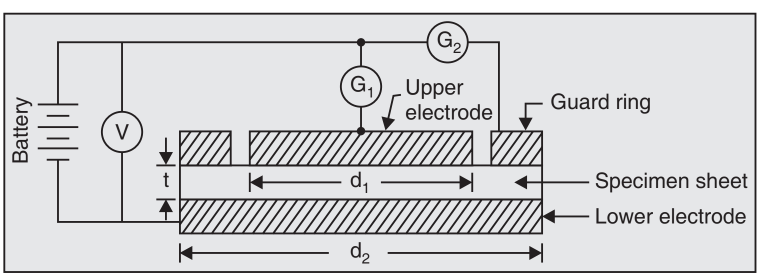


Fig. 4.20.

Surface resistance $R_s = \dfrac{V_2}{I_2}$

The leakage current flows along a path of length 't' and width 'πd_2', therefore surface resistivity,

$$\rho_s = \frac{R_s \times \pi d_2}{t} = \frac{\pi d_2}{t} \cdot \frac{V_2}{I_2} \quad \ldots(iv)$$

The volume and surface resistivity is defined from the equation (*iii*) and (*iv*).

4.23 Loss of Charge Method

Fig. 4.21 shows the loss of charge method. This method is used for measuring the insulation resistance of very high value where C is a known capacitance, V is electrostatic voltmeter, and R_{leak} is the total leakage resistance of the capacitor and voltmeter. R_X is the unknown resistance to be measured. There are two parts of the circuit, the inner part comprising C, V and R_{leak} and other is the outer part comprising of R_X and battery. The inner part of the circuit is connected to the outer part through a switch.

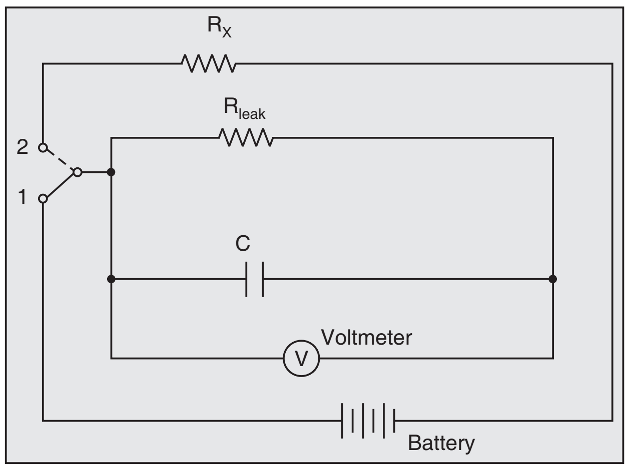


Fig. 4.21. Loss of Charge Method.

The switch is first connected to the point 1 and capacitor is charged by the battery, the voltmeter reading, say V_1 is recorded. Then the switch is connected to the point 2 and capacitor is discharged through the resistance R_X and R_{leak}. After discharging the capacitor, the voltmeter reading is recorded again, say V_2. The time taken for the potential difference to fall from V_1 to V_2 during discharge is 't'. The effective resistance is the equivalent resistance of R_X and R_{leak} connected parallel.

Determine the value of $R_{eff.}$

Let at any instant 't' the voltage across the discharge capacitor is V volts, the charge on the discharging capacitor is q coulombs and the capacity of the capacitor is C farads. Then current I is given by,

$$i = -\frac{dq}{dt} = -C \cdot \frac{dv}{dt} \quad \ldots(i)$$

$$i = \frac{\text{potential drop across } R_{\text{eff}}}{R_{\text{eff}}} = \frac{v}{R_{\text{eff}}} \quad \ldots(ii)$$

Comparing the equations (*i*) and (*ii*) we get,

$$-C \cdot \frac{dv}{dt} = \frac{v}{R_{\text{eff}}}$$

$$\frac{dv}{v} = -\frac{dt}{C\,R_{\text{eff}}}$$

Integrating on both sides we get,

$$\frac{dv}{v} = -\frac{dt}{C\,R_{\text{eff}}}$$

$$\int_{v_1}^{v_2} \frac{dv}{v} = \int_0^t -\frac{dt}{C\,R_{\text{eff}}}$$

$$[\ln v]_{v_1}^{v_2} = -\frac{t}{C\,R_{\text{eff}}}$$

or $$\ln\left(\frac{v_2}{v_1}\right) = -\frac{t}{C\,R_{\text{eff}}} \qquad \ldots(iii)$$

or $$\frac{v_2}{v_1} = e^{\left(-\frac{t}{C\,R_{\text{eff}}}\right)}$$

$$v_2 = v_1 \,.\, e^{\left(-\frac{t}{C\,R_{\text{eff}}}\right)} \qquad \ldots(iv)$$

Using equation (*iii*) we can determine the value of R_{eff}. Thus,

$$R_{\text{eff}} = \frac{-t}{C\,.\ln\left(\frac{v_2}{v_1}\right)} = \frac{t}{C\,.\ln\left(\frac{v_1}{v_2}\right)}$$

Determine the value of R_{leak}

The test is repeated again with the R_{leak} resistance only. The resistance R_X is disconnected from the circuit. The value of leakage resistance is determined.

Value of R_X

We know that R_{eff} is the parallel combination of the resistance R_X and R_{leak}, then the value of R_X is given by,

$$\frac{1}{R_X} = \frac{1}{R_{\text{eff}}} - \frac{1}{R_{\text{leak}}}$$

In this method leakage resistance of the voltmeter can be neglected if its value is low. If it is high then it must be considered R_{leak}.

When insulation resistance of a cable or a capacitor is to be measured, the test needs not to be repeated. In this case C will be the capacitance of the cable and R_{leak} will be the insulation resistance.

Example 4.6. *The value of high resistance is measured by loss of charge method. A capacitor having a capacitor of 2.5 μF is charged to a potential of 500 V dc and is discharged through the high resistance. An electrostatic voltmeter, kept across the high resistance, reads the voltage as 300 V at the end of 60 seconds. Calculate the high resistance.*

Solution. Given: $C = 2.5\ \mu\text{F} = 2.5 \times 10^{-6}$ F; $V_1 = 500$ V; $V_2 = 300$ V and $t = 60$ s

We know that,

$$v_2 = v_1 \,.\, e^{\left(-\frac{t}{C\,R_{\text{eff}}}\right)}$$

$$e^{\left(-\frac{t}{C\,R_{\text{eff}}}\right)} = \frac{v_2}{v_1}$$

$$R_{\text{eff}} = R_X$$

taking logarithms on both sides we get,

$$\frac{t}{C\,R_X} = ln\left(\frac{v_1}{v_2}\right)$$

$$R_X = \frac{t}{C\,ln\left(\frac{v_1}{v_2}\right)} = \frac{60}{2.5\times 10^{-6}\,ln\left(\frac{500}{300}\right)}$$

$$= 46.98\text{ M}\Omega \textbf{ Ans.}$$

Example 4.7. *A length of cable was tested for insulation resistance using loss of charge method. A capacitance formed by sheath of cable of 300 pF is found to have drop in voltage from 300 V to 100 V in 120 seconds. Calculate the insulation resistance of the cable.*

(GBTU/MTU, 2002-03)

Solution. Given: Capacitance, C = 300 pF; V_1 = 300 V, V_2 = 100 V and t = 120 s;

We know that the value of insulation resistance,

$$R_{\text{insulation}} = \frac{t}{C\,.\,ln\left(\frac{v_1}{v_2}\right)}$$

$$R = \frac{120}{(300\times 10^{-12})\,ln\left(\frac{300}{100}\right)}$$

$$= 0.364 \times 10^6\text{ M}\Omega \textbf{ Ans.}$$

4.24 Megohm Bridge

To remove leakage current in the bridge we use '*three terminal resistances*'. It is shown in Fig. 4.22. The high resistance is connected between two binding posts which are fixed to metal plate. The two main terminals of the resistor are connected to the R_X terminals in the bridge. The third terminal is the common point of resistances R_1 and R_2, which represent the leakage paths from the main terminal along the insulating post of the metal plate.

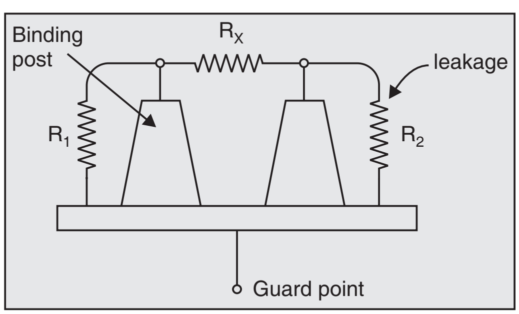


Fig. 4.22. Three Terminal Resistances

Fig. 4.23 shows the Magaohm Bridge. This bridge uses the guard terminal in connection. It include the following

(*a*) Power Supplies
(*b*) Bridge members
(*c*) Amplifiers
(*d*) Indicating Instrument

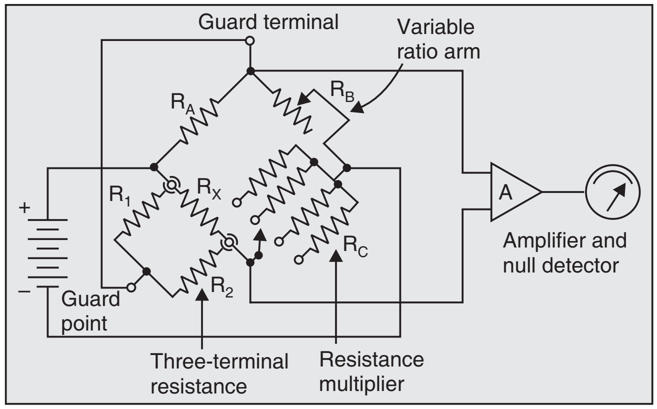


Fig. 4.23. Megohm Bridge

The resistance R_1 in parallel with arm resistance R_A, but R_1 is very much larger then R_A thus its shunting effect is negligible. Similarly the resistance R_2 is in parallel with galvanometer and has no effect as R_2 is much higher than galvanometer resistance. The external leakage path can be removed by using the guard circuit on the three terminal resistances.

Sensitivity for balancing against high resistance is obtained by use of adjustable high voltage supplies. The resistance R_B is the variable resistance. Resistance R_C gives the multipliers of different range of resistance. The junction of ratio arms R_1 and R_2 is Guard terminal.

The value of the unknown resistances is given by

$$R_X = \frac{R_A\, R_C}{R_B}$$

4.25 Megger

The megger is an instrument used for the measurement of high resistance and insulation resistance. Essentially the megger insulation tester consists of a hand-driven dc generator and a direct reading true ohmmeter. Megger is also called meg-ohmmeter. It is shown in Fig. 4.24. An ordinary ohmmeter cannot be used for measuring resistance of multimillions of ohms, such as conductor insulation. Megger used to measure high resistance, of the order of one megaohm and above. The meg-ohmmeters or megger is a portable deflection instrument widely used to check the insulation resistance of electrical cables and equipment. This instrument measures the insulation resistance of the electric circuits relative to earth and one another.

Principle of Operation

This instrument is based on the electromagnetic induction. A current carrying conductor in a uniform magnetic field experiences a mechanical force. The magnitude of the force depends upon the strength of current and magnetic field. Direction of the mechanical force depends on the direction of current and magnetic fields.

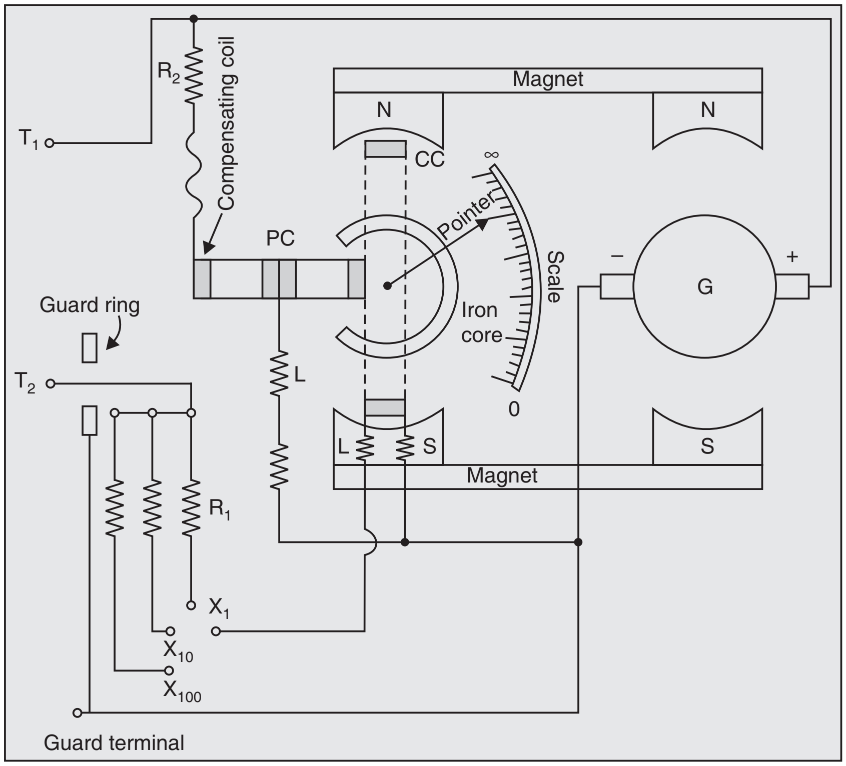


Fig. 4.24. Megger.

Construction of Megger

1. Megger consists of a permanent magnet which provides the field for both the generator *G* and ohmmeter
2. The moving element of the ohmmeter consist of three coils
   (*a*) Deflection coil
   (*b*) Pressure or control coil
   (*c*) Compensating coil
3. Coils are mounted on a central shaft which are free to rotate over stationary *C*-shaped iron core.
4. The coils are connected to the circuit through flexible leads called ligaments which do not produce a restoring torque on the moving element.
5. The current coil is connected in series with resistance R_1 between one generator terminal and the test terminal T_2.
6. The series resistance R_1 protects the current coil from short circuit of the test terminals and it also control the range of instrument.
7. The pressure coil, in series with a compensating coil and protection resistance R_2 is connected across the generator terminals.

Working of Megger

When the current flows from the generator through the pressure coil, the coil tends to set itself at right angles to the field of the permanent magnet.

When test terminals are open

1. When the test terminals are open, corresponding to infinite resistance. Then no current flows through deflection coil.
2. The pressure coil governs the motion of the moving element and makes it to move to its extreme anticlockwise position.
3. The pointer comes to rest at the infinity end of the scale.

When test terminals are short

1. When the test terminals are short, corresponding to zero resistance. The current from the generator flowing through the current coil is large to produce sufficient torque to overcome the counter-clockwise torque of the pressure coil.
2. The pointer moves over a scale showing zero resistance.

The high resistance to be tested is connected between terminals T_1 and T_2. The opposing torques of the coils balance each other so that pointer attains a stationary position at some intermediate point on scale.

The scale is calibrated in megaohms so that the resistance is directly indicated by pointer. The guard ring eliminates the error due to leakage current.

Fig. 4.25 shows the Megger from Megger Company Model No. MIT210.This instrument has a resistance measurement ranges from 10 kΩ to 1000 MΩ .The insulation testing ranges are 1000 V and 1000 MΩ.

Fig. 4.25.

SUMMARY

In this chapter you have learned that:

1. Resistances are classified according to their resistance value, low (less than or equal to 1 Ω), medium (1 Ω to 100 kΩ) and high resistance (above 100 kΩ).
2. Ammeter-voltmeter method is used for measuring low resistance values.
3. The potentiometer method compares the unknown resistance with a standard resistance of the same order of magnitude.

4. Kelvin bridge measure the low-value resistance generally below 1 Ω.
5. In substitution method the unknown resistance is substituted with the known variable resistance.
6. Wheatstone bridge is the most accurate method available for measuring resistance and is popular for laboratory use.
7. Carey-Foster slide-wire bridge is mainly used for comparing two nearly equal resistances.
8. The direct deflection method is used for measuring high resistance values.
9. Loss of charge method is for measuring the insulation resistance of very high value
10. Megger is used to measure high resistance, of the order of one mega ohm and above. This instrument measures the insulation resistance of the electric circuits relative to earth and one another.

GLOSSARY

Ammeter-Voltmeter method: The ammeter-voltmeter method employs the simple ohm's law to determine the value of an unknown resistance.

Carey-Foster slide-wire bridge: Carey-Foster slide-wire bridge is an elaboration of the Wheatstone bridge.

Direct Deflection method: In this method the sensitive moving coil galvanometer and high resistance (about 1 kΩ or more) is connected in series with the resistance to be measured along with supply voltage. The deflection of the galvanometer gives a measure of the insulation resistance.

Megger: Megger consists of a permanent magnet which provides the field for both the generator *G* and ohmmeter. This instrument measures the insulation resistance of the electric circuits relative to earth and one another.

Substitution method: In this method the unknown resistor is substituted by the known variable resistance R in the circuit. Then we compare voltage or current in both circuits to find the value of unknown resistance.

Wheatstone bridge: The Wheatstone bridge is a circuit used to compare an unknown resistance with a known resistance. The bridge is commonly used in control circuits.

NUMERICAL PROBLEMS

1. The ammeter-voltmeter method is used to measure a resistance. With the voltmeter connected across the resistance the reading on the ammeter and voltmeter are 0.4 A and 3.2 V respectively. The resistance of the voltmeter is 500 Ω. Calculate (*i*) true value of resistance. (*ii*) Percentage error in the value of resistance, if the voltmeter current is ignored.

   (**Ans.** 8.13 Ω; 1.6 %)
2. In a specific Kelvin bridge the ration of the arms are 1:100. The standard resistance is 20 Ω. Find out the unknown resistance.

   (**Ans.** 0.2 Ω)
3. The insulation resistance of 2 metre cable was measured by loss of charge method. The voltage across the standard capacitance of 0.003 pF drops from 222 V to 155 V in 1 minute. Calculate the insulation resistance of the cable.

   (**Ans.** 55,670 MΩ)
4. In a measurement of resistance by potentiometer, the voltage drops across a resistor under test and across 0.02 Ω standard resistor were found to be 0.735 V and 9.8 V respectively. Determine the value of resistor under test.

   (**Ans.** 0.015 Ω)
5. Determine the insulation resistance of a short length of cable in which voltage falls from 125 to 100 volts in 25 seconds. The capacity of the condenser is 600×10^{12} F.

   (**Ans.** 1,86,726 MΩ)
6. The Wheatstone bridge consists of the following parameters: R_1 = 10 kΩ R_2 = 15 kΩ and R_3 = 40 kΩ. Fine the unknown resistance R_X.

   (**Ans.** 60 Ω)

DESCRIPTIVE QUESTIONS

1. How are resistance classified?
2. Explain what do you mean by low, medium and high resistances. Suggest various suitable methods for measuring then giving justification. Describe any method to measure a low resistance with accuracy.
3. State various methods of measurement of low resistance. Why is ammeter-voltmeter method not suitable for precise measurement of low resistance?
4. What do you mean by low, medium and high resistance? Describe one method each for the measurement of low, medium and high resistance with their advantages and disadvantages?

   (GBTU/MTU, 2004-05)
5. Write different methods of measurement of medium resistance.

   (P.T.U, Dec. 2009)
6. Discuss substitution method for measurement of medium resistance.

   (P.T.U, Dec. 2009)
7. What are the difficulties associated with the measurement of low resistance? Describe how resistance is measured accurately by Kelvin's double bridge.
8. Explain the construction and principle of operation of Kelvin's double bridge. Mention why this bridge is used accurate measurement of low resistance.
9. Discuss the relevant circuit diagram how Kelvin's double bridge is used for measuring low value of resistance, more precisely in comparison to voltmeter-ammeter method.

   (GBTU/MTU, 2005-06)
10. What are the problems associated with measurement of low resistances? How are they overcome through use of Kelvin's double bridge? Derive the expression for the unknown resistance in the case of Kelvin's double bridge.
11. Explain the procedure of measuring a low resistance with help of Kelvin's double bridge. Derive the relation to finding unknown resistance.
12. List and discuss the principle applications of Kelvin's bridge.
13. Describe the operation of a Kelvin's bridge.
14. What is the primary use of Kelvin's bridge?
15. How does the basic circuit of Kelvin's bridge differ from that of Wheatstone's bridge?
16. Compare the measuring accuracy of a Wheatstone bridge with the accuracy of an ordinary ohmmeter?
17. In what two types of circuits do Wheatstone bridge find most of their applications.
18. Describe the operation of the Wheatstone bridge.
19. Describe how Wheatstone's bridge may be used to control various physical parameters.
20. What is the criterion for balance of a Wheatstone bridge?
21. What is the principle of using loss of charge technique for measurement of high resistance? Derive necessary relation.

    (GBTU/MTU, 2002-03)
22. Describe with the help of neat diagram, the loss of charge method to determine the insulation resistance of a short length of cable and derive an expression for determination resistance.

    (GBTU/MTU, 2001-02)
23. Describe megaohm bridge method of measuring high resistance with the help of a neat diagram.
24. Describe the construction and working of Carey-Foster Bridge.
25. Describe Carey Foster's slide wire bridge for the measurement of medium resistance.
26. Explain the Kelvin double bridge method for measurement of low resistance.

    (P.T.U, May 2010)

27. Describe and explain with the help of neat sketches the construction and working of megger.

28. Explain wheatstone bridge and derive the expression for bridge sensitivity.

(GBTU/MTU 2009-10)

29. Explain Ammeter-Voltmeter method of measurement of resistance with its advantages and disadvantages.

(Nagpur University, Summer 2010)

30. What do you understand by low, medium and high resistance? Describe Kelvin's double bridge method for measurement of small resistances.

(Nagpur University, Summer 2010)

31. Explain the significance of using four terminals for measurement of low resistance.

(Nagpur University, Summer 2010)

32. State various methods of measurement of low resistance. Why are ammeter-voltmeter methods not sutiable for the precise measurement of low resistance?

(GBTU/MTU, 2010-11)

MULTIPLE CHOICE QUESTIONS

1. Low resistance are provided with four terminals,
- (*a*) to facilitate the connection of current and potential circuits
- (*b*) in order that the resistance value becomes definite irrespective of the nature of contacts at the current terminals.
- (*c*) to eliminate the effects of thermo-electric emfs.
- (*d*) to eliminate the effect of leads.

2. In a Kelvin's double bridge two sets of reading are taken when measuring a low resistance, one with the current in one direction and the other with direction of current reversed. This is done to,
- (*a*) eliminate the effect of contact resistance.
- (*b*) eliminate the effect of resistance of leads.
- (*c*) correct for changes in battery voltage.
- (*d*) eliminate the effect of thermo-electric emfs.

3. A resistance of value 10 Ω approximately is to be measured by ammeter-voltmeter method with resistance of ammeter as 0.02 Ω and that of voltmeter as 5000 Ω. The resistance should be measured,
- (a) by connecting the ammeter on the side of unknown resistance as this connection gives batter accuracy.
- (*b*) by connecting the voltmeter on the side of unknown resistance as this connection gives batter accuracy.
- (*c*) by any of the two connections, as both of them give equal accuracy.
- (*d*) none of the above.

4. Equal resistance of 100 Ω each are connected in each arm of a Wheatstone bridge which is supplied by a 2 V battery source. The galvanometer of negligible resistance connected to the bridge can sense as low current as 1 μA . The smallest value of resistance that can be measured is,
- (*a*) 20m Ω
- (*b*) 2 μΩ
- (*c*) 20 μΩ
- (*d*) none of the above.

5. A whetstone bridge cannot be used for precision measurements because errors are introduced into it on account of,
- (*a*) Resistance of connecting leads
- (*b*) Thermo-electric emfs
- (*c*) Contact resistances
- (*d*) All of the above

6. A Wheatstone bridge has ratio arms of 1000 Ω and 100 Ω resistance, the standard resistance arms consist 4 decade resistance boxes of 1000, 100, 10, 1 Ω steps. The maximum and minimum values of unknown resistance which can be determine with this steps are,

(*a*) 111100 Ω, 1 Ω. (*b*) 11110 Ω, 10 Ω.
(*c*) 111100 Ω, 10 Ω. (*d*) none of the above.

7. Megger is a measuring instrument, used to measure,
(*a*) low resistance (*b*) very low resistance
(*c*) high resistance (*d*) very high resistance

8. The reading of high impedance voltmeter V in the bridge circuit shown in given Fig. 4.26 is,

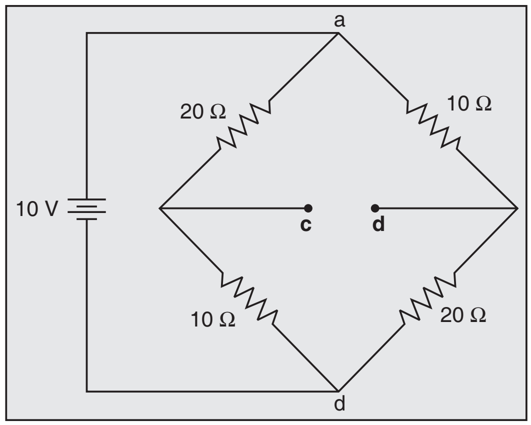


Fig. 4.26.

(*a*) Zero (*b*) 3.33 V (*c*) 4.20 V (*d*) 6.66 V
(UPSC Engg. Service. 2001)

9. The Wheatstone bridge method of measuring resistance is ideally suited for the measurement of resistance values in the range of,
(*a*) 0.001 to 1 Ω (*b*) 0.1 to 100 Ω
(*c*) 100 Ω to 10 kΩ (*d*) 100 kΩ 10 MΩ
(UPSC Engg. Service. 2009)

10. The value of resistance as measured by a Wheatstone bridge is 10.0 k Ω using a voltage source of 10.0 V. The same resistance is measured by the same bridge using 15.0 V. The value of resistance is
(*a*) 15.0 kΩ (*b*) 15.5 kΩ (*c*) 16.6 kΩ (*d*) 10.0 kΩ
(UPSC Engg. Service. 2010)

ANSWERS

1. (*b*)	**2.** (*d*)	**3.** (*c*)	**4.** (*a*)	**5.** (*d*)	6. (*c*)
7. (*c*)	**8.** (*b*)	**9.** (*c*)	**10.** (*d*)		

Chapter 5

Inductance and Capacitance Measurements

Outline

Objectives

After completing this chapter, you should be able to:

- Draw a sketch of an AC bridge and derive the general equation for its balance.
- List the advantages and limitations of different types of detectors used in AC bridge.
- Explain how an inductance can be measured using Maxwell bridge
- Draw a circuit diagram of Maxwell bridge and derive the equation for determining unknown quantity.
- List the advantages and disadvantages of Maxwell bridge.
- Describe the operation of Hay bridge for measurement of inductance.
- Derive the balanced conditions of Owen bridge arrangement?
- Draw vector diagram of currents and voltages of the Owen bridge arms at the balanced condition.
- Derive the relation for unknown impedance for Anderson bridge.
- Describe how a capacitance can be measured with help of De Sauty bridge.
- Explain how capacitance can be measured by the use of Schering bridge.
- Explain the working principle of Schering bridge and derive an expression for measurement of an unknown capacitance.
- Describe how the Wien bridgecan be used for the measurement of frequency.
- Draw the circuit diagram of Wagner earthing device and explain its working.

5.1 Introduction

We have already discussed in the last chapter about the DC Bridge. In this chapter we shall discuss the AC Bridge in detail. The AC Bridge is the outgrowth of the DC Bridge. AC bridge are the best and most usual methods for the precise measurement of self and mutual inductance and capacitance. These bridges are used to determine the value of inductance, capacitance and frequency.

Measurement of Inductance

The inductance is measured with the following bridge circuit:

1. Maxwell Bridge
2. Hay Bridge
3. Anderson Bridge
4. Owen Bridge

Measurement of Capacitance

The capacitance is measured with the following bridge circuit:

1. De Sauty Bridge
2. Schering Bridge

5.2 A.C. Bridges

The basic circuit of an AC bridge is same as the DC bridge circuit. It consists of four bridge arms, a source of excitation and a null detector. The power source supplies an AC voltage to the bridge at the desired frequency. In an AC bridge each of the four arms is impedance and we use AC source in the place of battery. A detector sensitive to small alternating potential difference is used to find the balance condition of bridge circuit. For measurement at low frequencies, the power line may acts as the source of supply to the bridge circuits. For high frequencies electronic oscillators are used as bridge source supplies. The detectors used for A.C bridges are given below:

1. **Head Phones.** Head phones are widely used as detectors at frequencies of 250 Hz upto 3 or 4 kHz. They are most sensitive detectors for this range of frequency.
2. **Vibration Galvanometers.** Vibration galvanometers are extremely used for power and low audio frequency ranges. These work at frequencies ranging from 5 Hz to 1000 Hz. The vibration galvanometers are used for power frequency range and low range of audio-frequency as these instruments are very sensitive and selective for this frequency range.
3. **Tunable Amplifier Detectors.** The transistor amplifier can be tuned electrically to any desired frequency and then it can be made to respond to a narrow bandwidth at a bridge frequency. Tunable amplifier detectors are most versatile of all the detectors. These detectors can be used over a frequency range of 10 Hz to 100 kHz.

5.3 Condition for Bridge Balance

Fig. 5.1 shows the general form of ac bridge. The four bridge arms Z_1, Z_2, Z_3, and Z_4 are indicated as unspecified impedances and the detector is represented by headphones. In balanced condition there is no current through the detector. The potential difference between point 'b' and 'd' should be zero.

The voltage drop from 'a' to 'b' equals to the voltage drop from point 'a' to 'd' in magnitude and phase. In complex notation, it given by,

$$E_1 = E_2$$

$$I_1 Z_1 = I_2 Z_2 \qquad \ldots(i)$$

at balanced condition,

$$I_1 = I_3 = \frac{E}{Z_1 + Z_3} \quad \ldots(ii)$$

and

$$I_2 = I_4 = \frac{E}{Z_2 + Z_4} \quad \ldots(iii)$$

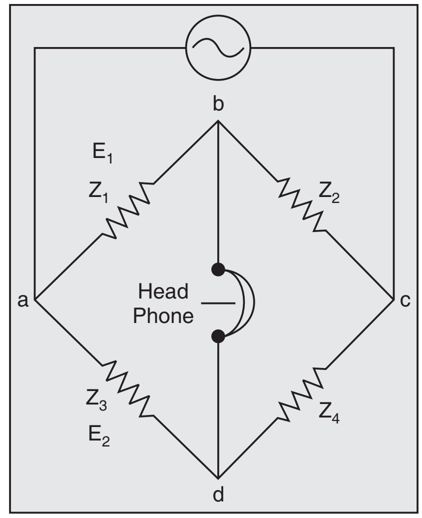


Fig. 5.1. A.C. Bridge

Substituting the values of I_1 and I_2 from equations (*ii*) and (*iii*) in equation (*i*) we get,

$$Z_1 Z_4 = Z_2 Z_3 \quad \ldots(iv)$$

In the admittances form, the above equation can be rewritten as:

$$Y_1 Y_4 = Y_2 Y_3$$

If the impedance is written in form $Z = Z\angle\theta$ where Z represents the magnitude and θ represent the phase angle of the complex impedance, then we can rewrite the equation (*iv*) as,

$$(Z_1\angle\theta_1)\,(Z_4\angle\theta_4) = (Z_2\angle\theta_2)\,(Z_3\angle\theta_3)$$

$$Z_1 Z_4\,(\angle\theta_1 + \angle\theta_4) = Z_2 Z_3\,(\angle\theta_2 + \angle\theta_3)$$

The above equation indicates that two conditions must be satisfied simultaneously to balance the AC bridge. The two balance conditions are given below:

Condition 1: The products of the magnitudes of impedances of the opposite arms must be equal, *i.e.,*

$$Z_1 Z_4 = Z_2 Z_3$$

Condition 2: The sum of phase angles impedances in the opposite arms must be equal, i.e.,

$$\angle\theta_1 + \angle\theta_4 = \angle\theta_2 + \angle\theta_3$$

It is not necessary for the four impedances to have identical phase angles or even for the impedances to be of the same kind, so long as the phase angle differences satisfy the above condition.

The individual branches may themselves be in series or parallel combinations, and may include resistance, inductance and capacitance elements separately or in combination. This leads to a very large number of possible combinations, but not all of these form workable bridges. A particularly useful group of bridges is obtained if two of the four arms are purely resistive. There are other useful methods which are more complicated than the four-arm ac bridge e.g. Anderson bridge, Carey-Foster bridge etc.

The number of possible bridge circuits is obviously extremely large. Not all of these are of practical importance, but the number which has been developed for partial use is continuously increasing. The selection of bridge circuits described here is so made to illustrate the main use of such networks; each is of theoretical interest and practical value.

Example 5.1. *The following data relates to the basic AC bridge of Fig. 5.2.* $\overline{Z_1} = 50\angle 80°$; $\overline{Z_2} = 125\ \Omega$ *and* $\overline{Z_3} = 200\angle 30°$. *Find the value of* $\overline{Z_4}$.

Solution. Given: $\overline{Z_1} = 50\angle 80°$; $\overline{Z_2} = 125\ \Omega$ and $\overline{Z_3} = 200\angle 30°$

We know that magnitude of impedances given by the relationship,

$$Z_1 Z_4 = Z_2 Z_3$$

$$Z_4 = \frac{Z_2 Z_3}{Z_1} = \frac{125 \times 200}{50} = 500\ \Omega$$

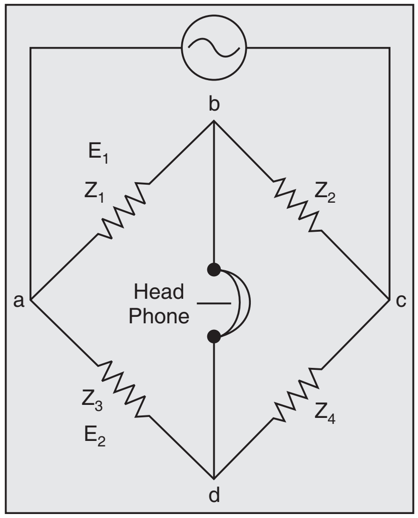


Fig. 5.2.

We know that the phase angles of the impedances given by the relationship,

$$\angle\theta_1 + \angle\theta_4 = \angle\theta_2 + \angle\theta_3$$
$$80° + \angle\theta_4 = 0° + 30°$$
$$\angle\theta_4 = -50°$$

then,

$$\overline{Z_4} = 500 \angle -50° \Omega \textbf{ Ans.}$$

5.4 Maxwell Inductance Bridge

This method is suitable for accurate measurement of medium inductance. This circuit measures the inductance by comparison with a variable standard self-inductance. The circuit diagram is shown in Fig. 5.3. Here L_X is an unknown self-inductance of resistor R_X, L_3 is a known variable inductance of fixed resistor r_3 and variable resistance R_3, R_2 and R_1 are pure resistances and D is a detector. The bridge is balanced by varying L_3 and one of the resistance R_2 and R_1. The bridge can also be balanced by keeping R_2 and R_1 constant and by varying the resistance of any one of the other two arms by connecting an additional resistance in that arm.

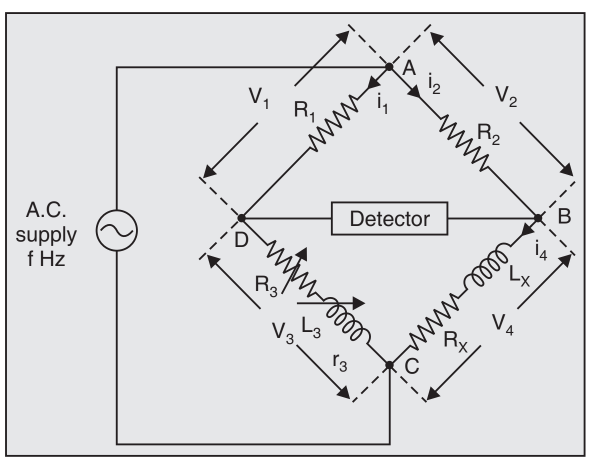


Fig. 5.3. Maxwell Inductance Bridge

The general equation of the bridge,

$$Z_1 Z_x = Z_2 Z_3 \quad \ldots(i)$$

$$Z_x = \frac{Z_2 Z_3}{Z_1}$$

The values of Y_1, Z_2, Z_3 and Z_X are

$$Z_1 = R_1$$

$$Z_2 = R_2$$

$$Z_3 = R_3 + j\omega L_3 + r_3$$

$$Z_X = R_X + j\omega L_X$$

Substituting all the above values in equation (*i*) we get,

$$R_1 (R_X + j\omega L_X) = R_2 (R_3 + j\omega L_3 + r_3)$$

$$R_X R_1 + j\omega L_X R_1 = R_3 R_2 + j\omega L_3 R_2 + r_3 R_2 \quad \ldots(ii)$$

Comparing the real terms on both sides of the above equation, we get,

$$R_X = \frac{R_2}{R_1} (R_3 + r_3) \quad \ldots(iii)$$

Comparing the imaginary term on both sides of the equation (*ii*), we get,

$$\omega L_X R_1 = \omega L_3 R_2$$

$$L_X = \frac{L_3 R_2}{R_1} \quad \ldots(iv)$$

The value of unknown resistance R_X and inductance L_X is given by equation (*iii*) and (*iv*) respectively. The quality factor (*Q*-factor) of coil is given by,

$$Q = \frac{\omega L_X}{R_X}$$

5.5 Maxwell Inductance Capacitance Bridge

This is also known as Maxwell Wien Bridge. The Maxwell bridge measures an unknown inductance in terms of a known capacitance. Fig. 5.4 shows a simple circuit and phasor diagram in which one of the ratio arms has unknown inductances L_X and resistance R_X, connected in series.

One of the ratio arms consists of resistance and capacitance in parallel. It is more simple and easier to write the admittance equation of this arm instead of writing impedance equation.

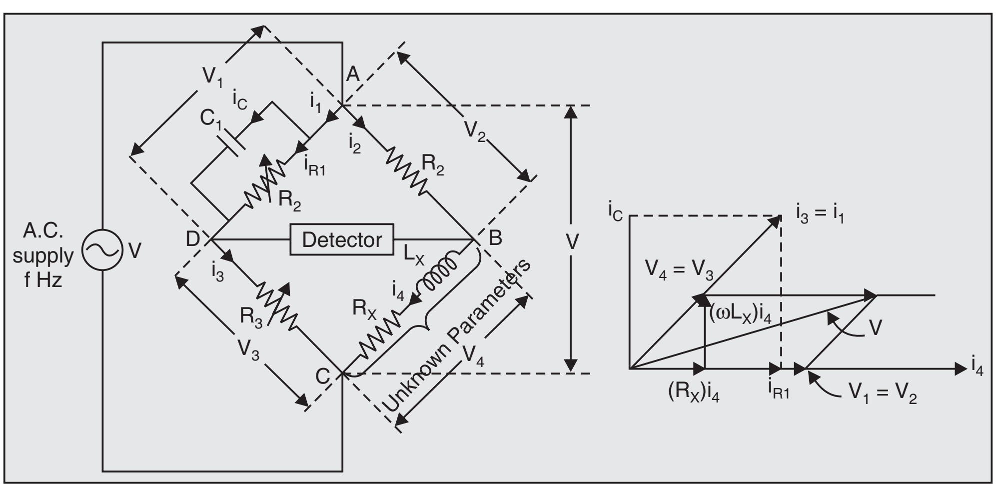


Fig. 5.4. Maxwell Inductance Capacitance Bridge

The general equation of the bridge,

$$Z_1 Z_x = Z_2 Z_3$$

$$Z_x = \frac{Z_2 Z_3}{Z_1}$$

Admittance of branch 1 is given by,

$$Y_1 = \frac{1}{Z_1}$$

then,

$$Z_X = Z_2 Z_3 Y_1 \qquad \ldots(i)$$

The values of Y_1, Z_2, Z_3 and Z_X are

$$Y_1 = \frac{1}{Z_1} = R_1 \,||\, C_1$$

$$= R_1 \,||\, \left(\frac{1}{j\omega C_1}\right)$$

$$Z_2 = R_2$$

$$Z_3 = R_3$$

$$Z_X = R_X + j\omega L_X$$

Substituting all the above values in equation (i) we get,

$$R_X + j\omega L_X = R_2\, R_3 \left\{R_1 \,||\, \left(\frac{1}{j\omega C_1}\right)\right\}$$

$$= R_2\, R_3 \left(\frac{1}{R_1} + j\omega C_1\right)$$

$$R_X + j\omega L_X = \frac{R_2 R_3}{R_1} + jR_2 R_3\, \omega C_1$$

Comparing the real terms on both sides of the above equation, we get,

$$R_X = \frac{R_2 R_3}{R_1}$$

Comparing the imaginary terms on both sides, we get,

$$\omega L_X = R_2 R_3\, \omega C_1$$

$$L_X = R_2 R_3 C_1$$

where the resistances are expressed in ohm, inductance in henrys and capacitance in farads. To obtain the bridge balance, first R_3 is adjusted for inductive balance and then R_1 is adjusted for resistive balance.

The quality factor of the coil is given by,

$$Q = \frac{\omega L_X}{R_X} = \frac{R_2 R_3 C_1}{\dfrac{R_2 R_3}{R_1}}$$

$$= \omega C_1 R_1$$

The Maxwell bridge is limited to measurement of medium-Q coils (.i.e., coils with Q in the range of 1 to 10).

Advantages

The Maxwell inductance capacitance bridge has a number of advantages. Following are the ones important from subject point of view:

1. The measurement is independent of the excitation frequency.
2. The balance equation is independent of losses associated with inductance.
3. The Maxwell bridge is very useful for measurement of a wide range of inductance at power and audio frequency.

Disadvantages

Maxwell inductance capacitance bridge has some disadvantages also. These are given below:

1. The bridge cannot be used to measure very low Q or High Q values. A mentioned previous, it is suitable measurements for $1 < Q < 10$.
2. The bridge balance equations are independent of frequency. But practically, the properties of coil under test vary with frequency which can cause error.

Example 5.2. *A Maxwell bridge is used to measure inductance and impedance. The bridge constants at balance are*:

$$R_1 = 235\ k\Omega$$
$$C_1 = 0.012\ \mu F$$
$$R_2 = 2.5\ k\Omega \text{ and}$$
$$R_3 = 50\ k\Omega$$

Find the series equivalent of the unknown impedance.

Solution. Given: R_1 = 235 kΩ = 235 × 10^3 Ω; C_1 = 0.012 μF = 10^{-6} F; R_2 = 2.5 k = 2.5 × 10^3 Ω and R_3 = 50 kΩ = × 10^3 Ω.

We know that,

$$R_X = \frac{R_2 R_3}{R_1} = \frac{2.5\,k \times 50\,k}{235\,k} = 0.532 \text{ k}\Omega \text{ or } 532\ \Omega \textbf{ Ans.}$$

and

$$L_X = R_2 R_3 C_1$$
$$= (2.5 \times 10^3) \times (50 \times 10^3) \times (0.012 \times 10^{-6}) = 1.5 \text{ H } \textbf{Ans.}$$

5.6 Hay Bridge

The Hay bridge is another modification of the Maxwell Inductance Capacitance Bridge. This bridge has a resistor R_1 in series with standard capacitor C_1 instead of in parallel. The Hay bridge measures an unknown inductance. Fig. 5.5 shows a circuit and phasor diagram in which one of the ratio arms has unknown inductances L_X and resistance R_X are connected in series. R_1, R_2 and R_3 are 'known' non-inductive resistances and C_1 is a standard variable capacitor. It is often more convenient to use a capacitor of fixed value and to make R_1 and either R_2 or R_3 adjustable.

The equation of the bridge,

$$Z_1 Z_x = Z_2 Z_3 \qquad \ldots(i)$$

The values of Z_1, Z_2, Z_3 and Z_X are

$$Z_1 = R_1 + \frac{1}{j\omega C_1}$$
$$Z_2 = R_2$$
$$Z_3 = R_3$$
$$Z_X = R_X + j\omega L_X$$

Substituting all the above values in equation (*i*) we get,

$$\left(R_1 + \frac{1}{j\omega C_1}\right)(R_X + j\omega L_X) = R_2 R_3$$

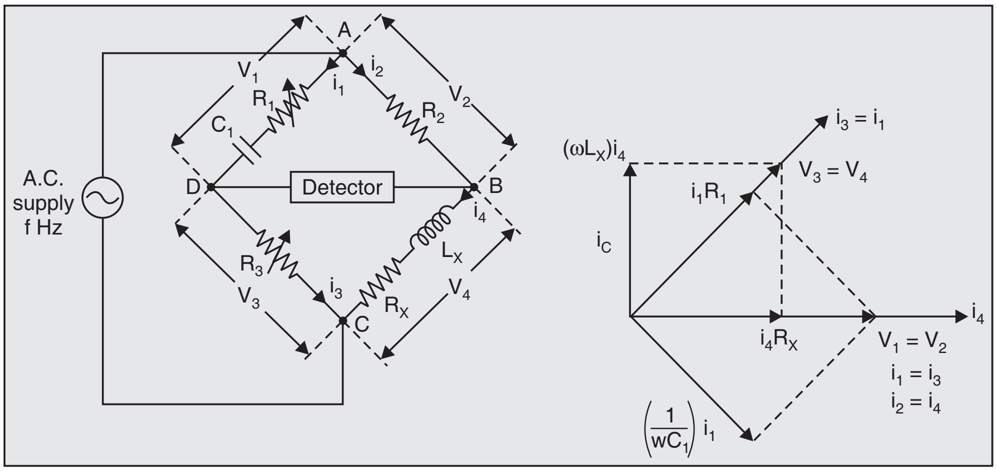


Fig. 5.5. Hay Bridge.

Rearranging the above equation,

$$R_1 R_X + \frac{L_X}{C_1} - \frac{j R_X}{\omega C_1} + j\omega L_X R_X = R_2 R_3$$

Comparing the real terms of the above equation,

$$R_1 R_X + \frac{L_X}{C_1} = R_2 R_3 \qquad \ldots(ii)$$

Similarly comparing the imaginary term we get,

$$\frac{R_X}{\omega C_1} = \omega L_X R_X \qquad \ldots(iii)$$

The equation (*ii*) and (*iii*) contains L_X and R_X, so we must solve the equation simultaneously, we get,

$$R_X = \frac{\omega^2 C_1^2 R_1 R_2 R_3}{1 + \omega^2 C_1^2 R_1^2} \qquad \ldots(iv)$$

and

$$L_X = \frac{R_2 R_3 C_1}{1 + \omega^2 C_1^2 R_1^2} \qquad \ldots(v)$$

The equation (*iv*) and (*v*) indicate that the term ω appears in the expression for both L_X and R_X. This indicates that the bridge is frequency sensitive.

The *Q* factor of the coil,

$$Q = \frac{\omega L_X}{R_X} = \frac{\omega\left(\dfrac{R_2 R_3 C_1}{1 + \omega^2 C_1^2 R_1^2}\right)}{\dfrac{\omega^2 C_1^2 R_1 R_2 R_3}{1 + \omega^2 C_1^2 R_1^2}} = \frac{1}{\omega C_1 R_1}$$

Now the term $\omega^2 C_1^2 R_1^2$ in the denominators of equations (*iv*) and (*v*) has the value of 0.01 if $Q = 10$ and even more smaller for higher values of Q so the term $\omega^2 C_1^2 R_1^2$ can be dropped without causing an appreciable error. In case, this term is to be included in calculations of L_X and R_X then it is of such minor importance that it may be computed with sufficient accuracy form an approximate values of frequency. Here it should be noted that if the terms $\omega^2 C_1^2 R_1^2$ is excluded from the equation, then it is the same for L_X as for the Maxwell Inductance Capacitance Bridge.

$$L_X = \frac{R_2 R_3 C_1}{1 + \omega^2 C_1^2 R_1^2}$$

but
$$Q = \frac{1}{\omega C_1 R_1}$$

so
$$L_X = \frac{R_2 R_3 C_1}{1 + (1/Q)^2}$$

For the value of Q greater than 10, the term $\omega^2 C_1^2 R_1^2$ will be smaller than 1/100 and so can be neglected. Therefore $L_X = R_2 R_3 C_1$ and it is the same as for Maxwell Inductance Capacitance Bridge. The Hay bridge is also used in the measurement of increment inductance. The inductance balance equation depends on the losses of the inductor (or Q) and also on the operating frequency.

Advantages

The Hay bridge is suitable for high Q coils, i.e., coils having $Q > 10$.

Disadvantage

The Hay bridge is not suitable for measurement of inductance of coils with low Q value.

Example 5.3. *Find the series equivalent inductance and resistance of the network that causes an opposite angle (Hay Bridge) to null the following bridge arms.*

ω = *3000 rad/s*
R_2 = *9 k*Ω
R_1 = 1.8 *k*Ω
C_1 = *0.9* μ*F and*
R_3 = *0.9* kΩ

Solution. Given: ω = 3000 rad/s; R_2 = 9 kΩ = 9 × 10^3 Ω, R_1 = 1.8 kΩ = 1.8 × 10^3 Ω; C_1 = 0.9 μF = 0.9 × 10^{-6} F and R^3 = 0.9 kΩ = 0.9 × 10^3 Ω

We know that for Hay Bridge,

$$R_X = \frac{\omega^2 C_1^2 R_1 R_2 R_3}{1 + \omega^2 C_1^2 R_1^2}$$

$$R_X = \frac{(3000)^2 \times (0.9 \times 10^{-6})^2 \times (1.8 \times 10^3) \times (9 \times 10^3) \times (0.9 \times 10^3)}{1 + (3000)^2 \times (0.9 \times 10^{-6}) \times (1.8 \times 10^3)^2}$$

= 6822 Ω = 6.822 kΩ **Ans.**

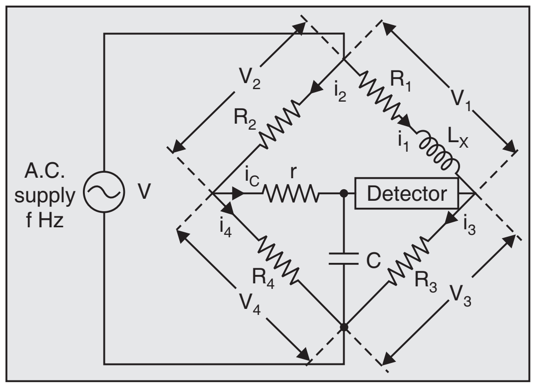
$$L_X = \frac{R_2 R_3 C_1}{1 + \omega^2 C_1^2 R_1^2}$$

$$= \frac{(9 \times 10^3) \times (0.9 \times 10^3) \times (0.9 \times 10^{-6})}{1 + (3000)^2 \times (0.9 \times 10^{-6})^2 \times (1.8 \times 10^3)^2} = 0.468 \text{ H}$$ **Ans.**

5.7 Anderson Bridge

This method is one of the commonest and best bridge method for precise-measurement of inductance over a wide range. The Anderson bridge is used for measurement of self-inductance in terms of the standard capacitor. It is the modified form of Maxwell bridge. The value of self-inductance is obtained by comparing it with a standard capacitor.

Fig. 5.6 shows the circuit and phasor diagram in which L_X is the self-inductance to be measured, R_1 is the resistance of arm 4 (including the resistance of the self-inductance), R_2, R_3, R_4 and r are "known" non-inductive resistances and C is a standard known capacitor.



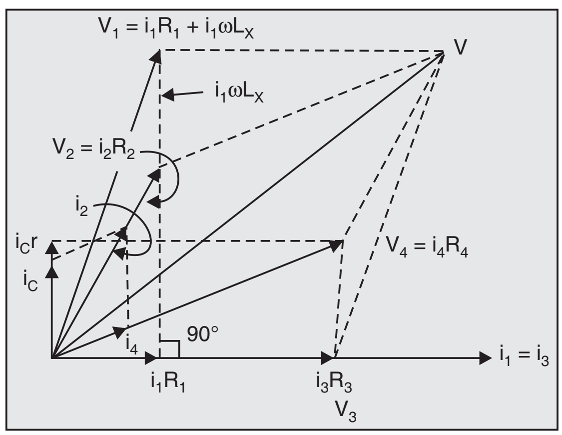


Fig. 5.6. Anderson Bridge.

The bridge is preliminary balanced for steady current by adjusting R_2, R_3 and R_4 and using an ordinary detector. Then the bridge is balanced in AC by varying r and using vibration galvanometer or telephone depending upon the supply frequency.

The balance bridge equations are,

$$i_1 = i_3$$
$$i_2 = i_4 + i_c$$
$$V_2 = i_2$$
$$V_3 = i_3 R_3$$
$$V_1 = V_2 + i_c r$$
$$V_4 = V_3 + i_c r$$
$$V_1 = i_1 R_1 + i_1 \omega L_1$$
$$V_4 = i_4 R_4$$

Transforming a star formed by R_2, R_4 and r into its equivalent delta as shown in Fig. 5.7.

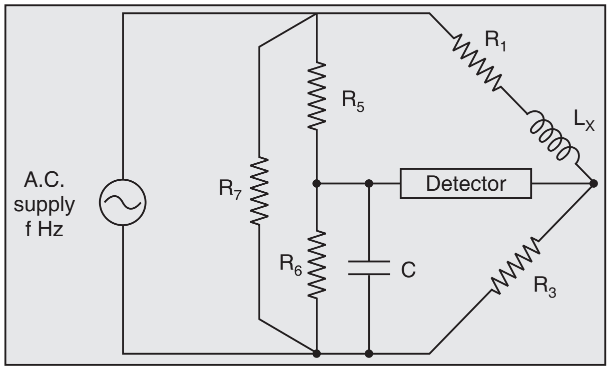


Fig. 5.7.

Elements in equivalent delta are given by,

$$R_5 = \frac{R_2 r + R_4 r + R_2 R_4}{R_4}$$

$$R_6 = \frac{R_2 r + R_4 r + R_2 R_4}{R_2}$$

$$R_7 = \frac{R_2 r + R_4 r + R_2 R_4}{r}$$

The resistance R_7 is the shunt resistor hence its does not effect on the balance condition. Rearranging the network again as shown in Fig. 5.8, we get a Maxwell inductance bridge.

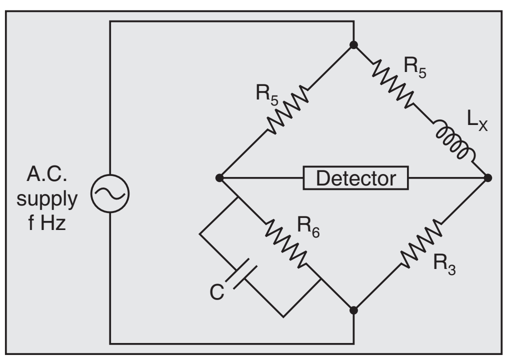


Fig. 5.8.

The balance equations are given by,

$$L_X = CR_3\, R_5$$

$$R_1 = R_3\, \frac{R_5}{R_6}$$

Substituting the values of R_5 and R_6 we get,

$$L_X = \frac{CR_3}{R_4}\, [R_2 r + R_4 r + R_2 R_4]$$

$$R_1 = \frac{R_2 R_3}{R_4}$$

Advantages

The advantages of Anderson bridge are:

1. easy to balance from convergence point of view compared to Maxwell bridge in case of low values of Q.
2. used for accurate measurement of capacitance in terms of inductance.

Disadvantages

Anderson bridge has some disadvantages also, they are given below:

1. bridge circuit is more complex as compared to other bridge circuits.
2. balance equations are not that simple as compared to the balance equations of the other bridge circuits.

Example 5.4. *Fig. 5.9 shows the connection of an Anderson bridge for measuring the inductance L and resistance R of the coil. Find R and L, if balance is obtain when,*

$$R_4 = R_2 = 1\ k\Omega,\ R_3 = 500\ \Omega,\ r = 100\ \Omega \text{ and } C = 0.5\ \mu F.$$

(GBTU/MTU, 2008-09)

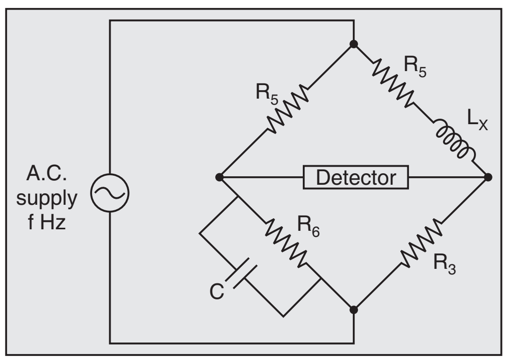


Fig. 5.9.

Solution. Given: $R_4 = R_2 = 1\ k\Omega = 1 \times 10^3\ \Omega$, $R_3 = 500\ \Omega$, $r = 100\ \Omega$ and $C = 0.5\ \mu F = 0.5 \times 10^{-6}$ F.

We know that in balance condition,

$$R_1 = \frac{R_2 R_3}{R_4} = \frac{500 \times 1000}{1000} = 500\ \Omega \textbf{ Ans.}$$

$$L_X = \frac{C R_3}{R_4}\ [R_2 r + R_4 r + R_2 R_4]$$

$$L_X = \frac{(0.5 \times 10^{-6}) \times 500}{1000}\ [100 \times 1000 + 100 \times 1000 + 1000 \times 1000]$$

$$= 0.3 \text{ H } \textbf{Ans.}$$

5.8 Owen Bridge

The Owen bridge circuit also determines the unknown inductance in terms of resistance and capacitance. The advantage of this method is that the inductance over a very range can be determined by employing capacitors of reasonable size.

The Owen Bridge is shown in Fig. 5.10. As seen from this figure, the unknown inductance L_X is connected in series. The capacitance C_3 is connected in series with a non-inductive variable resistor R_3, R_2 is a known non-inductive resistor and C_1 is known standard capacitor. The bridge is balanced by successively varying R_3 in the circuit. This bridge is used for measurement of an inductance in terms of capacitance.

The general equation of the bridge,

$$Z_1 Z_x = Z_2 Z_3 \qquad \ldots(i)$$

The values of Z_1, Z_2, Z_3 and Z_X are,

$$Z_1 = \frac{1}{j\omega C_1}$$

$$Z_2 = R_2$$

$$Z_3 = R_3 + \frac{1}{j\omega C_3}$$

$$Z_X = R_X + j\omega L_X$$

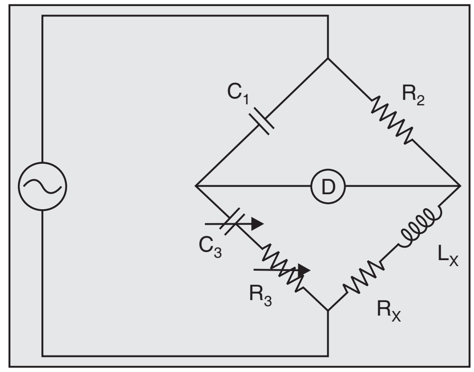


Fig. 5.10. Owen Bridge

Substituting all the above values in equation (*i*) we get,

$$\left(\frac{1}{j\omega C_1}\right)(R_X + j\omega L_X) = R_2\left(R_3 + \frac{1}{j\omega C_3}\right)$$

Comparing the real terms of the above equation we get,

$$\frac{L_X}{C_1} = R_2 R_3$$

$$L_X = R_2 R_3 C_1 \qquad \ldots(ii)$$

Similarly comparing the imaginary terms we get,

$$\frac{R_X}{\omega C_1} = \frac{R_2}{\omega C_3}$$

$$R_X = \frac{R_2 C_1}{C_3} \qquad \ldots(iii)$$

We can find the values of unknown inductance and resistance using equation (*ii*) and (*iii*). The unknown quantities R_X and L_X do not have ω, so the balancing of bridge is independent of frequency and waveform.

Advantages

Owen bridge has number of advantages. Some of the important ones are given below:

1. The equations do not contain any frequency component.
2. It can be used over a wide range of measurement of inductances.

Disadvantages

Owen bridge has few disadvantages also. These are given below:

1. This bridge uses variable capacitor which is an expensive and its accuracy is about 1%.
2. The value of capacitance C_2 becomes large when measuring high Q coils.

Example 5.5. *The Owen bridge is used to measure the properties of a sample of sheet at 2 kHz. At balance, R_2 = 100 Ω, C_1 = 0.1 μF and R_3 = 834 Ω in series with C_3 = 0.124 μF. Calculate the effective impedance of the specimen under teat conditions.*

Solution. Given: f = 2 kHz = 2 × 1000 Hz; R_2 = 100 Ω; C_1 = 0.1 μF = 0.1 × 10^{-6}; R_3 = 834 Ω and C_3 = 0.124 μF = 0.124 × 10^{-6} F.

We know that at balance condition,value of unknown inductance,

$$L_X = R_2 R_3 C_1$$

$$= 100 \times 834 \times 0.1 \times 10^{-6} = 8.34 \times 10^{-3} \text{ H}$$

$$= 8.34 \text{ mH}$$

and the value of unknown resistance,

$$R_X = \frac{R_2 C_1}{C_3} = \frac{100 \times 0.1}{0.124} = 80.6\ \Omega$$

We also know that reactance of a specimen at 2 kHz,

$$X_1 = 2\pi f L_x$$

$$X_x = 2\pi \times (2 \times 1000) \times 8.34 \times 10^{-3} = 104.8\ \Omega$$

and impedance of specimen,

$$Z_x = \sqrt{R_x^2 + X_x^2}$$

$$= \sqrt{(80.6)^2 + (104.8)^2}$$

$$= 132.2\ \Omega \ \textbf{Ans.}$$

5.9 De Sauty Bridge

This bridge is used to determine the unknown capacitance by comparing it with known standard capacitor. Fig. 5.11 shows the circuit and phasor diagram of De Sauty bridge. C_1 is the unknown capacitor and C_3 is a standard capacitor of known magnitude and R_1 and R_2 are known non-inductive resistances. This bridge is the simplest method of comparing two capacitances.

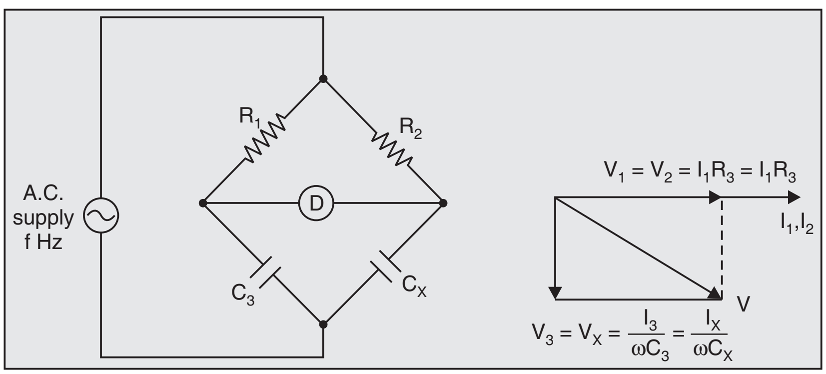


Fig. 5.11. De Sauty Bridge

The general equation of the bridge,

$$Z_1 Z_x = Z_2 Z_3 \qquad \ldots(i)$$

The values of Y_1, Z_2, Z_3 and Z_X are

$$Z_1 = R_1$$

$$Z_2 = R_2$$

$$Z_3 = \frac{1}{j\omega C_3}$$

$$Z_X = \frac{1}{j\omega C_X}$$

Substituting all the above values in equation (*i*),

$$R_1 \frac{1}{j\omega C_X} = R_2 \frac{1}{j\omega C_3}$$

$$C_X = \frac{R_1 C_3}{R_2}$$

The advantage of this bridge is its simplicity. But it is impossible to obtain if both the capacitors are not free from dielectric loss. The balance can be obtained by varying R_3 or R_4. This is used for only loss less capacitors like air capacitors.

Fig. 5.12 shows a De Sauty Bridge with decade dials x10, x100 and 1000 ohms in one arm. While the other hand has decade dials x10, x100 and 1000 ohms. A special morse key is fitted in the centre of the two arms connecting the battery and the galvanometer.

Fig. 5.12.

5.10 Schering Bridge

The Schering bridge is one of the most important and useful circuits available for measurement of capacitance,dielectric loss and power factor. It is widely used, both for precision measurements of capacitors on low voltage and for study of insulation and insulating structures at high voltages. It is good in several arrangements, or modification to adapt to special applications. Fig. 5.13 shows the circuit diagram of a Schering bridge. As seen from the diagram, a perfect capacitor C_1 in parallel with a resistance R_1, is to represent it as perfect capacitor C_X in series with resistance R_X.

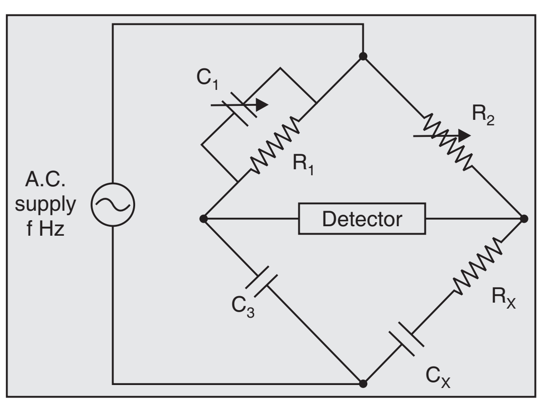


Fig. 5.13. Schering Bridge.

In this bridge, arm 1 contains a parallel combination of a resistor and a capacitor. The capacitor C_3 is a high quality mica capacitor (low-loss) for general measurements, or an air capacitor for insulation measurement.

The general equations of the bridge are,

$$Z_1 Z_x = Z_2 Z_3$$

$$Z_x = \frac{Z_2 Z_3}{Z_1}$$

Admittance in branch 1 is given by,

$$Y_1 = \frac{1}{Z_1}$$

then,

$$Z_X = Z_2 Z_3 Y_1 \qquad \ldots(i)$$

The values of Y_1, Z_2, Z_3 and Z_X are

$$Y_1 = \frac{1}{R_1} + j\omega C_1$$

$$Z_2 = R_2$$

$$Z_3 = -\frac{j}{\omega C_3}$$

$$Z_X = R_X - j\frac{1}{\omega C_X}$$

Substituting all the above values in equation (i),

$$R_X - j\frac{1}{\omega C_X} = R_2\left(-\frac{j}{\omega C_3}\right)\left(\frac{1}{R_1} + j\omega C_1\right)$$

Rearranging the above equation, we get,

$$R_X - j\frac{1}{\omega C_X} = \frac{R_2 C_1}{C_3} - \frac{j R_2}{\omega C_3 R_1}$$

Comparing the real and imaginary terms we get

$$R_X = \frac{R_2 C_1}{C_3}$$

and

$$C_X = \frac{R_1 C_3}{R_2}$$

1. **Power Factor.** The power factor of a series RC combination is defined as the cosine of the phase angle of the circuit.

   The power factor $P.F = \dfrac{R_X}{Z_X}$

   For phase angle very close to 900, the reactance is almost equal to the impedance, so we can write

   $$P.F \approx \frac{R_X}{X_X} = \omega C_X R_X$$

2. **Dissipation factor.** The dissipation factor of a series *RC* circuit is defined as the cotangent of the phase angle

$$D = \frac{R_X}{X_X} = \omega C_X R_X$$

D indicates the quality factor. It is the reciprocal of the quality factor Q, i.e., $D = 1/Q$.

The Schering bridge is widely used for testing small capacitors (100 pF – 1μF) at low voltages with very high precision. The reactance of capacitor C_3 and C_X are much higher than the resistance of R_1 and R_2. Hence most of the voltage drops across C_3 and C_X, and little across R_1 and R_2.

Example 5.6. *The Schering Bridge shown in Fig. 5.14 has the following constants R_1 = 1.5 kΩ, C_1 = 0.4 μF, R_2 = 3 kΩ and C_3 = 0.4 μF at frequency 1 kHz. Determine the unknown resistance and capacitance of the bridge circuit and dissipation factor.*

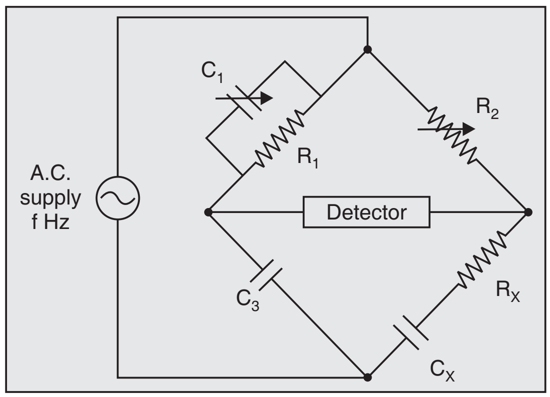


Fig. 5.14.

Solution. Given: R_1 = 1.5 kΩ = 1.5 × 10^3 Ω; C_1 = 0.4 μF = 0.4 × 10^{-6} F; R_2 = 3 kΩ = 3 × 10^3 Ω; C_3 = 0.4 μF = 0.4 × 10^{-6} F and f = 1 kHz = 1 × 10^{-3} Hz.

We know that unknown resistance,

$$R_X = \frac{R_2 C_1}{C_3} = \frac{(3 \times 10^3) \times (0.4 \times 10^{-6})}{0.4 \times 10^{-6}}$$

$$= 3 \times 10^3 \ \Omega = 3 \text{ k}\Omega \ \textbf{Ans.}$$

and the unknown capacitance,

$$C_X = \frac{R_1 C_3}{R_2} = \frac{(1.5 \times 10^3) \times (0.4 \times 10^{-6})}{3 \times 10^3}$$

$$= 0.2 \times 10^{-6} = 0.2 \ \mu\text{F} \ \textbf{Ans.}$$

We also know that dissipation factor,

$$D = \frac{R_X}{X_X} = \omega C_X R_X = 2\pi f \, C_X R_X$$

$$= 2\pi \times 1000 \times (0.2 \times 10^{-6}) \times (3 \times 10^3)$$

$$= 3.77 \ \textbf{Ans.}$$

5.11 Wien Bridge

The Wien bridge is primary known as a frequency determining bridge. The circuit diagram is shown in Fig. 5.15. It has a series RC combination in one arm and a parallel RC combination in the adjoining arm.

This bridge circuit was widely used for mea-suring capacitance of capacitors and their losses, even at high voltages, until the advantages of the Schering bridge were generally realized. The bridge circuit is frequency sensitive, and now a days it is employed for determination and control of frequency.

The general equation of the bridge,

$$Z_1 Z_4 = Z_2 Z_3 \qquad \ldots(i)$$

Admittance in branch 3 is given by

$$Y_3 = \frac{1}{Z_3}$$

then,

$$Z_1 Z_4 Y_3 = Z_2$$

The values of Z_1, Z_2, Z_4 and Y_3 are

$$Z_1 = -\frac{j}{\omega C_1}$$

$$Z_2 = R_2$$

$$Y_3 = \frac{1}{R_3} + j\omega C_3$$

$$Z_4 = R_4$$

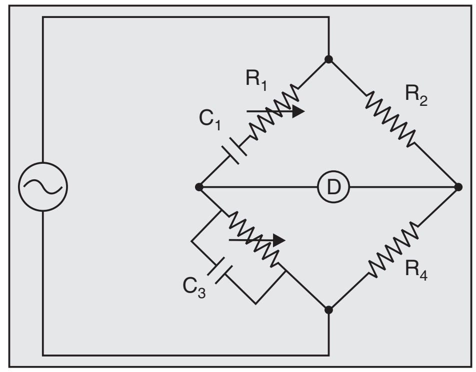


Fig. 5.15. Wien Bridge.

Substituting all the above values in equation (*i*) we get,

$$\left(R_1 - \frac{j}{\omega C_1}\right) R_4 \left(\frac{1}{R_3} + j\omega C_3\right) = R_2$$

$$\frac{R_1 R_4}{R_3} + j\omega C_3 R_1 R_4 - \frac{j R_4}{\omega C_1 R_3} + \frac{R_4 C_3}{C_1} = R_2$$

Comparing the real terms on both sides of the above equation, we get,

$$R_2 = \frac{R_1 R_4}{R_3} + \frac{R_4 C_3}{C_1}$$

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_1} \qquad \ldots(ii)$$

Comparing the imaginary term we get,

$$\omega C_3 R_1 R_4 - \frac{R_4}{\omega C_1 R_3} = 0$$

or

$$\omega C_3 R_1 R_4 = \frac{R_4}{\omega C_1 R_3}$$

where $\omega = 2\pi f$ and solving for f, we get

$$f = \frac{1}{2\pi \sqrt{C_1 C_3 R_1 R_3}} \qquad \ldots(iii)$$

The equation (*ii*) determines the resistance ratio, R_2/R_4 and equation (*iii*) determining the frequency of the applied voltage. When the circuit components $R_1 = R_3$ and $C_1 = C_2$, the equation (*ii*) is

$$\frac{R_2}{R_4} = 2$$

and equation (*iii*),

$$f = \frac{1}{2\pi RC}$$

This is the general expression of the frequency of the Wien bridge.

The Wien bridge is difficult to balance unless the waveform of the applied voltage is purely sinusoidal because of its frequency sensitivity. Since the bridge is not balanced for any harmonics present in the applied voltage, these harmonics will sometimes produce an output voltage masking the true balance point.

Applications

Following are some of the important applications of Wien bridge that are important from the subject point of view:

1. This bridge is used for measuring the frequency in audio range.
2. The Wien bridge is used in audio and HF oscillators as the frequency determining device.
3. The bridge is used in a harmonic distortion analyser, as a notch filter, and in audio frequency and radio frequency oscillators as a frequency determining element.

Example 5.7. *Determine the equivalent parallel resistance and capacitance that causes a Wien bridge to null with the following component values:*

$$R_1 = 2.8\ k\Omega,\ C_1 = 4.8\ \mu F,\ R_2 = 20\ k\Omega,\ R_4 = 80\ k\Omega \text{ and } f = 2\ kHz$$

Solution. Given: $R_1 = 2.8\ \text{k}\Omega = 2.8 \times 10^3\ \Omega$; $C_1 = 4.8\ \mu\text{F} = 4.8 \times 10^{-6}$ F, $R_2 = 20\ \text{k}\Omega = 20 \times 10^3\ \Omega$, $R_4 = 80\ \text{k}\Omega = 80 \times 10^3\ \Omega$ and $f = 2$ kHz $= 2 \times 10^3$ Hz.

We know that

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_1}$$

and,

$$C_3 = \frac{1}{\omega^2 C_1 R_1 R_3}$$

$$= \frac{1}{(2\pi f)^2 C_1 R_1 R_3}$$

Substituting the value of C_3,

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{C_3}{C_1}$$

$$\frac{R_2}{R_4} = \frac{R_1}{R_3} + \frac{1}{(2\pi f)^2 (C_1)^2 R_1 R_3}$$

$$= \frac{(80 \times 10^3)}{(20 \times 10^3)} \left[\frac{1}{(2\pi \times 2 \times 1000)^2 \times (4.8 \times 10^{-6})^2 \times (2.8 \times 10^3)} \right]$$

$= 11.2$ kΩ **Ans.**

$$C_3 = \frac{1}{(2\pi \times 2 \times 1000)^2 \times (4.8 \times 10^{-6})^2 \times (2.8 \times 10^3) \times (11.2 \times 10^3)}$$

$= 42.04$ pF **Ans.**

5.12 Wagner Ground Connection

In the various bridge circuits discussed in pervious section, we assume that the four bridge arms consist of simple limped impedances which do not interact in any way. In practice, however, stray capacitances exist between the various bridge elements and ground, and also between the bridge arms themselves. These stray capacitances shunt the bridge arms and cause measurement errors at high frequencies or when small capacitors or large inductors are measured.

If each component in a bridge has a defining screen connected to one end, a very high accuracy in measurement can be achieved by using wagner ground connection in the bridge circuit. This device removes all the earth capacitances from the bridge network.

The way to control to stray capacitances is by shielding the arms and connecting the shields to ground. This does not eliminate the capacitances but makes them constant in value, and they can therefore be compensated. Fig. 5.16 shows the circuit diagram where C_1 and C_2 represent these stray capacitances. The oscillator is removed from its usual ground connection and bridged by a series combination of resistor R_W and capacitor C_W. The junction of R_W and C_W is grounded and is called the Wagner ground connection.

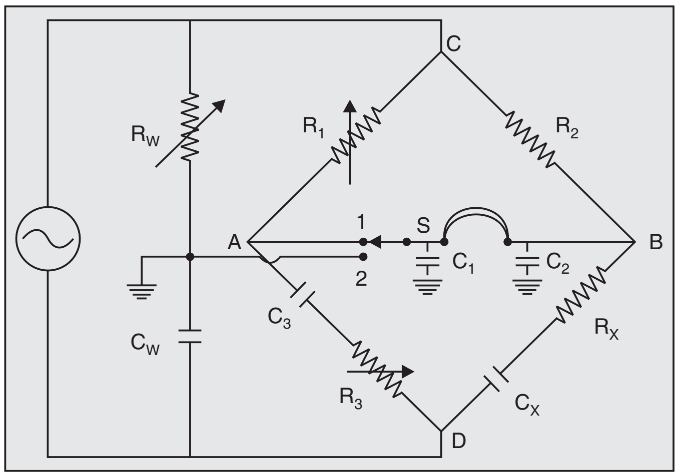


Fig. 5.16. Wagner ground Connection.

One of the most widely used methods for eliminating some of the effects of stray capacitance in a bridge circuit is the Wagner ground connection. This circuit eliminates the capacitance which exists between the detector terminal and ground.

Procedure for Adjustment of the Bridge

The detector is connected to point 1, and R_1 is adjusted for null or minimum sound in the headphones. The switch is then thrown to position 2, which connect the detector to the Wagner ground point. The resistor R_W is now adjusted for minimum second. When the switch is connected to position 1 again, some unbalance will be shown. Resistors R_1 and R_3 are then adjusted for minimum detector response and the switch is again connected to position 2. A few adjustments of R_W and R_1 (R_3) are necessary before a null is reached on both switch positions.

When null is obtained, the point 1 and 2 are at the same potential, ground potential. The stray capacitances C_1 and C_2 are then effectively shorted out and have no effect on normal bridge balance. There are also capacitances from points C and D to ground, but the addition of the Wagner ground point eliminates them from the detector circuit, since current through these capacitances will enter through the Wagner ground connection.

The capacitances across the bridge arms are not eliminated by this Wagner ground connection and they will still affect the accuracy of the measurement.

5.13 Resonance Bridge

The resonance bridge is shown in Fig. 5.17. One of the arms of this bridge consists of series resonance circuit. The series resonance circuit is formed by R_d, C_d and L_d in series. All the other arms consist of resistors only.

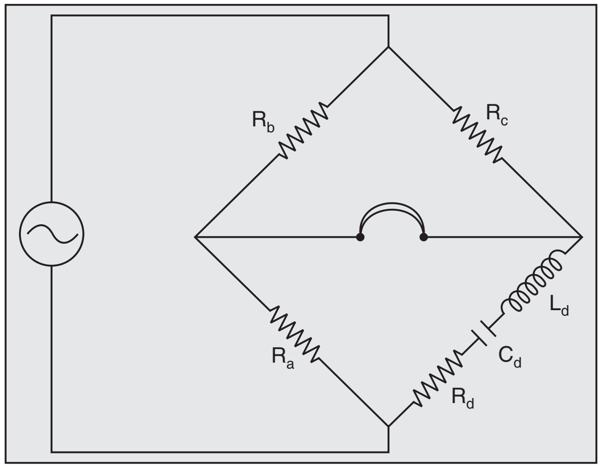


Fig. 5.17. Resonance Bridge

The general equation of the bridge,

$$Z_b Z_d = Z_a Z_c \qquad \ldots(i)$$

The values of Z_a, Z_b, Z_c and Z_d are

$$Z_a = R_a$$

$$Z_b = R_b$$

$$Z_c = R_c$$

$$Z_d = \left(R_d + j\omega L_d + \frac{1}{j\omega C_d}\right)$$

Substituting all the above values in equation (i) we get,

$$R_b\left(R_d + j\omega L_d + \frac{1}{j\omega C_d}\right) = R_a R_c$$

$$R_b R_d + j\omega L_d R_b + \frac{R_b}{j\omega C_d} = R_a R_c$$

Comparing the real terms on the both sides of the above equation, we get,

$$R_b R_d = R_a R_c$$

$$R_d = \frac{R_a R_c}{R_b}$$

Similarly, comparing the imaginary terms we get,

$$\omega L_d = \frac{1}{\omega C_d}$$

$$\omega^2 = \frac{1}{L_d C_d}$$

$$f = \frac{1}{2\pi\sqrt{L_d C_d}}$$

The bridge can be used to measure unknown inductance or capacitances. The lossess R_d can be determined by keeping a fixed ratio R_a/R_b and using a standard variable resistance to obtain balance.

If an inductance is being measured, a standard capacitor is varied until balance is obtained. If a capacitance is being measured, a standard inductor is varied until balance is obtained. The operating frequency of the generator must be known in order to calculate the known quantity. Balance is indicated by the minimisation of sound in the headphones.

5.14 Sources of Errors in Bridge Measurements and Elimination of Errors

Strictly speaking, every AC bridge method is associated with particular errors during operation and use. Therefore, every bridge needs separate treatment. However in our discussion below, we will focus on usual errors found in all bridge measurements and the methods for their elimination.

1. Errors due to stray field effects: Errors may be introduced due to unintentional coupling of the various arms of the bridge owing to the stray magnetic or electric fields around the bridge network. Due to stray field effects the theory of bridge network based on the assumption of each arm being entirely separate from the other arms except where coupling is intentionally made, remains no longer quite true. On account of the stray field effects, the detector may indicate zero deflection when the bridge is truly balanced.

When the bridge network is made of resistances and inductances only then stray magnetic field will have more effect as a source of error than electrostatic field. But if the bridge contains capacitors then electrostatic field will have more effect owing to inner capacitances between the various arms.

Loops formed by the leads used in the bridge network also introduce errors because of their inductance. In the bridge networks, which are used for measurement of inductances, the leads should be twisted together in order to avoid such loops whereas in the bridge networks employed for measurement of capacitances the leads should be separated from one another in order to avoid capacitance between them. The errors due to leads are also eliminated in most of the cases by conducting two test-one with the apparatus under test in the circuit and another with the apparatus under test short-circuited or eliminated from the bridge circuit.

A statically wound inductance coil should be used in order to avoid magnetic coupling between the arms. The errors due to magnetic coupling between the arms can also the avoided by placing magnetic screen (thin sheet of high permeability material) in between the arms. The magnetic screen placed in between the arms short circuits stray fields and prevent them from reaching the components of other arms of the bridge. When external inductors and mutual inductors are used, they should be placed as far apart as possible in order to avoid magnetic coupling.

Sometime direct induction effects between the source of the supply to the bridge and the detector circuit might exist and cause a current to flow in the detector even when the bridge is truly balanced. Such effects are eliminated by placing the source of supply at some distance from the bridge network and using inter-bridge transformer. The inner-bridge transformer have winding very well insulated from each other to avoid magnetic leakage and provided with several separate coils to have a choice of working voltage.

In order to eliminate errors due to electrostatic coupling between the various arms of the bridge and earth capacitances, use of electrostatic screen is necessary. The use of electrostatic screen renders the capacitance effects definite and independent of the distribution of the bridge components. Wagner ground connection is usually used for this purpose.

2. Leakage Errors: Poor insulation between the various parts of the bridge network may result in flow of leakage currents through the weak insulation and cause errors in the measurements. This particularly true in the case of high impedance bridges. Such errors are avoided by using high grade insulation and mounting the apparatus on insulating stands.

3. Eddy Current Errors: Errors may results due to variation in the values of the standards which may occur because of induced eddy currents in the standard resistors and inductors. In order to avoid such errors the presence of large masses near the bridge network is avoided.

4. Residual Errors: Through the resistors used are taken as non-inductive and non-capacitive resistors but their inductance and capacitance are never zero. Residual means small inherent inductance or capacitance of the resistors. In precise work it becomes necessary to evaluate them in order to eliminate them or compensate errors due to these. The self inductance is important only when the coils used are multi-turn coils and supply used is of high frequency.

5. Frequency and Waveform Errors: In case of bridges whose results are independent of frequency the supply frequency is important only from the point of view of its effects on resistance and inductance of the apparatus under test. The presence of harmonics in the supply waveform is also important form the same point of view.

In the case of bridge networks whose balance condition involves frequency, the variation in supply frequency is very important both from the point of view balance and evaluation. The waveform of the supply is also important as the bridge cannot be balance both for fundamental and harmonics in the waveform (if any) simultaneously. If telephones are used, it will not be possible to obtain complete silence at all, but only a point of minimum sound can be achieved.

This difficulty is overcome either by employing wave-filters, which eliminates the unwanted harmonics from the source or by employing tuned detectors in place of telephone such as vibration galvanometers which do not respond to harmonics and respond readily only to the fundamental for which these are tuned.

SUMMARY

1. The basic circuit of bridge consists of four bridge arms, a source of excitation, and a null detector.
2. Head phones are widely used as detectors at frequencies of 250 Hz and over upto 3 or 4 kHz.
3. Vibration galvanometers are extremely used for power and low audio frequency ranges.
4. Tuneable amplifier detector used over a frequency range of 10 Hz to 100 kHz.
5. Balanced condition for Bridge Balance are

$$(Z_1 \angle\theta_1)\,(Z_4 \angle\theta_4) = (Z_2 \angle\theta_2)\,(Z_3 \angle\theta_3)$$

$$Z_1 Z_4\,(\angle\theta_1 + \angle\theta_4) = Z_2 Z_3\,(\angle\theta_2 + \angle\theta_3)$$

6. Wien bridge is primary known as a frequency determining bridge.
7. The Q-meter is an instrument which is designed tomeasure of the electrical properties of the coils and capacitors by measuring the Q-value of an R-L-C circuit.

GLOSSARY

Anderson Bridge: The Anderson bridge is used for measurement of self inductance in terms of the standard capacitor.

De Sauty Bridge: This bridge is the simplest method of comparing two capacitances.

Hay Bridge: The Hay bridge is more convenient for measuring high-Q coils. It measures an unknown inductance.

Maxwell Inductance Bridge: This circuit measures the inductance by comparison with a variable standard self-inductance.

Maxwell Inductance Capacitance Bridge: The Maxwell bridge measures an unknown inductance in terms of a known capacitance.

Owen Bridge: This bridge is used for measurement of an inductance in terms of capacitance.

Resonance Bridge: This bridge can be used to measure unknown inductance or capacitances.

Schering Bridge: It is widely used for measurement of unknown capacitors, dielectric loss and power factor.

Wien Bridge: It has a series RC combination in one arm and a parallel RC combination in the adjoining arm.

NUMERICAL PROBLEMS

1. The impedance of the basic AC bridge are given $\overline{Z_1}$ = 100 ∠80°; $\overline{Z_2}$ = 250 Ω and $\overline{Z_3}$ = 400 ∠30° .Find the value of $\overline{Z_4}$.

(**Ans.** 100 ∠–50°)

2. The impedance of the basic AC bridge are given $\overline{Z_1}$ = 200 ∠60°; $\overline{Z_2}$ = 400 ∠–60°Ω, $\overline{Z_3}$ = 300 ∠0° and $\overline{Z_4}$ = 600 ∠30°. Determine whether it is possible to balance the bridge under this condition.

(**Ans.** No as $\angle\theta_1 + \angle\theta_4 \neq \angle\theta_2 + \angle\theta_3$)

3. A Maxwell bridge is used to measure inductive impedance. The bridge constants at balance are:

R_1 = 470 kΩ,
C_1 = 0.01 μF,
R_2 = 5.1 kΩ and
R_3 = 100 kΩ

Find the series equivalent of the unknown impedance.

(**Ans.** R_X = 1.09 kΩ; L_X = 5.1 H)

4. The four arms of a Maxwell capacitance bridge at balance are unknown inductance L_x having inherent resistance R_x. The resistance R_2 = 1 kΩ and R_3 = 1 kΩ. The capacitor of 0.5 μF in parallel with a resistance of 1000 Ω. Derive the equation for the bridge and determine the value of L_x and R_x.

(**Ans.** L_x = 0.5 H, R_X = 1000 Ω)

5. In the Schering Bridge has the constants R_1 = 1 kΩ, C_1 = 0.5 μF, R_2 = 3 kΩ and C_3 = 0.5 μF at frequency 1 kHz. Determine the unknown resistance and capacitance of the bridge circuit and dissipation factor.

(**Ans.** 2 Ω, 0.25 μF, 3.1416)

6. An Anderson bridge for measuring the inductance L and resistance R of the coil. Find R and L, if balance is obtain when, R_4 = 400 Ω, R_3 = 400 Ω, R_2 = 400 Ω, r = 100 Ω and C = 2 μF.

(**Ans.** 400 Ω; 1.12 H)

7. Determine the equivalent parallel resistance and capacitance that causes a Wien bridge to null with the following component values:

R_1 = 3.1 kΩ,
C_1 = 5.2 μF,
R_2 = 25 kΩ,
R_4 = 100 kΩ and
f = 2.5 kHz

(**Ans.** 12.4 kΩ, 20.3 pF)

DESCRIPTIVE QUESTIONS

1. Draw the general form of an AC bridge and derive the general equation for its balance.
2. Discuss briefly the merits and limitations of different types of detectors used in an bridge methods
3. Explain how inductance can be measured by using a Maxwell bridge
4. What are the advantages and disadvantages of a Maxwell bridge
5. Explain Maxwell bridge for measurement of unknown inductance. Determine condition for balance. Mention its application.

(GBTU/MTU, 2005-06)

6. Draw the circuit diagram of Maxwell bridge and derive the equation for determine unknown quantities

7. Describe the working of Hay bridge for measurement of inductance.

(GBTU/MTU, 2008-09)

8. Describe the working of Hays bridge. It is said that this bridge is suitable for measuring high Q inductors. Give reasons for such a statement.

(GBTU/MTU, 2004-05)

9. Describe the working of Hay bridge for measurement of inductance. Derive the equations for balance conditions and draw the phasor diagram under balance condition. Why is this bridge suited for measurement of inductance of high Q-coils?

(GBTU/MTU, 2005-06)

10. Derive the balance conditions of Owen bridge arrangement? Draw the vector diagram of currents and voltage of the bridge arms at the balance condition.

(GBTU/MTU, 2004-05)

11. For Anderson bridge. Derive the relation for unknown impedance. What are the advantages and limitations of this bridge?

(GBTU/MTU, 2002-03)

12. With the help of circuit diagram explain how capacitance can be measured by the use of Schering bridge

13. Describe how an known capacitance can be measured with help of De sauty bridge. What are the limitations of this bridge and how are they overcome by using modified De sauty bridge? Draw phasor diagram to illustrate your answers.

(GBTU/MTU, 2005-06)

14. Explain the working principle of Schering bridge and derive an expression for measurement of unknown capacitor. Draw the phasor diagram under null condition and explain how dissipation factor of the capacitor can be calculated.

15. Prove that Schering Bridge can be used to measure the insulating properties and value of capacitance with high precision.

(GBTU/MTU, 2006-07)

16. Describe briefly wien bridge can be used for the measurement of frequency.

17. Explain briefly Resonance Bridge with the help of a neat circuit diagram. Name the parameter which can be measured by this bridge.

18. Explain with a neat circuit diagram the working of a Wagner earthing device

19. Discuss Maxwell bridge for measurement of inductance ? For what range of Q-factor of coil the bridge is suitable.

(P.T.U, Dec. 2008)

20. How is inductance measured?

(P.T.U, Dec. 2009)

21. What type of null detectors is suitable for use in an ac bridge?

(P.T.U, May 2011)

22. Write short note on.

(*i*) Sources and detectors used in AC bridges

(*ii*) De Sauty bridge

(Nagpur University, Summer 2011)

23. Which bridge is used for measurement of frequency and capacitance? Explain in a detail.

(Nagpur University, Summer 2011)

24. Draw the general form of an A.C. bridge and derive the general equation for its balance.

(Nagpur University, Summer 2010)

25. Explain the operation of capacitance bridge in general with suitable neat diagram.

(GBTU/MTU, 2009-10)

26. Explain the working and use of "*Q*-meter" in measurement.

(Nagpur University, Summer 2010)

27. Describe the operation of Schering bridge.

(GBTU/MTU, 2010-11)

MULTIPLE CHOICE QUESTIONS

1. Maxwell inductance capacitance bridge is used for measurement of inductance of,
(*a*) Low *Q* coils (*b*) Medium Q coils
(*c*) High *Q* coils (*d*) Low and medium Q coils

2. The advantage of Hay bridge over Maxwell inductance bridge is because,
(*a*) Its equations for balance do not contain any frequency term
(*b*) It can be used for measurement of inductance of high *Q* coils
(*c*) It can be used for measurement of inductance of low *Q* coils
(*d*) None of the above

3. Frequency can be measured by using,
(*a*) Maxwell bridge (*b*) Schering bridge
(*c*) Heaviside Campbell bridge (*d*) Wien bridge

4. Wagner's earth device is used in ac bridge circuits for,
(*a*) Eliminating the effect of earth capacitances
(*b*) Eliminating the effect of inter-component capacitances
(*c*) Eliminating the effect stray electrostatic fields
(*d*) Shielding the bridge elements

5. A bridge circuit works at a frequency of 2 kHz. The following can be used as detectors for detection of null conditions in the bridge,
(*a*) Vibration galvanometer and headphones
(*b*) Headphones and tuneable amplifiers
(*c*) Vibration galvanometers and tuneable amplifiers
(*d*) Vibration galvanometer, headphones and tuneable amplifiers

6. Wagner earth in AC bridge circuits is used to eliminate the effect of,
(*a*) Stray electrostatic fields (*b*) Stray electromagnetic fields
(*c*) Inter-component capacitances (*d*) Parasitic capacitance to earth

(UPSC Engg. Services. 2000)

7. Hay bridge is suitable for measuring inductance of which one of the following inductors?
(*a*) Having *Q* value less than 10
(*b*) Having *Q* value greater than 10
(*c*) Of any value of *Q*
(*d*) Having phase angle of reactance very large

(UPSC Engg. Services 2007)

8. In the balanced bridge shown in Fig. 5.18 '*X*' should be,
(*a*) A self-inductance having resistance (*b*) A capacitance
(*c*) A non-inductive resistance (*d*) An inductance and a capacitance in parallel

(UPSC Engg. Services 1999)

9. The AC bridge shown in Fig. 5.19 is balanced if $Z_1 = 100\ \angle 30°$; $Z_2 = 150\ \angle 0°$; $Z_3 = 250\ \angle -40°$ and Z_4 is equal to,
(*a*) $350\ \angle 70°$ (*b*) $375\ \angle -70°$
(*c*) $150\ \angle 0°$ (*d*) $150\ \angle 20°$

(UPSC Engg. Services 1999)

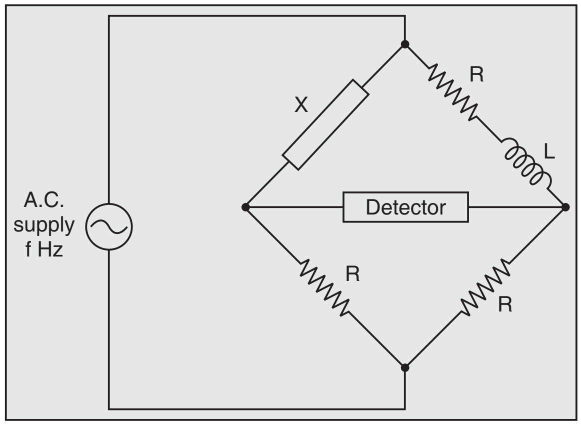


Fig. 5.18.

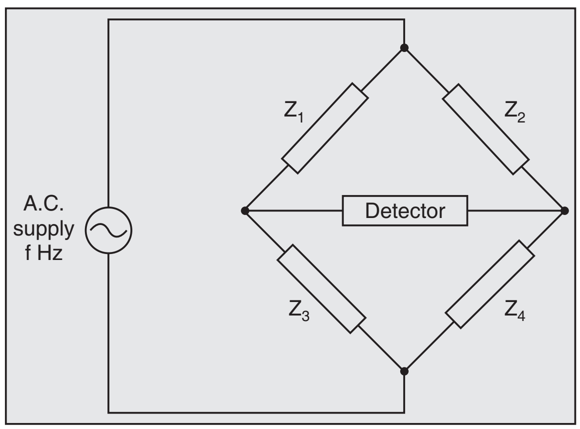


Fig. 5.19.

10. At balance condition of the AC bridge shown in Fig. 5.20, the value of Z_4 would be,

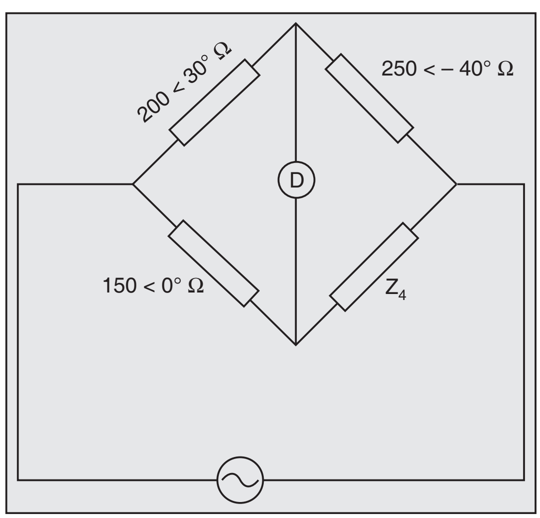


Fig. 5.20.

(*a*) 120 ∠70° (*b*) 187.5 ∠–10°
(*c*) 187.5 ∠–70° (*d*) 333.3 ∠–70°

(UPSC Engg. Services 2000)

11. For the Owen-bridge circuit shown in Fig. 5.21 when balanced, the value of L and R are,

(*a*) $L = C_S R_S / R_1$, $R = R_S C_S / C_1$ (*b*) $L = C_S R_S R_1$, $R = R_s C_S / C_1$
(*c*) $L = C_1 R_S R_1$, $R = R_S C_S C_1$ (*d*) $L = C_S / C_1 R_S R_1$, $R = R_1 C_s / C_1$

(UPSC Engg. Service. 2003, 2007)

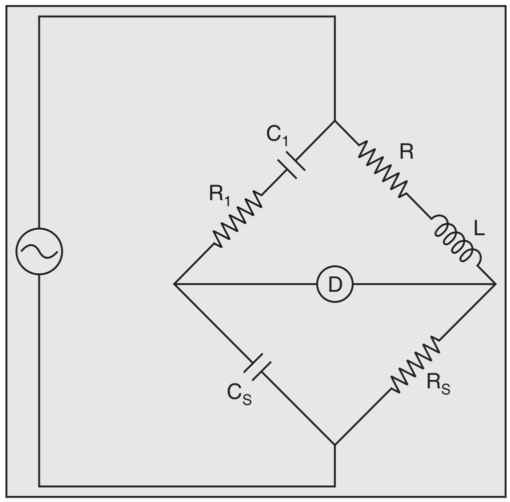


Fig. 5.21.

12. In the bridge circuit shown in Fig. 5.22, at balance condition, the value of C_s = 0.5 μF and R_s = 1000 Ω. The value of inductance and resistance R_X are,

(*a*) L_X = 0.5 H, R_X = 1000 Ω (*b*) L_X = 0.25 H, R_X = 2000 Ω
(*c*) L_X = 0.5 H, R_X = 3000 Ω (*d*) L_X = 0.25 H, R_X = 500 Ω

(UPSC Engg. Service. 2003)

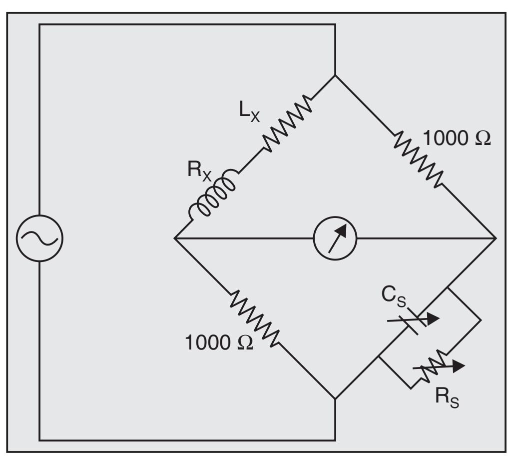


Fig. 5.22.

13. The AC bridge is supplied with a source of 10 kHz as shown in the Fig. 5.23. What is the value of C_X?

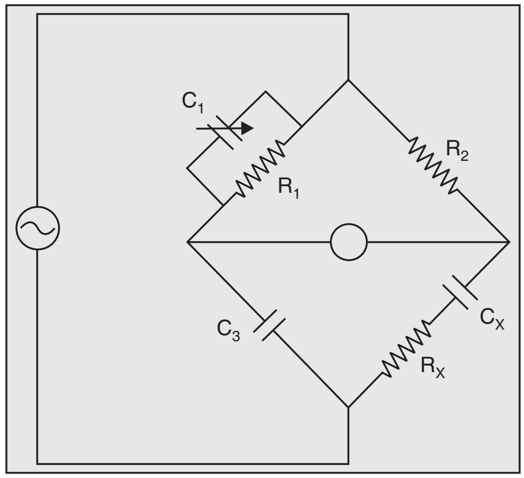


Fig. 5.23.

(*a*) $C_3 \dfrac{R_1}{R_2}$ (*b*) $C_3 \dfrac{R_2}{R_1}$ (*c*) $C_3 \dfrac{R_X}{R_1}$ (*d*) $C_3 \dfrac{R_2}{R_x}$

(UPSC Engg. Service. 2007)

ANSWERS

1. (*b*)	**2.** (*b*)	**3.** (*d*)	**4.** (*a*)	**5.** (*b*)	**6.** (*d*)
7. (*b*)	**8.** (*a*)	**9.** (*b*)	**10.** (*c*)	**11.** (*b*)	**12.** (*a*)
13. (*a*)					

Chapter 6

Measurements using Electrical Instruments

Outline

Objectives

After completing this chapter, you should be able to:

- Know the permanent-magnet moving-coil.
- Know the different types of analog and digital instruments.

- Describe the operation of electronic voltmeter.
- Understand the transistor voltmeter circuit.
- Explain the various types of AC voltmeter circuits.
- Describe how true RMS reading voltmeter is used to measure the RMS value of current.
- Understand the measurement of current with electronic instruments.
- List the different types of digital voltmeter.
- Describe the digital multimeter and frequency meter.
- Explain the Q meter
- Knowing the RF measurement of Impedance, Voltage and Power.

6.1 Introduction

Electronic instrumentation is afield that combines elements of technologies ranging from the nineteenth to the twenty first centuries. Although modern computer-based instrumentation is now evident in every reasonably equipped laboratory, workshop, catalogs and advertisements of all of the manufacturers, yet at the root of many space-age instruments, is a circuitry such as the Wheatstone bridge that is found in nineteenth-century textbooks. Newer techniques are still in widespread use in new as well as old instruments. In this chapter we shall study both the old and new electronic instruments.

The scientific and technological progress of any nation depends on its ability to measure, calculate and finally, estimate the unknown. Also, the success of an engineer or technician is judged by his ability to measure precisely and to correctly interpret the circuit performance. There are three ways of making such measurements:

(*a*) **by mechanical means**–like measuring gas pressure by Bourdon pressure gauge.

(*b*) **by electrical means**–like measuring potential difference with an electrical voltmeter.

(*c*) **By electronic means**–which is a very sensitive way of detecting the measured quantity because of amplification provided by the active electronic device.

The electronic instruments generally have higher sensitivity, faster response and greater flexibility than mechanical or electrical instruments in indicating, recording and, where required, in controlling the measured quantity.

6.2 Analog and Digital Instruments

The deflection type instruments with a scale and movable pointer are called ***analog*** instruments. The deflection of the pointer is a function of (and, hence, analogous to) the value of the electrical quantity being measured.

Digital instruments are those which use logic circuits and techniques to obtain a measurement and then display it in numerical-reading (digital) form. The digital readouts employ either LED displays or liquid crystal displays (LCD).

Some of the advantages of digital instruments over analog instruments are as under:

1. easy readability
2. greater accuracy
3. better resolution
4. automatic polarity and zeroing

Classification of Electronics Instruments

The electronics instruments may be classified into the following three categories:

1. **Indicating Instruments.** These are the instruments which indicate the instantaneous value of quantity being measured, at the time it is being measured. The indication is in the

form of pointer deflection (analog instruments) or digital readout (digital instruments). Ammeters and voltmeters are examples of such instruments.

2. **Recording Instruments.** Such instruments provide a graphic record of the variations in the quantity being measured over a selected period of time. Many of these instruments are electromechanical devices which use paper charts and mechanical writing instruments such as an inked pen or stylus. Electronic recording instruments are of two types:
   (*a*) **null type**–which operate on a comparison basis.
   (*b*) **galvanometer type**–which operate on deflection type.
3. **Controlling Instruments.** These are widely used in industrial processes. Their function is to control the quantity being measured with the help of information feed back to them by monitoring devices. This class of electronic instruments forms the basis of automatic control systems (automation) which are extensively employed in the field of engineering.

6.3 Electronic Versus Electrical Instruments

Both electrical and electronic instruments measure electrical quantities like voltage and current etc. Electrical instruments do not have any built-in amplifying device to increase or decrease the amplitude of the quantity being measured. A dc voltmeter is an example of electrical instrument; itis based on moving-coil meter movement.

On the other hand the electronic instruments always include in their make-up some active electron device such as vacuum tube, semiconductor diode or an integrated circuit etc.

As seen, the main distinguishing factor between the two types of instruments is the presence of an electron device in the instruments. The movement of electrons is common to both types of instrument but the main difference being that the control of electron movement. The electronic instruments control the electron movement more effectively than the electrical instruments.

Although electronic instruments are usually more expensive than their electrical instruments but they offer following advantages for measurements purposes:

1. Electronics Instruments can amplify the input signal, they have very high sensitivity. They are capable of measuring extremely small input (low amplitude) signals.
2. Due to the high sensitivity, their input impedance is increased which means less loading effect when making measurements,
3. These instruments have greater speed i.e. faster response to the input signal and flexibility,
4. It can be interfaced very easily with a computer system. This advantage allows the signal to be processed using digital signal processing techniques.

6.4 Main Elements of an Electronic Instrument

Most of the electronic instruments have the following main three elements: (*i*) transducer (*ii*) signal modifier and (*iii*) indicating device. The block diagram of electronic instruments is shown in Fig. 6.1. They are discussed below:

1. **Transducer.** It is the first sensing element and is required only when measuring a non-electrical quantity, say, temperature or pressure. Its function is to convert the non-electrical physical quantity into an electrical signal. Of course, a transducer is not required if the quantity being measured is already in the electrical form.
2. **Signal Modifier.** It is the second element and its function is to make the incoming signal suitable for application to the indicating device. For example, the signal may need amplification before it can be properly displayed. Other types of signal modifiers are: voltage dividers for reducing the amount of signal applied to the indicating device or wave shaping circuits such as filters, rectifiers or chopper etc.

3. **Indicating Device.** For general purpose instruments like voltmeters, ammeters or ohm meters, the indicating device is usually a deflection type meter as shown in Fig. 6.1. In digital readout instruments; the indicating device is of digital design.

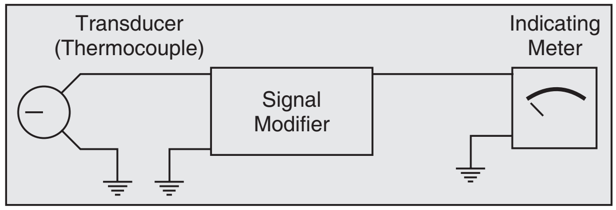


Fig. 6.1.

6.5 Electronic Voltmeter

Electronic Voltmeter has become a very important tool for instrument and control engineers. An electronic voltmeter uses rectifiers, amplifiers and other circuits to generate a current proportional to the voltage being measured. In an electronic voltmeter, a measured alternating voltage is rectified using a diode rectifier or decoder and a rectified direct current is produced which is the measure of the original alternating voltage.

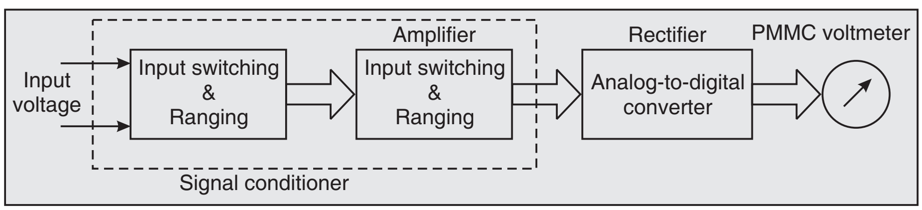


Fig. 6.2. Electronics Voltmeter

Fig. 6.2. shows the block diagram of modern electronic voltmeter. As seen from the diagram it consists of input switching and ranging circuit, amplification circuit and analog-to-digital conversion (rectification) circuit and a voltmeter. The voltmeter would be a simple permanent moving coil voltmeter or an electronic voltmeter.

A VOM (volt-ohm meter)can be used to measure voltages but it lacks both sensitivity and high input resistances. Moreover, its input resistance is different for each range. The electronic voltmeter (EVM), on the other hand, has input resistance ranging from 10 MΩ to 100 MΩ, thus producing less loading of the circuit under test than the VOM. Another advantage of EVM is that its input resistance remains constant over all ranges.

Two types of electronic voltmeters are in use today namely (i) analog and (ii) digital voltmeters. However, a distinction must be made between a digital instrument and an instrument with digital readout. A digital instrument is one which uses internal circuitry of digital design. A digital readout instrument is one whose measuring circuitry is of analog design but the indicating device is of digital design.

The electronic voltmeters go by a variety of names reflecting the technology used.

(*i*) vacuum-tube voltmeter (VTVM)–it uses vacuum tubes with deflection meter movement. With the advancement in solid state devices technology, vacuum tubes have become obsolete.

(*ii*) digital voltmeters like transistor voltmeter (TVM) and FET voltmeter (FETVM).

6.6 Advantages of Electronics Voltmeters

Although there are several advantages of electronic voltmeters as compared to non-electronic voltmeters, yet the following are important from the subject point of view:

1. Low level signal detection
2. Low power consumption
3. High frequency range
4. Low input capacitance
5. No loading errors

6.7 Direct Current FET VM

Fig. 6.3. shows the diagram of a FET VM. As seen from this diagram, it makes use of a difference amplifier. The two FETsin the diagram are identical so that increase in the current of one FET is offset by corresponding decrease in the source current of the other. The two FETs form the lower arms of the balanced bridge circuit whereas the two drain resistors RD form the upper arms. The meter movement is connected across the drain terminals of the FETs.

The circuit is balanced under zero-input-voltage condition provided the two FETsidentical. In that case, there would be no current through M. Zero-Adjust potentiometer is used to get null deflection in case there is a small current through M under zero-signal condition.Full-scale calibration is adjusted with the help of variable resistor R.

When positive voltage is applied to the gate of Q_1, the current flows through M. The magnitude of this current is proportional to the voltage being measured. Hence, meter is calibrated in volts to indicate input voltage.

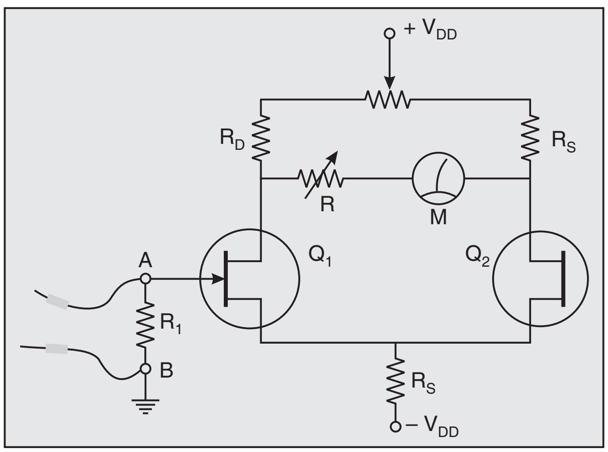


Fig. 6.3. Direct Current FET VM

6.8 Transistor Voltmeter (Direct Coupled Amplifier)

The transistor voltmeter (TVM) is also known as electronic voltmeter (EVM). Fig. 6.4 shows the transistor voltmeter (TVM) circuit. It is a dc coupled amplifier with an indicating meter. As seen from the diagram, the circuit consists of an input attenuator source follower and dc coupled amplifier.

The purpose of input attenuator is to provide input voltage levels which can be accepted by the dc amplifier. A FET is used to serve as source follower at input stage to obtain high input impedance. FET effectively isolates the meter circuit from the circuit under measurement.

The transistors, Q_1 and Q_2 forms a dc coupled amplifier driving the meter movement. The meter deflection is proportional to the magnitude of the applied input voltage. The input overload does not burn the meter because the amplifier saturates, limiting the maximum current through the meter. The gain of the dc amplifier allows the instrument to be used for measurement of voltage in the millivolt range. Instruments in the microvolt range of measurement require a high gain dc amplifier to supply sufficient current for driving the meter movement.

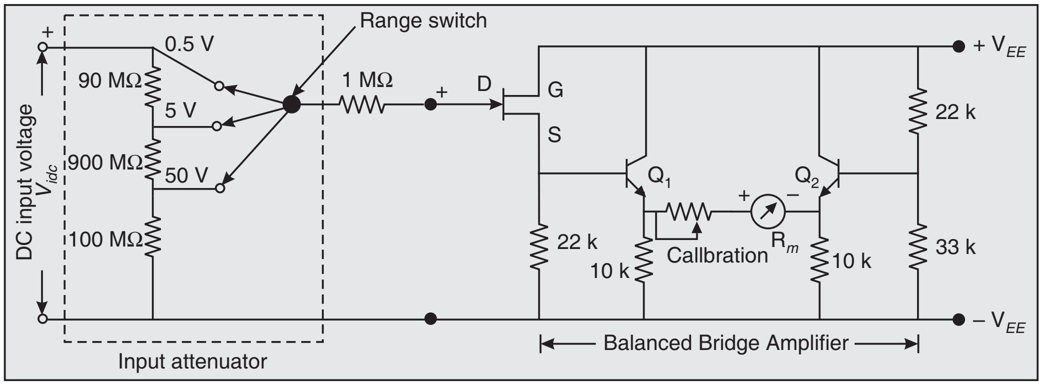


Fig. 6.4. Transistor Voltmeter

Advantages

Some of the main advantages of transistor voltmeter are:

1. High input impedance to isolate meter from the measurement circuit.
2. The amount of power drawn is very low.
3. The overloading cannot damage the meter.

6.9 A.C. Electronic Voltmeter

Fig. 6.5 shows the block diagram of an alternating current electronic voltmeter (AC EVM). Here the voltage divider allows selection of voltage range. The amplifier provides the necessary gain to establish voltmeter sensitivity as well as high input impedance. The negative circuit is for stability and accurate overall gain. A rectifier and filter is used to convert ac to dc.

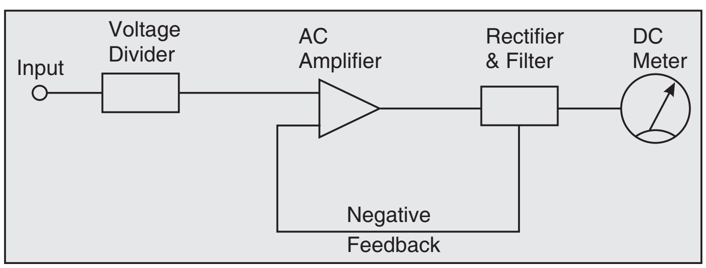


Fig. 6.5. AC Electronic Voltmeter

An AC electronic voltmeter is used to measure AC voltage. Note that the PMMC meter movement is used for measurement of AC voltage by inserting a rectifier in the measuring circuit. Such meters are widely used and more accurate.

AC analog voltmeters are one of the most popular electronic measuring instruments in use today. They are used to measure the r.m.s value of voltage of many waveforms commonly found in electronics.

AC voltmeters are designed to respond to one of these three values: average value, rms value or peak value of ac input voltage. Accordingly, this classifies the ACmeters into:

1. Rectifier Type AC Voltmeter
2. Average Responding AC Voltmeter
3. Peak Responding AC Voltmeter
4. True RMS AC Voltmeter

The average and peak responding voltmeters are designed to measure only sine waves. Now we shall study all the four types of ac electronic voltmeters in more details in the following pages.

6.10 Rectifier Type AC Voltmeter

Fig. 6.6 shows a simple rectifier type AC voltmeter. Here the diodes D_1 and D_2 are used for rectification. For the positive half cycle the diode D_1 is ON and meter deflection is proportional to the avarage value of the half cycle.

In the negative half cycle, the diode D_2 is ON and and D_1 is OFF. The current throught the meter is in opposite direction and hence meter movement is bypassed in. It produces pulsating dc and the meter indicates the average value of the input.

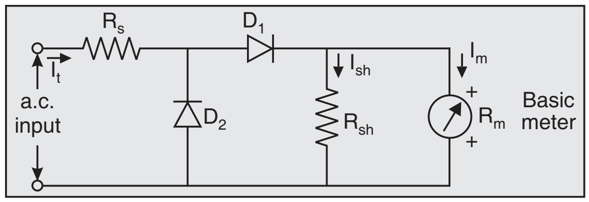


Fig. 6.6. Rectifier Type AC voltmeter

The rectifier type AC voltmeters are of different types, these are:

(*a*) AC voltmeter using Half-wave rectifier

(*b*) AC voltmeter using Full-wave rectifier

(*c*) Multirange AC voltmeter using rectifier

We shall study each type of AC voltmeter in the following pages.

(a) A.C. Voltmeter using half-wave rectifier

The circuit of an AC Voltmeter using half-wave diode rectifier is shown in Fig. 6.7. The half-wave rectifier circuit has been combined in series with a dc meter movement.

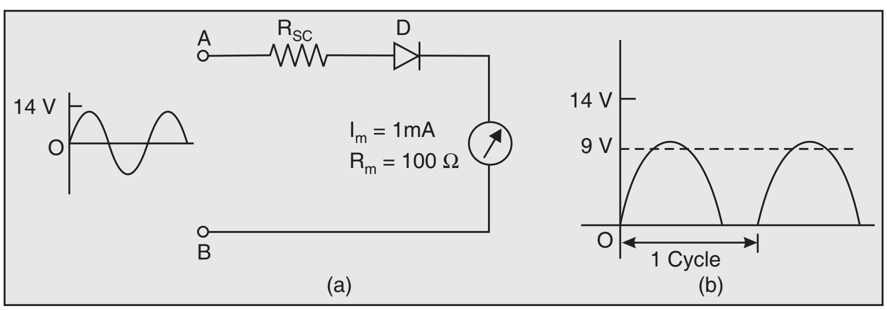


Fig. 6.7. AC Voltmeter using half-wave rectifier

When used as a DC voltmeter (i.e. without rectifier) it would have (say, for example) a range of 10 V. However, if an ac voltage of rms value of 10 V is applied across input terminals *AB*, it would read 4.5 V. This can be explained as follows,

We know that r.m.s value of input voltage,

$$E_{rms} = 10 \text{ V}$$

Then the peak value is given by

$$E_{peak} = E_{rms}\sqrt{2}$$

$$= 10 \times \sqrt{2} = 14.14$$

Therefore an average value of half-wave rectifier

$$E_{avg} = 0.636 \times E_{peak}$$

$$= 0.636 \times 14.14 = 8.99 \text{ V}$$

Since in the half-wave rectified output, one half-cycle is absent, the average for the full cycle is

$$E_{avg} = \frac{8.99}{2} \approx 4.5 \text{ V}$$

The meter movement will, therefore read 4.5 V *i.e.* 45% of the dc value. It may also be noted that ac sensitivity of a half-wave ac meter is only 45 per cent of the dc sensitivity.

(b) A.C. voltmeter using full-wave rectifier

The circuit of an AC voltmeter using full-wave rectifier is shown in Fig. 6.8. In this case, the meter reading would be 90% of r.m.s input voltage *i.e.* 90% of the dc value.

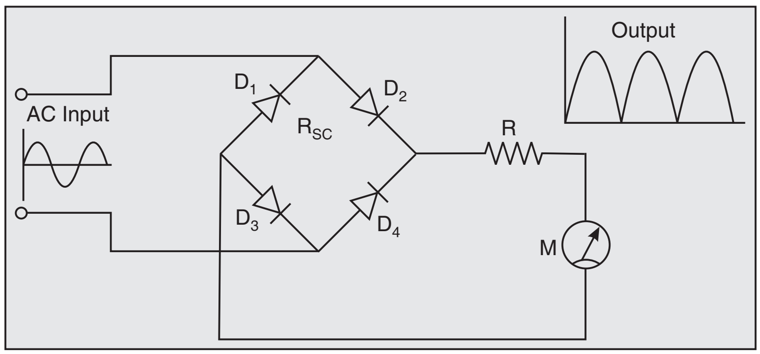


Fig. 6.8. AC Voltmeter using full-wave rectifier

Fig. 6.8 shows the circuit diagram of an AC voltmeter using full-wave rectifier. The voltmeter will indicate 90 % of the r.m.s input voltage. This is explained as below:

We know that the peak value is of an input voltage with an r.m.s value of 10,

$$E_{peak} = E_{rms} \sqrt{2}$$
$$= 10 \times \sqrt{2} = 14.14$$

and average value of half wave rectifier

$$E_{avg} = 0.636 \times E_{peak}$$
$$= 0.636 \times 14.14 = 8.99 \text{ V} \approx 9 \text{ V}$$

It may also be noted that ac sensitivity of a full-wave ac meter is only 90 per cent of the dc sensitivity.

6.11 Multirange A.C. Voltmeter

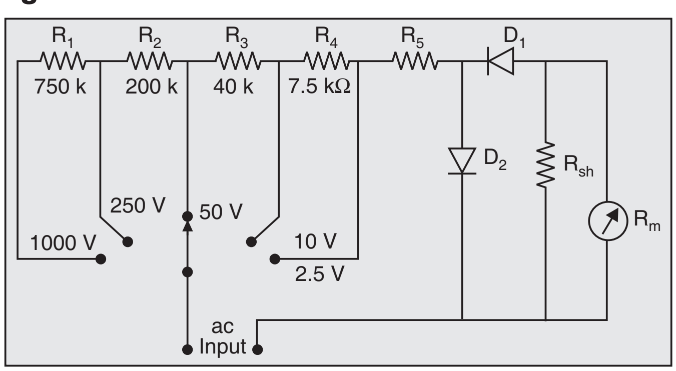


Fig. 6.9. Multirange AC voltmeter

The main purpose of the multirange ac voltmeter is for measuring ac voltage for different ranges. Fig. 6.9 shows the circuit diagram of such an electronic instrument. The rectifier type ac voltmeter is used with series of multiplier resistance R_1, R_2, R_3, R_4 and R_5. Due to different multiplier resistances various voltage ranges is achieved.

The resistance R_5 acts as a basic multiplier resistance and corresponds to the multiplier Rs. AC Analog voltmeters are one of the most popular electronic measuring instruments in use today. They are used to measure the rms voltage of the many waveforms commonly found in electronics.

4.12 Average Responding A.C. Voltmeter

Fig. 6.10 shows the average responding AC voltmeter. As seen from this diagram a sine wave being measured is fed through a DC blocking capacitor, amplified or attenuated, rectified by the diode bridge and fed to the meter. The meter then responds to this rectified average or DC value.

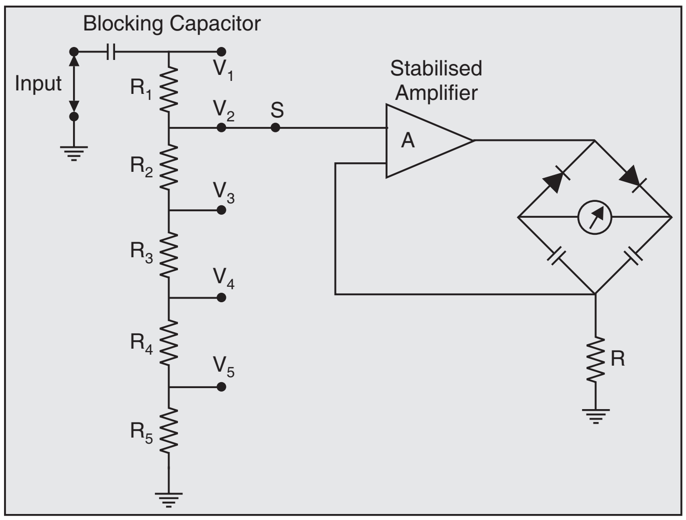


Fig. 4.10.

The applied waveform is amplified with a high gain stabilized amplifier to a required high level. This voltage is rectified using diodes D_1 and D_2. The rectified voltage is fed to a dc mA used as a measuring meter. In this meter instrument, the rectifier current is averaged by a filter to produce a steady deflection of the meter pointer. This dc component deflects a d'Arsonval (moving coil) meter to indicate the rms value of a sine wave.

The blocking capacitor used at the input side blocks the dc component of the input voltage. The negative feedback is used for the amplifier to ensure stability for measurement. Capacitors C_1 and C_2 in the rectifier circuit act as storing capacitors or filter capacitors. The dc milliammeter is calibrated in terms of rms value of the input voltage.

Advantages

Following are the main advantages of Average Responding AC Voltmeter:

1. The diode nonlinearity is minimized using meter in feedback path.
2. Variations in the meter impedance are compensated by the negative feedback
3. High frequency range of operation is provided.

Disadvantages

Errors in the reading of an average responding voltmeter may be due to the application of complex waveforms like distorted or nonsinusoidal input or presence of noise etc.

The average responding meter is the most popular and economical type of AC voltmeter. Its voltage scale has been made to indicate the rms value of a sine wave. If any other waveform is measured, the meter will read incorrectly. Typical average responding voltmeters are the HP 400 D/H/L, 403A/B and 400E/EL.

4.13 Peak Responding Voltmeter

Peak responding voltmeter is also designed to indicate the RMS value of a sine wave. The difference between average responding meter and this meter is the use of storage capacitors with the rectifying diode.

A capacitor is charged through a rectifying diode to the positive peak of the applied sine wave. The voltmeter then responds to the DC output.

The two types ofpeak responding voltmeter are

1. DC coupled peak responding voltmeters.
2. AC coupled peak responding voltmeters.

Both these peak responding voltmeters are discussed one by one in the following pages.

6.14 D.C Coupled Peak Responding Voltmeters

Fig. 6.11. show the dc coupled peak voltmeter, in which the capacitor charges to the total peak voltage above ground reference. The meter reading will be affected by the presence of dc with ac voltage.

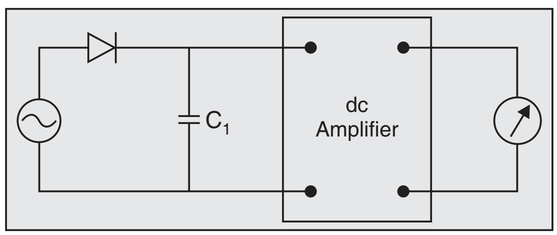


Fig. 6.11. DC coupled peak voltmeter

6.15 A.C. coupled peak responding voltmeters

Fig. 6.12 shows ac coupled peak responding voltmeter. In this the circuit if the positions of diode and capacitor are interchanged. The capacitor still charges to the peak value of the ac input.

In both the circuits, capacitor discharges very slowly through the high impedance input of the dc amplifier. So a negligible small amount of current supplied by the circuit under test keeps the capacitor charged to the peak ac voltage.

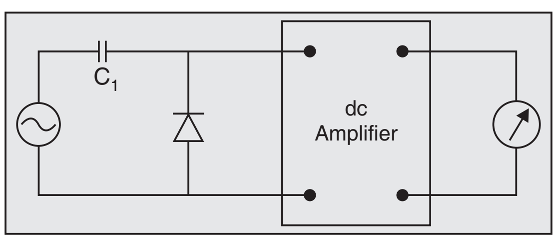


Fig. 6.12. AC coupled peak responding voltmeter

6.16 Advantages of Peak Responding Voltmeters

The primary advantage of peak responding voltmeter is that the rectifying diode and the storage capacitor may be taken out of the instrument and placed in the probe when no ac pre-amplification is required. The peak responding voltmeter is able to measure frequencies up to several hundreds of MHz with a minimum of circuit loading.

6.17 Disadvantages of Peak Responding Voltmeters

The major disadvantage is caused due to harmonic distortion in the input waveforms and limited sensitivity of the instrument. This is because of imperfect diode characteristics.

6.18 True RMS Reading Voltmeter

The complex waveforms in instrumentation engineering are most accurately measured with a true rms reading voltmeter. This instrument indicated the rms value of any waveform by using an rms detector that responds directly to the heating value of the input signal. True rms voltmeters are unique because they are the only type that accurately measure non-sinusoidal waveforms. They respond to the rms or heating value of the impressed signal.

The input signal is AC coupled, amplified or attenuated and heats a thermocouple. The thermocouple produces a DC output proportional to the rms value of the AC input. This DC voltage is amplified and deflects the meter needle to the rms value. The response of the thermocouple is not dependent on the wave shape and thus true rmsvoltmeters can accurately measure non-sinusoidal waveforms.

Principle of working

The thermocouple is a junction of two dissimilar metals whose contact potential is a function of the temperature of the junction of the power delivered to the heater.

$$P = \frac{V_{rms}^2}{R_{heater}}$$

$$V_0 = f(p) = f\left(\frac{V_{\text{rms}}^2}{R_{\text{heater}}}\right)$$

$$= KV_{rms}^2$$

where K is the constant of proportionality.

Fig. 6.13 shows the block diagram of true responding voltmeter. The effect of non-linear behavior of the thermocouple in the circuit is cancelled by similar non-linear effects of the thermocouple in the feedback circuit. The unknown ac voltage is amplified and applied to the heating element of the measuring thermocouple. This produces an output voltage that upsets the balance of the bridge.

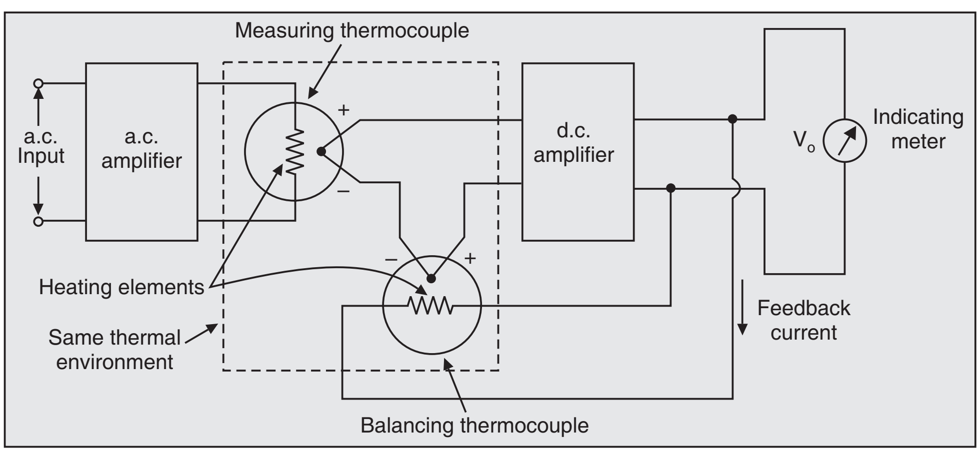


Fig. 6.13. True rms reading voltmeter.

This unbalanced voltage is amplified by the dc amplifier and feed back to the balancing thermocouple. This heats the thermocouple again so that the bridge is balanced. Then the output of both the thermocouples is equal. Under this situation, bridge balance will be re-established. At this instant, the ac current in the input thermocouple is equal to the dc current in the heating element of the feedback thermocouple. Therefore the dc current is directly proportional to the effective or rms value of the input voltage, and is indicated by the meter in the output circuit of the dc amplifier.

6.19 Advantages of True RMS Reading Voltmeter

Following are the main advantages of True rms Reading Voltmeter:

1. Nonlinear behavior is avoided by using two thermocouples placed in same thermal environment.
2. The true rms value is independent of the waveform of the ac input.
3. Sensitivities in the millivolt region are possible.

6.20 Solid State Voltmeter

Electronic Voltmeter using an IC Op-Amp is shown in Fig. 6.14. This is a direct coupled high gain amplifier. The gain of the Op-Amp is adjusted by providing the appropriate resistance between the output terminal (pin -6) and inverting input (pin-2). The ratio R^2/R_1 determines the gain. Terminal 1 and 5 are called offset null terminals. A 10 kΩ potentiometer is connected between these two offset null terminals with its centre tap connected to a -5V supply. This potentiometer is called zero set and is used for adjusting zero output for zero input conditions.

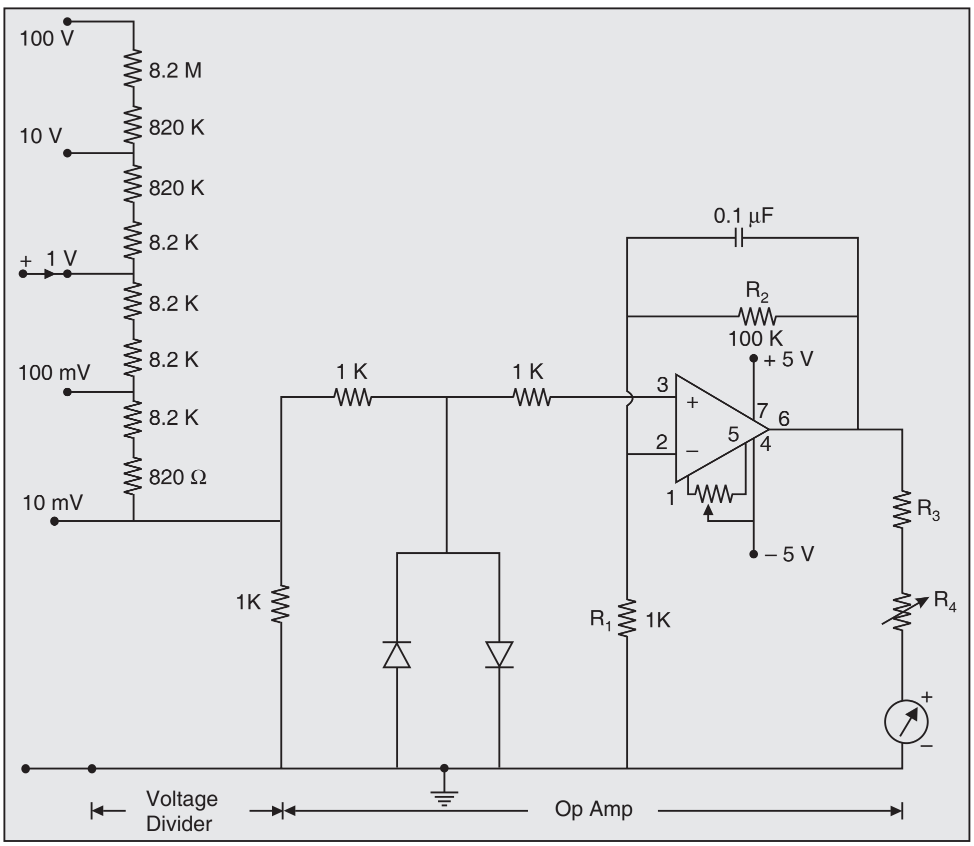


Fig. 6.14. Solid State Voltmeter

Diodes are used for IC protection. Under normal conditions they are non-conducting as the maximum voltage across them is 10 m V. If a voltage more than 100 mV appears across them, then depending upon the polarity of the voltage, one of the diodes conducts and protects the IC.

A µA scale of 50-1000 µA full scale deflection can be used as an indicator. R_4 is adjusted to get maximum full scale deflection.

6.21 Current Measurement with Electronic Instruments

Electronic instruments are used to measure the current in the following ways.

1. D.C. Current Measurements

Electronic voltmeters are frequently constructed to act as multipurpose instruments so that they can be used to measure current as well as voltage. The unknown current is made to flow through a known standard resistance. The voltage drop across this resistance is proportional to the current and is measured by a Transistor Voltmeter (TVM). The scale of the meter is calibrated in terms of current.

2. A.C. Current Measurements

When alternating current is to be measured, a rectifier is used to change the alternating current to a corresponding direct current, which is then measured by a Transistor voltmeter (TVM).

Another methodis to use an AC current probe which enables the AC current to be measured without disturbing the circuit under test. The AC current probe clips around the wire carrying the current and in effect makes the wire a one turn primary of a current transformer (C.T). The C.T has a ferrite core and the secondary consists of a large number of turns. The voltage induced in the secondary winding is amplified and the amplifier's output can be measured by any suitable AC voltmeter. Normally the amplifier is designed so that 1mA current in the wire being measured produced 1 mV at the amplifier output. The current is then read directly on the voltmeter, using the same scale as for voltage measurements.

6.22 Multimeter Probe

Using a multimeter is one of the most basic skills in electronics. Reading a multimeter is not difficult but requires some basic electronics knowledge. Fig. 6.15 shows the multimeter probes. Both digital and analog (measurements are indicated on a dial) can be found today.These directions are applicable to either and only cover functions that use the multimeter's probes.

1. Turn on multimeter and connect to the probes if necessary. The negative probe is black and the positive is red in color.
2. Use the probes to measure resistance by placing one on each side of the component to be measured. For this function, the probes are interchangeable. Some multimeters have the ability to check for continuity, or unbroken connections and wiring.
3. Measuring voltage requires the electricity to be on in the device being measured. To measure DC voltage, set the multimeter to VDC. Touch the negative (black) probe to ground and positive (red) probe to the point in the circuit where DC voltage is to be checked. The voltage reading in volts will register on the display with a -ve symbol indicating voltage towards ground; a +ve symbol may or may not be displayed to indicate voltage moving away from ground. To measure AC voltage, set the multimeter to VAC. The reading will also be in volts although there is no direction to AC voltage.
4. Checking diodes is accomplished by setting the multimeter to diode check, which may be symbolized with an arrow against a vertical line. Turn the device off, and measure the diode resistance by placing the negative probe on the cathode of the diode and the positive probe on the anode side.
5. Reading capacitance, on meters equipped with this option, requires removing the capacitor from the circuit unless the meter measures "*in circuit capacitance*." This is almost always a feature only found in meters designed for this purpose. After removing the capacitor, set the meter to capacitance, which is often symbolized by a curved line and a vertical line.

Some capacitors have a positive and negative side; others do not. If there is a negative side, it will be indicated by a stripe or even - symbols and the negative probe should be placed on that lead, positive on the other. If a negative side is not indicated then probe orientation will not matter. Capacitance measurement will take several seconds to register and will display in farads.

6. Turn the meter off when not in use and store probes so they will not be damaged.

Fig. 6.15. Multimeter Probe

6.23 Digital Multimeter Probe

Fig. 6.16 shows a digital multimeter probe. It is a compact auto-ranging digital multimeter probe and is ideal for on the board testing. This handheld probe, measures voltage, current, resistance, logic and continuity. No need for stopping to adjust the range switch while testing your circuit. This unit also includes data hold and a continuity tester with buzzer. This tool is ideal for the electronics technician or circuit designengineer.

Features: Following are some of the important features of digital multimeter probe.

1. Auto-Ranging
2. Measures AC/DC Voltage
3. Resistance Measurement
4. Continuity Tester with Buzzer
5. Maximum Value Hold
6. Compact and Handheld
7. Overload Protection

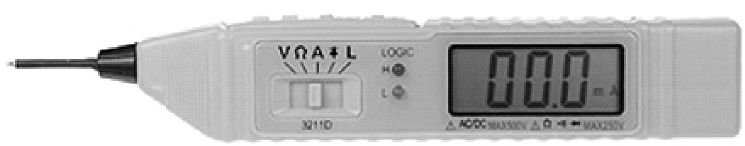


Fig. 4.16. Digital multimeter Probe

6.24 Digital Voltmeter Systems

The digital voltmeter systems are measuring instruments that convert analog voltage signals into a digital or numeric readouts. A digital voltmeter is also called digital electronic voltmeter, it measures and displays dc or ac voltages as discrete number instead of a pointer deflection on a continuous scale. Such a voltmeter displays measurements of dc or ac voltages as discrete numerals instead of pointer deflections on a continuous scale as in analog instruments.

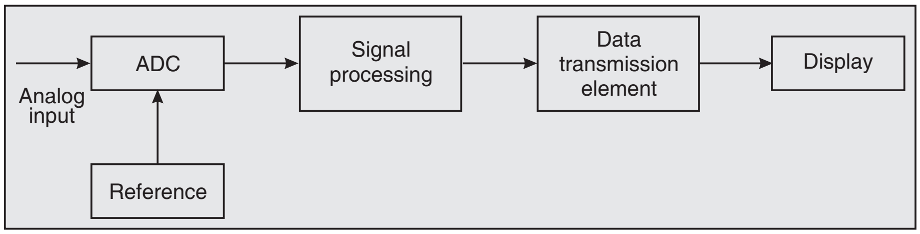


Fig. 4.17. Digital Voltmeter

Fig. 6.17 shows a block diagram of digital voltmeter.A digital instrument requires analog to digital converter (ADC) to converter the analog value into digital value. We shall study Analog-to-Digital converter in chapter 11. The ADC requires a reference. The reference is generated internally and reference generator circuitry depends on the type of ADC technique. The output of the ADC is applied to the signal processing unit. Then it is transmitted to the display. The data transmission elements may be latches, counter etc. depending on the method used. The digital display shows the digital result of the measurement.

6.25 Types of Digital Voltmeter

Following are the different types of digital voltmeters:

1. Ramp type DVM
2. Dual-slope integrating type DVM.
3. Successive-approximation DVM
4. Potentiometer type DVM

All these types of digital voltmeter are discussed one by one in the following pages.

Advantages of Digital Voltmeter

Although there are several advantages of DVMs yet the following are important from the subject point of view:

1. Due to digital display the human errors like parallax are removed
2. The accuracy is upto ± 0.005 % of the reading.
3. The reading speed is high due to digital display.
4. Compatibility with other digital equipment for further processing and recording.
5. Due to small size, portable.

6.26 Ramp-Type DVM

Fig. 6.18 shows the block diagram of a ramp-type digital voltmeter. As seen from this diagram, it consists of voltage-to-time conversion unit and a time measurement unit.

Operation

The operating principle of the ramp type DVM is based on the measurement of the time taken by the DVM for a linear ramp voltage to rise from 0 V to the level of the input voltage, or to decrease from level of the input voltage to zero. This time period is measured with an electronic time-interval counter, and the count is displayed as a number of digits on digital display.

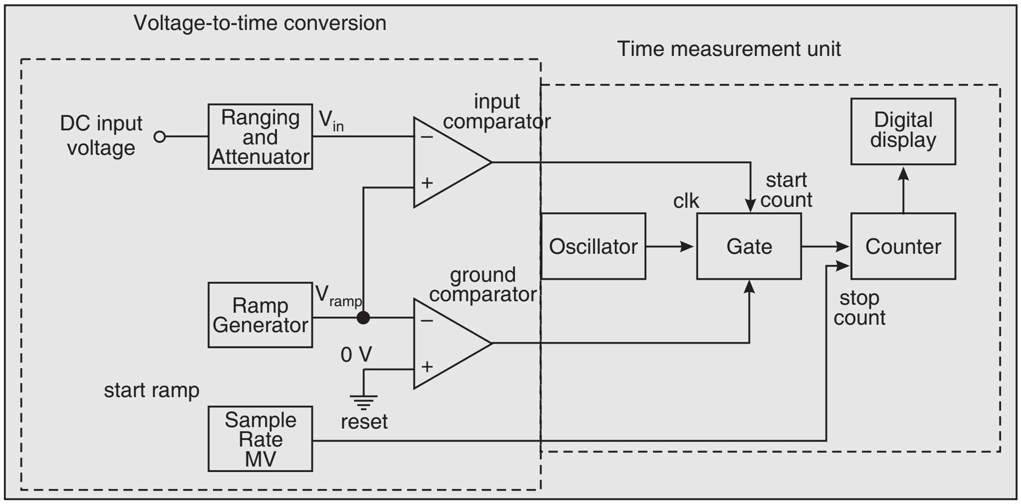


Fig. 6.18.

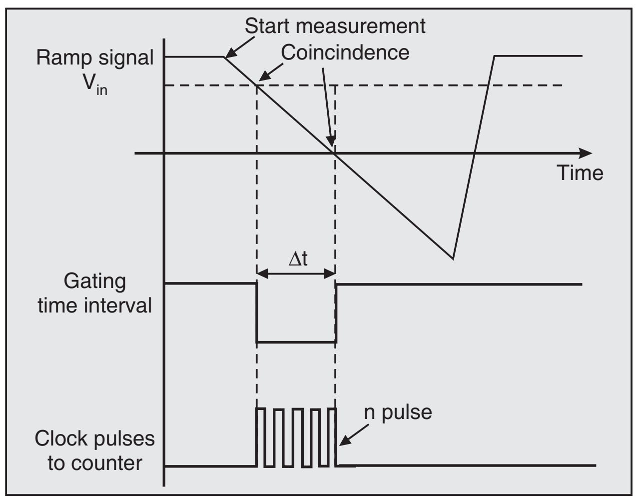


Fig. 6.19.

At the start of measurement a ramp voltage is initiated. The ramp voltage can be negative or positive. Fig. 6.19 shows with a negative going ramp, this ramp is continuously compared with the unknown input voltage. At the instant that the ramp voltage equals to the unknown voltage to be measured, a coincidence circuit or comparator generates a pulse to open the gate. The ramp voltage continues to decrease with time until it finally reaches 0 V. At this instant the ground comparator generate an output pulse to close the gate.

The time between opening and closing of the gate is Δt as shown in Fig. 6.19. During this time interval pulses from a clock pulse generator pass through the gate and are counted and displayed.

An oscillator generates clock pulses which are allowed to pass through the gate to a number of counting units which totalize the number of pulses passed through the gate.

The sampling rate multivibrator determines the rate at which the measurement cycles are initiated. The sample-rate circuit provides an initiating pulse for the ramp generator to start its next ramp voltage.

Advantages of Ramp-Type DVM

Following are the two main advantages of ramp-type digital voltmeter:

1. Circuit is easy to design and low in cost.
2. Output pulse can be transmitted over long distance.

Disadvantages of Ramp-Type DVM

Following are the three main disadvantages of ramp-type digital voltmeter:

1. Single ramp requires excellent characteristics regarding linearity of ramp and time measurement.
2. Large errors are possible when noise is superimposed on the input signal.
3. Input filter are required for this type of converter.

6.27 Dual-Slope Integrating Type DVM.

With the development and perfection of IC modules, the size and power requirement of DVMs have reduced to a level where they can compete with conventional analog instrument both in price and portability.

The block diagram of a DVM based on dual-slope technique is shown in Fig. 6.20. The dual-slope analog-digital (A-D) converter consists of five basic blocks : an Op-Amp used as an integrator, a level comparator, a basic clock (for generating timing pulses), a set of decimal counters and a block of logic circuitry.

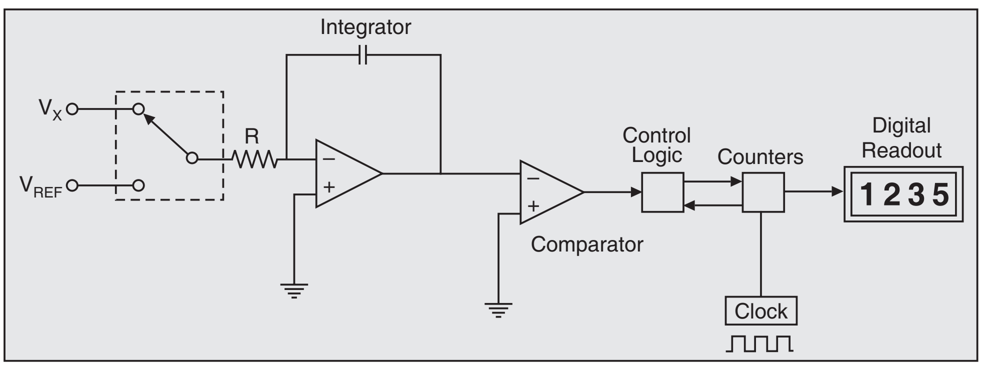


Fig. 6.20. Dual Slope Integrating type DVM.

Operation

The operation of the dual-slope integrating type digital voltmeter may be explained as follows:

The unknown voltage V_x is applied through switch S to the integrator for a known period of time T as shown in Fig. 6.21. This period is determined by counting the clock frequency in decimal counters. During time period T, C is charged at a rate proportional to V_x.

At the end of time interval T, S is shifted to the reference voltage V_{ref} of opposite polarity. The capacitor charge begins to decrease with time and results in a down-ward linear ramp voltage. During the second period a known voltage (i.e. V_{ref} is observed for an unkown time (t). This unknown time t is determined by counting timing pulses from the clock until the voltage across the capacitor reaches its

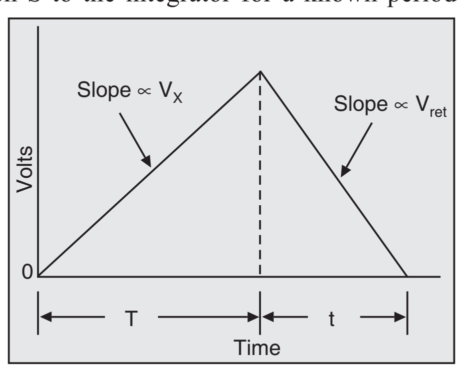


Fig. 6.21.

basic reference value (reference may be ground or any other basic reference level). From similar triangles of Fig. 6.21.

$$\frac{V_x}{T} = \frac{V_{ref}}{t} \qquad \therefore \quad V_x = \frac{T}{t} \times V_{ref}$$

The count after 't' which is proportional to the input voltage 'V_x' is displayed as the measured voltage. By using appropriate signal conditioners, currents, resistances and ac voltages can be measured by the same instrument.

Let time period of clock oscillator be 'T' and digital counter has counted the counts 'n_1' and'n_2'during the period 't_1' and 't_2' respectively, then

$$V_x = V_{ref} \cdot \frac{n_2 T}{n_1 T}$$

$$V_x = V_{ref} \cdot \frac{n_2}{n_1}$$

DVMs are often used in data processing systems or data logging systems. In such systems, a number of analog input signals are scanned sequentially by an electronic system and then each signal is converted into an equivalent digital value by the A/D converter in the DVM. The digital value is then transmitted to a printer alongwith the information about the input line from which the signal has been derived. The whole data is then printed out. In this way, a large number of intput signals can be automatically scanned or processed and their values either printed or logged.

Fig. 6.22. shows a portable digital dc micro-voltmeter (Agronic-112). It has a measurement range of 1 μV – 1000 V with an accuracy of ± 0.2% ± 1 digit. It uses latest MOS LSI ICs and glass epoxy PCB. It has 3½ digit, 7-segment LED display and is widely-used by the testing and servicing departments of industries, research laboratories, educational institutions and service centres.

Fig. 6.22.

Advantages

Following are the main advantages of dual-slope integrating type DVM.

1. Excellent noise rejection as noise and superimposed ac are averaged out during the process of integration.
2. The RC time constant does not affect the input voltage measurement.
3. Sample and hold circuit is not necessary.
4. The accuracy is high and can be readily varied according to the specific requirements.

Disadvantage

The speed of DVM is very slow, as compare to other DVMs.

6.28 Successive-approximation DVM

Operation

The operation of successive approximation DVM may be explained as follows:

The block diagram is shown in Fig. 6.23. The output of the DAC is compared with the unknown voltage by the comparator. The output of the comparator is applied to the control circuit. The control circuit generates the sequence of code which is applied to DAC. Conversion time is fixed (not depend on the signal magnitude) and relatively fast.

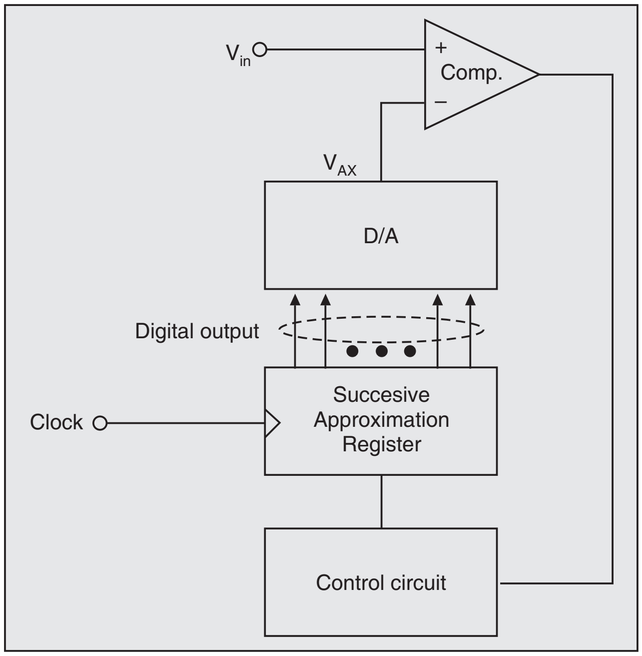


Fig. 6.23. Successive Approximation Type DVM

The operation is similar to the example of determination of weight of the object. The object is placed on one side of the balance and approximate weight on the other side of the balance to determine the weight of the unknown object.

If the weight placed is more than the unknown weight, the weight is removed and another weight of smaller value is placed and again the measurement is performed. Now if it is found that the weight placed is less than that of the object, another weight of smaller value is added to the weight already present, and the measurement is performed. If it is found to be greater than the unknown weight, the added weight is removed and another weight of smaller value is added. By such procedure of adding and removing the appropriate weight, the weight of the unknown object is determined.

In successive approximation type DVM, the comparator compares the output of digital to analog converter with the unknown voltage. The comparator provides logic high or low signals. The digital to analog converter successively generates the set of pattern signals. The procedure continues till the output of the digital to analog converter becomes equal to the unknown voltage.

Advantages

Following are the main advantages of sucessive approximation type DVM:

1. Very high speed of the order of 100 readings per second possible.
2. Resolution upto 5 significant digits is possible.
3. Accuracy is high.

Disadvantages

Following are the main disadvantages of sucessive approximation type DVM:

1. Circuit is complex.
2. Digital to Analog is required.
3. Input impedence is variable.
4. Noise can be cause error.

6.29 Digital Multimeter

A digital multimeter (DMM) displays the quantity measured as a number, its eliminates parallax errors.

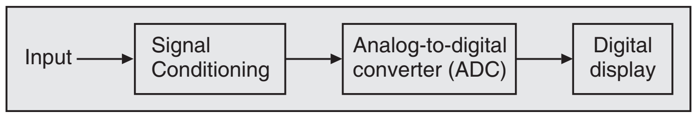


Fig. 6.24. Digital Multimeter

A basic block diagram of a digital multimeter (DMM) is shown in Fig. 6.24. The information from analog input signal passes through the various analog signal conversion circuits which convert the measured quantity to a dc voltage equivalent. Then the A/D converts the dc value to digital form and display unit display the value. The DMM is made up of following three basic elements:

(*a*) Signal conditioning
(*b*) Analog-to-digital (A/D) conversation
(*c*) Numeric digital display

Features of Basic Digital Multimeter

The main features of any digital multimeter is the types of measurement and the ranges over which it will operate. Most DMMs will offer a variety of measurements. The basic measurements will include:

(*a*) Current (DC)
(*b*) Current (AC)
(*c*) Voltage (DC)
(*d*) Voltage (AC)
(*e*) Resistance

Block Diagram of Digital Multimeter

The digital multimeter can measure ac voltage, dc voltage, ac current, dc current and resistance over several ranges. The basic circuit is shown in Fig. 6.25.

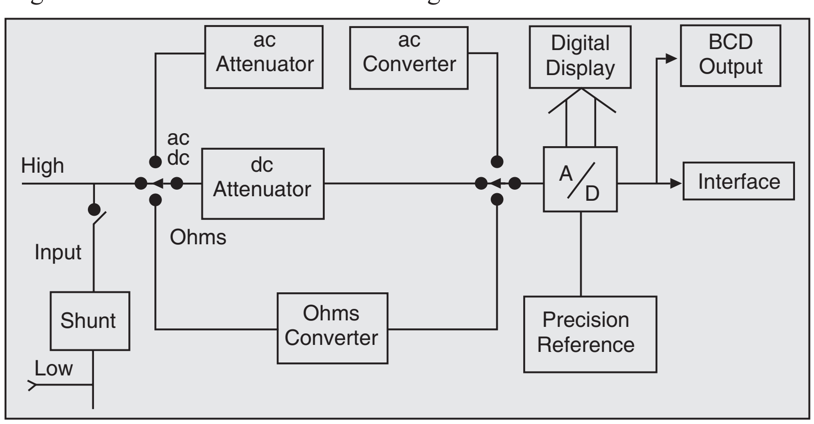


Fig. 6.25. Digital Multimeter

For D.C. voltage measurement

For DC voltage measurement by DMM, a wide range of DC voltage inputs is scaled to the limited range of the A/D Converter. A resistive divider and switching are generally used for this function.

For A.C. voltage measurement

The signal is converted to a DC equivalent before sending it to the A/D Converter.

For D.C. and AC current measurement

It is necessary to convert the current at the input to a voltage. This is done through a series of switched resistors, called shunts. AC current is converted into DC by rectifiers and filters circuit.

For resistance measurement

It is necessary to create a voltage proportional to the resistance because A/D Converter measures only DC volts. The DMM input circuit must provide a DC current flowing through the resistor and then measure the resulting voltage.

To measure the unknown current with DMM we have to first convert the current to the voltage with current to voltage converter as shown in Fig. 4.26. The current to voltage circuit is implemented in DMM.

The known current is applied at the input of the op-amp. When the input current of op-amp is zero, the current I_R is almost same as I_1. This current I_R causes the voltage drop, which is proportional to the current to be measured. This voltage drop is the analog input to the analog to digital converter.

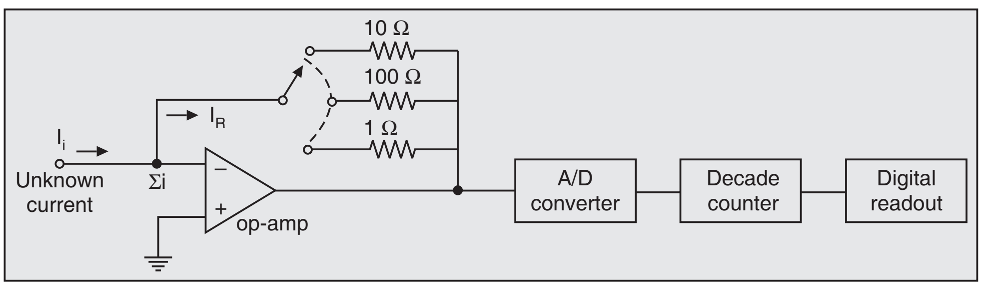


Fig. 6.26. Current to Voltage Converter

Advantage of Digital Multimeter (DMM)

Following are the main advantages of Digital Multimeter:

1. DMM offer high measurement accuracy.
2. These instruments have a high input impedance.
3. They are smaller in size.
4. These meters eliminate observational, parallax and approximation errors.
5. The output of these instruments can be directly feed to a computer for further analysis and use.

6.30 Specification of Digital Multimeter

The important specifications of a digital multimeter are:

1. **D.C. Voltage**

   Five ranges available from ± **200 mV to** ± **1000 V**.

   Resolution is **10 μV** on the lowest range.

   Accuracy is ± 0.03 % of the reading + two digits

2. **A.C. Voltage**

   Five ranges from **200 mV to 750 V**

   Resolution is **10 μV** on the lowest range.

   Accuracy is frequency dependent but the best accuracy is 0.5 % + 10 digits between 45 Hz and 1 Hz on all ranges.

3. **D.C. Current**

   Five ranges available from ± **200 μV to** ± **2000 mA.**

   Resolution is ± **0.01 μA** on the lowest range.

   Accuracy is ± 0.03 % of the reading + two digits

4. **A.C. Current**

   Five ranges from **200 μA** to **2000 mA**.

   Accuracy is frequency dependent but the best accuracy is ± 1 %% + 10 digits between 45 Hz and 2 Hz on all ranges.

5. **Resistance**

   Six ranges are available from 200 Ω to 20 MΩ.

   Accuracy is ± 0.1 % of reading + two digits + 0.02 Ω on the lowest range.

Fig. 6.27. shows the digital multimeter of voltcraft.

Fig. 6.27.

6.31 Digital frequency meter System

The signal is converted to trigger pulse and applied continuously to an AND gate, as shown in Fig. 6.28. A pulse of 1s is applied to the other terminal, and the number of pulses counted this period indicates the frequency.

The frequency of the signal is converted into a train of pulse for each cycle of the signal. The number of pulses occurring in a definite interval of time is then counted by an electronic counter. Since each pulse represents the cycle of the unknown signal, the number of counts is a direct indication of the frequency of the signal (unknown). Since electronic counters have a high speed of operation, high frequency signals can be measured.

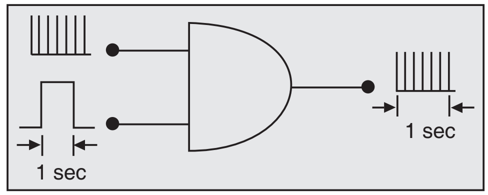


Fig. 6.28.

The block diagram of a digital frequency meter is shown in Fig. 4.29. The signal may be amplified before being applied to the Schmitt trigger. The Schmitt trigger converts the input signal into a square wave with fast rise and fall times, which is then differentiated and clipped. As a result, the output from the Schmitt trigger is a train of pulses, one pulse for each cycle of the signal.

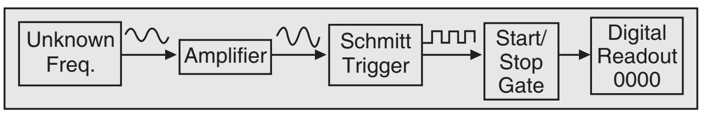


Fig. 4.29. Block Diagram of Digital Frequency Meter

The output pulses from the Schmitt trigger are feed to a START/STOP gate. When this gate is 'ON', the input pulses pass through this gate and are feed directly to the electronic counter, which counts the number of pulses. When this gate is 'OFF', the counter stops counting the incoming pulses.

The counter displays the number of pulses that have passed through it in the time interval between start and stop. If this interval is known, the pulses rate and hence the frequency of counts displayed by counter and t is the time interval between start and stop of gate. Therefore frequency of the unknown signal,

$$f = \frac{N}{t}$$

A simplifier circuit of digital frequency meter is shown in Fig. 4.30.

There are two signals to be traced:

(*i*) Input Signal (or the counted signal). The signal whose frequency is to be measured.

(*ii*) Gating Signal: This determines the length of time during which the counters (which consists of decade counter assemblies) are allowed to totalize the pulse separated by the period of the origin input signal.

The input signal is amplified and is applied to a Schmitt trigger where it is converted to a train of pulses separated by the period of the original input signal.

The oscillation frequency is 1 MHz Therefore, the time base output is shaped be a Schmitt trigger into positive pulses, 1 μs apart. These pulses are selected are applied to 6 decade divider assemblies (DDAs). A selector switch allows the time interval to be selected from 1 μs to 1 s.

The first output pulse from the time base selector switch passes through the Schmitt trigger to the gate control flip-flop. The gate control flip-flop assumes a state such that an enable signal is applied to the main gate. The main gate being an AND gate, the input signal pulses are allowed to enter the DCAs where they are totalized and displayed. This process continues till a second pulses arrive at the control gate flip-flop from the DDAs (Decade dividing assemblies). The control gate reverses its state which removes the enabling signal from the main gate and no more pulses are allowed to get to counting assemblies since the main gate closes. Thus the number of pulses which have passed during a specific time are counted and displayed on the DCAs. The frequencies can be read directly in Hz, kHz or MHz in case the time base selector moves the decimal point in the display area.

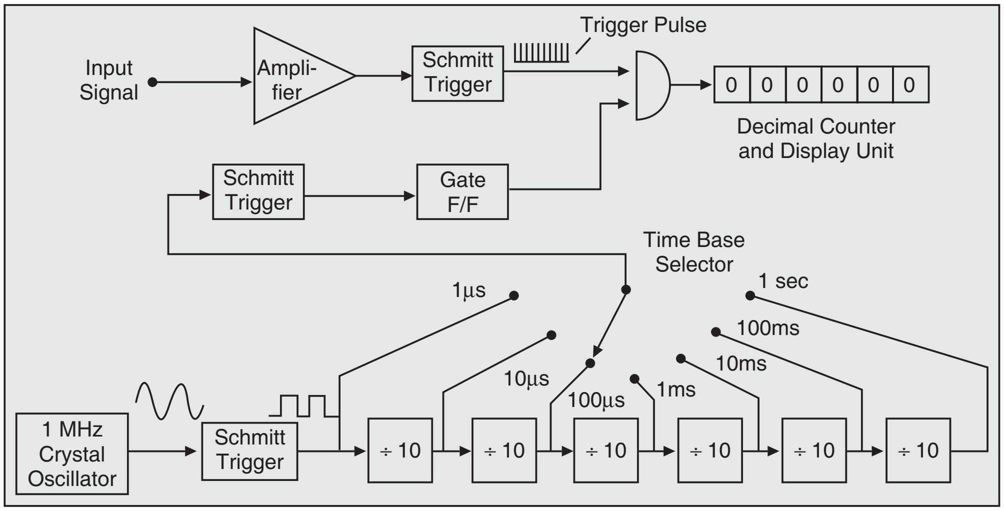


Fig. 6.30. Digital Frequency meter

6.32 High Frequency Measurement

The direct count range of digital frequency meter (FDM) extends from dc to a few 100 MHz. The limitation arises because of the counters used along with the DFM. The counters cannot count at the speed demanded by high frequency measurement.

This range of a few 100 MHz covers only a small portion of the frequency spectrum. Therefore, techniques other than direct counting have been used to extend the range of digital frequency meters to above 40 GHz. The input frequency is reduced before it is applied to a digital counter. This is done by special techniques. Some of the techniques used are as follows.

1. Prescalling

The high frequency signal by the use of high speed is divided by the integral numbers such as 2,4,6,8 etc. divider circuits, to get it within the frequency range of DFM

2. Heterodyne Converter

The high frequency signal is reduced in frequency to a range within that of the meter, by using heterodyne techniques.

3. Transfer Oscillator

A harmonic or tunable LF continuous wave oscillator is zero beat (mixed to produce zero frequency) with the unknown high frequency signal. The LF oscillator frequency is measured and multiplied by an integer which is equal to the ratio of the two frequencies, in order to determine the value of the unknown HF.

4. Automatic Divider

The high frequency signal is reduced by some factor, such as 100:1, using automatically tuned circuits which generated an output frequency equal to 1/100th or 1/1000th of the input frequency.

6.33 Q-Meter

The Q-meter is an instrument which is designed to measure of the electrical properties of the coils and capacitors by measuring the Q-value of an *R-L-C* circuit. It is a useful laboratory instrument.

Working Principle

The Q meter is based on the characteristics of a series circuit. The series resonant has characteristics the voltage across the coil or capacitor is equal to the applied voltage times the Q factor of the circuit.

The Q-factor is called quality factor or storage factor. It is define as the ratio of power stored in the element to the power dissipated in the element.

If a fixed voltage is applied to the circuit, a voltmeter across the capacitor can be calibrated to read Q directly. The voltage and current relationships of series-resonant circuit are shown in Fig. 6.31.

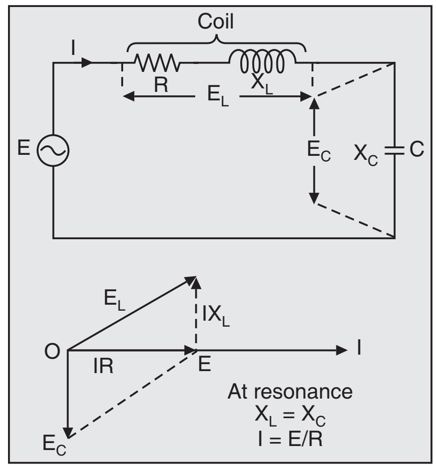


Fig. 6.31.

At resonance

$$X_C = X_L$$
$$E_C = I_{XC} = I_{XL}$$
$$E = IR$$

where

E = applied voltage
I = circuit current
E_C = voltage across the capacitor
X_C = capacitive reactance
X_L = capacitive reactance
R = coil resistance

The magnification of the circuit, by delimination is Q, where,

$$Q = \frac{X_L}{R} = \frac{X_C}{R} = \frac{E_C}{E}$$

If E is maintained constant and known level, a voltmeter connected across the capacitor can be calibrated directly in terms of Q.

Practical Q-Meter

Q-meter circuit consists of a wide range of oscillator with a frequency range from 50 kHz to 50 MHz. It delivers current to a low value shunt resistance R_{sh}. The value of the shunt is very low about 0.02 Ω. It introduces almost no resistance into the oscillatory circuit and it therefore represents a voltage source of magnitude E with a very small internal resistance. The voltage E across the shunt is measured with a thermocouple meter marked "Multiple Q by." The voltage across the variable capacitor E_C is measured with an electronic voltmeter whose scale is calibrated directly in Q values.

Procedure of Measurement

1. The unknown coil is connected to the test terminals of the instrument between T_1 and T_2.
2. The circuit is tuned to the resonance by setting oscillator to a given frequency and varying the internal resonating capacitor or by pre-setting the capacitor to a desired value and adjusting the frequency of the oscillator.
3. The Q reading of the output meter must be multiplied by the index setting of the "*Multiple Q by*" meter to obtain the actual Q value.

The indicated Q is the resonant reading on the "Circuit Q" meter and is called the circuit Q. The effective Q of the measured coil will be greater than the indicated Q. The difference is generally neglected.

The inductance of the coil can be calculated from the known values of frequency (f) and resonating capacitance (C),

$$X_L = X_C \quad \text{and} \quad L = \frac{1}{(2\pi f)^2 C} \text{ henry}$$

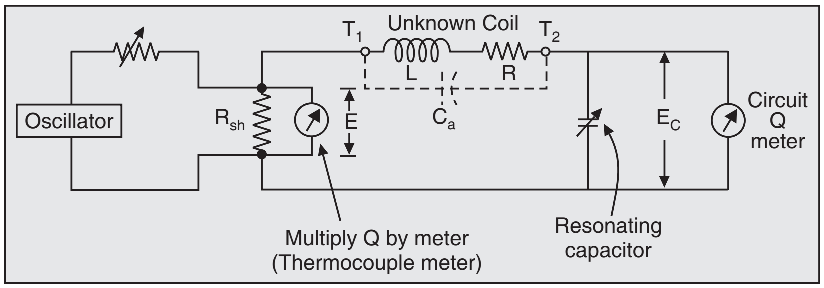


Fig. 6.32. Q meter

6.34 Measurement Methods of Q Meter

There are three methods for connecting unknown components to the terminals of a Q meter. They are given below:

1. Direct Connection
2. Series Connection
3. Parallel Connection

We shall discuss all these connection methods one by one in the following pages.

6.35 Direct Connection of Q Meter

In this connection the coil is connected directly across the test terminals as shown in Fig. 6-32. The circuit is resonated by adjusting either the oscillator frequency or the resonating capacitor. The indicated Q is read directly from the "*Circuit Q*" meter. The previous article is the direct connection method.

6.36 Series Connection of Q Meter

The series connection is mainly used for measuring the low-impedance component, such as low-value resistors, small coils, and large capacitors. Figure 6.34. shows the series connection. The component to be measured is placed in series with a stable working coil across the test terminals. It's indicated by *Z*.

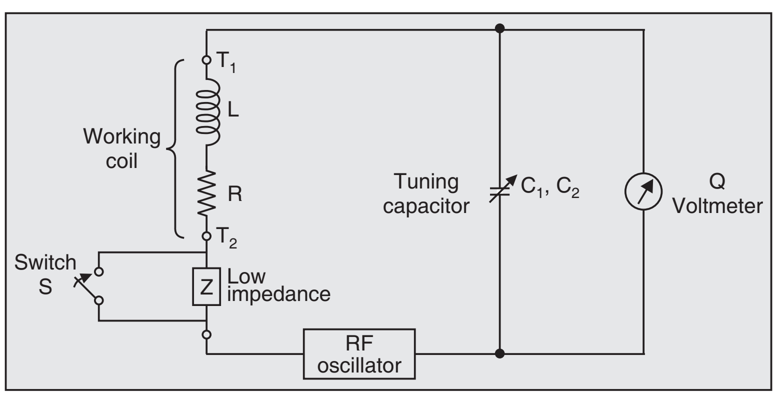


Fig. 6.33. Series Connection of Q meter

Measurements Procedure

1. In first measurement the unknown is short-circuited by a small shorting strap and the circuit is resonated. The value of the tuning capacitor (C_1) and the indicated Q (Q_1) are recorded.
2. In second measurement the shorting strap is removed and the circuit is returned. The new value for the tuning capacitor (C_2) and a change in the Q value from Q_1 to Q_2 is recorded.

For the reference condition,

$$X_{c1} = X_L \quad \text{or} \quad \frac{1}{\omega C_1} = \omega L$$

Neglecting the resistance of the measuring circuit,

$$Q_1 = \frac{\omega L}{R} = \frac{1}{\omega C_1 R}$$

For the second measurement, the reactance of the unknown can be expressed in terms of the new value of the tuning capacitor (C_2) and the in-circuit value of the inductor (L),

$$X_s = X_{c2} - X_L$$

$$= \frac{1}{\omega C_2} - \frac{1}{\omega C_1}$$

$$= \frac{C_1 - C_2}{\omega C_1 C_2} \qquad ...(i)$$

if $C_1 > C_2$: X_s is inductive

and if $C_1 < C_2$: X_s is capacitive

The resistive component of the unknown impedance

$$R_1 = \frac{X_1}{Q_1}$$

$$R_2 = \frac{X_2}{Q_2}$$

and

$$R_S = R_2 - R_1$$

$$= \frac{X_2}{Q_2} - \frac{X_1}{Q_1}$$

$$= \frac{1}{\omega C_2 Q_2} - \frac{1}{\omega C_1 Q_1}$$

$$= \frac{C_1 Q_1 - C_2 Q_2}{\omega C_1 C_2 Q_1 Q_2} \qquad ...(ii)$$

If the unknown is purely resistive then the tuning capacitor would not change in the measuring process, $C_1 = C_2$.

$$R_s = \frac{Q_1 - Q_2}{\omega C_1 Q_1 Q_2} = \frac{\Delta Q}{\omega C_1 Q_1 Q_2}$$

If the unknown is a small inductor, the value of the inductance is found from equation (*i*)

$$X_s = \frac{C_1 - C_2}{\omega C_1 C_2}$$

$$X_s = \omega L_s$$

$$L_s = \frac{C_1 - C_2}{\omega^2 C_1 C_2} \qquad ...(iii)$$

The Q of the coil is found from equation (*i*) and (*ii*),

$$Q_s = \frac{X_s}{R_s}$$

$$Q_s = \frac{(C_1 - C_2)(Q_1 Q_2)}{C_1 Q_1 - C_2 Q_1} \qquad ...(iv)$$

If the unknown is large capacitor, it value is determined from equation (*i*),

$$C_s = \frac{C_1 C_2}{C_1 - C_2}$$

The Q of the capacitor may be found by equation (*iv*).

Example 6.1. *In a Q meter after connecting a standard coil, the resonance is obtained with a frequency* f_1 *with resonating capacitor set at* C_1*, the indicated Q factor is* Q_1*. Unknown impedance is connected in series with the standard coil and the resonance is re-established by resetting the resonating capacitor at* C_2*, the corresponding Q factor being* Q_2*.*

Determine the resistive and reactive components of the unknown impedance when C = 190 pF, $Q_1 = 75$*,* $C_2 = 170$ *pF and* $Q_2 = 45$*. The frequency is 200 kHz.*

Solution. Given: $C_1 = 190$ pF $= 190 \times 10^{-12}$ F; $Q_1 = 75$, $C_2 = 170$ pF $= 170 \times 10^{-12}$ F; $Q_2 = 45$, and $f = 200$ kHz $= 200 \times 10^3$ *Hz*.

We know that the resistive component,

$$R_s = \frac{C_1 Q_1 - C_2 Q_1}{\omega C_1 C_2 Q_1 Q_2}$$

$$= \frac{(190 \times 10^{-12}) \times 75 - (170 \times 10^{-12}) \times 45}{(2\pi \times 200 \times 1000) \times (190 \times 10^{-12}) \times 75 \times (170 \times 10^{-12}) \times 45} = 48.18\ \Omega\ \textbf{Ans.}$$

Reactive component,

$$X_s = \frac{C_1 - C_2}{\omega C_1 C_2}$$

$$X_s = \frac{(190 \times 10^{-12}) - (170 \times 10^{-12})}{(2\pi \times 200 \times 1000) \times (190 \times 10^{-12}) \times (170 \times 10^{-12})} = 492.74\ \Omega\ \textbf{Ans.}$$

6.37 Parallel Connection of Q Meter

The parallel connection is shown in Fig. 6.35. This circuit is sued for measuring the high-impedance such as high-value resistors, certain inductors and small capacitors. The unknown component is connected in parallel with the measuring circuit.

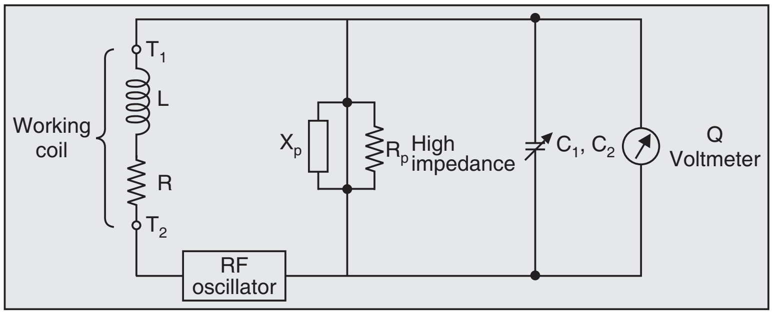


Fig. 6.34. Parallel Connection of Q meter

Measurement Procedure

Before connecting the unknown impedance, the circuit is resonated by using a suitable working coil. This establishes a value Q and C (Q_1 and C_1). Then the component under test is connected to the circuit and the capacitor is readjusted for resonance. The new value for tuning capacitance (C_2) is obtained and a change in the value of circuit Q (ΔQ) from Q_1 to Q_2.

When the unknown impedance is not connected to the circuit, the working coil (L) is tuned by the capacitor (C_1).

$$\omega L = \frac{1}{\omega C_1} \qquad \text{...}(i)$$

and

$$Q_1 = \frac{\omega L}{R} = \frac{1}{\omega C_1 R} \qquad \text{...}(ii)$$

When the unknown impedance is not connected into the circuit and the capacitor is tuned for resonance. Then the reactance of the working coil (X_L) equals the parallel reactance of the tuning capacitor (X_{C2}) and the unknown (X_P).

$$X_L = \frac{(X_{C2})(X_P)}{X_{C2} + X_P}$$

$$X_P = \frac{1}{\omega(C_1 - C_2)} \qquad (iii)$$

If the unknown is inductive,

$$X_P = \omega L_P$$

From the equation (*iii*),

$$L_P = \frac{1}{\omega^2 (C_1 - C_2)}$$

If the unknown is capacitive,

$$X_P = \frac{1}{\omega C_P}$$

From the equation (*iii*)

$$C_P = C_1 - C_2$$

The total resistance at resonance is equal to the product of the circuit Q and reactance of the coil, therefore,

$$R_T = Q_2 X_L$$

We know that the value of X_L is given by equation (*i*),

$$R_T = Q_2 X_{C1} = \frac{Q_2}{\omega C_1}$$

The resistance (R_P) of the unknown impedance is found by computing the conductance in the circuit,

G_T = total conductance of the resonance circuit

G_P = conductance of the unknown impedance

G_L = conductance of the working coil

$$G_T = G_P + G_L$$

$$G_P = G_T - G_L$$

From equation (*iv*) value of G_T,

$$G_T = \frac{1}{R_T} = \frac{\omega C_1}{Q_2}$$

$$\frac{1}{R_P} = \frac{1}{R_T} - \frac{1}{R_L}$$

$$\frac{1}{R_P} = \frac{\omega C_1}{Q_2} - \frac{R}{R^2 + \omega^2 L^2}$$

$$= \frac{\omega C_1}{Q_2} - \left(\frac{1}{R}\right)\left(\frac{R}{1 + \omega^2 L^2 / R^2}\right)$$

$$= \frac{\omega C_1}{Q_2} - \frac{1}{RQ_1^2}$$

Substituting the value of R from equation (*ii*) to above equation we get,

$$\frac{1}{R_P} = \frac{\omega C_1}{Q_2} - \frac{\omega C_1}{Q_1}$$

$$R_P = \frac{Q_1 Q_2}{\omega C_1 (Q_1 - Q_2)} = \frac{Q_1 Q_2}{\omega C_1 \Delta Q} \quad \text{...}(v)$$

The value of Q of the unknown is found by using equation (*iii*) and (*v*),

$$Q_P = \frac{R_P}{X_P} = \frac{(C_1 - C_2) Q_1 Q_2}{C_1 (Q_1 - Q_2)} = \frac{(C_1 - C_2) Q_1 Q_2}{C_1 \Delta Q}$$

6.38 Applications of Q Meter

Some of the specialized applications of Q meter are to measure:

1. Q of a coil
2. Inductance and capacitance
3. Distributed capacitance of a coil
4. Q and power factor of a dielectric material
5. Mutual inductance of coupled circuits
6. Coefficient of coupling
7. Critical coupling
8. Reactance and effective resistance of an inductor at operating frequency
9. Bandwidth of a tuned circuit etc.

Example 6.2. *A circuit consisting of an unknown coil, a resistance and a variable capacitor connected in series is tuned to resonance using a Q-meter. If the frequency is 400 kHz, the resonating capacitor is set at 220 pF, the resistance is 0.8 W and the Q-meter indicates 110, determine the effective resistance and inductance of the unknown coil.*

Solution. Given: $f = 400$ kHz $= 400 \times 10^3$ Hz; C = 220 pF = 220×10^{-12} F; $R = 0.8\ \Omega$ and $Q = 110$.

We know that in resonance condition, inductance is given by

$$L_{\text{coil}} = \frac{1}{\omega^2 C}$$

$$= \frac{1}{(2\pi \times 400 \times 1000)^2 \times 220 \times 10^{-12}} = 719.6\ \mu H \textbf{ Ans.}$$

and resistance is given by,

$$R_{\text{coil}} = \frac{\omega L}{Q} - R_{sh}$$

$$= \frac{2\pi \times 400 \times 1000 \times 719.6 \times 10^{-6}}{110Q} - 0.8 = 16.44\ \Omega \textbf{ Ans.}$$

6.39 RF Impedance Measurement

The measurements of electrical impedance at frequencies range from KHz to GHz the iron-core inductors are useless, the coils designed for a particular frequency range. The measurement of impedance at radi frequencies cannot always be performed by measuring an RF voltage and dividing it by the corresponding RF current.

At radio frequency wire-wound resistance become almost useless above 1 MHx. RF impedance is measured with Schering bridge circuit having variable capacitors ad adjustable components and only small fixed resistors.

Figure 6.35 shows the bridge circuit. Both null condition may be met with the use of only variable capacitors. The bridge for one adjustment CP is in series with the known. Both component of the unknown an read as difference measurements. C_{A1} and C_{A2} refer to successive balance made with the terminals shorted and then with the unknown in place, we have

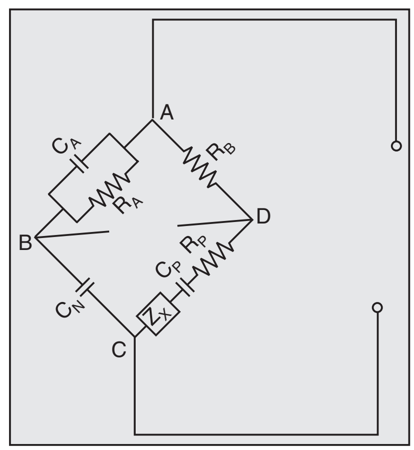


Fig. 6.35.

$$R_X = \frac{R_B}{C_N}(C_{A2} - C_{A1})$$

$$X_X = \frac{1}{\omega}\left(\frac{1}{C_{P_2}} - \frac{1}{C_{P_1}}\right)$$

Where R_X is the real part of Z_X and X_Z is the imaginary part of Z_X.

Since the impedance of all four bridge arm is the same in both cases, the accuracy of the other arms is immaterial and the bridge errors are largely cancelled.

6.40 RF Voltage Measurement

The RF voltage is measured by rectifying the alternating voltage and then amplifying the voltage. In RF range it is difficult to amplify and normal components are usually useless.

6.41 RF Power Measurement

The ordinary wattmeters are not suitable for measurement of power at high frequencies. There are number of method for measurement of power at high frequencies they are given below:

1. Bolometer Bridge for Measurement of Power
2. Measurement of RF Power by Calorimeter Method

We will discuss each method on by one in the following pages.

6.42 Bolometer Bridge for Measurement of RF Power

This method is based on the dissipation of the RF power in a small temperature sensitive resistive element called bolometer. This bolometer is a thin wire having a positive temperature coefficient of resistance, or a bead of semiconductor having a negative temperature coefficient of resistance or a thin conducting film of small dimensions.

Figure 6.36 shows the bolometer used into a bridge network so that small changes in resistance can be readily detected. The bridge is initially balanced bias power. When RF power is applied to bolometer the bias is withdraw until the bridge is balanced again. This method is suitable for measuring low and medium power.

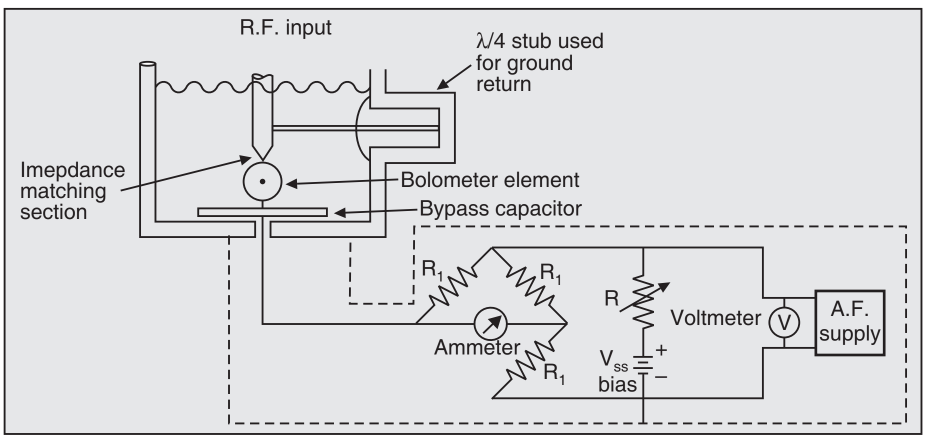


Fig. 6.36.

To measure the unknown FR power by using bolometer bridge, the known AF power is superimposed on unknown RF power.

The bolometer element is heated by adjusting the variable resistance R and dc bias voltage V_{SS} (V_1) till the resistance is equal to R_1. At this point the bridge is balance condition. The test RF input is switched OFF which again unbalances the bridge. To achieves the balance condition again the AF voltage is increased till RF power equals V_2,

$$\text{RF Power} = \frac{V_2^2 - V_1^2}{4R_1}$$

In a coaxial and waveguide transmission system, the bolometer mount must provide the necessary impedance matching.

6.43 Measurement of RF Power by Calorimeter Method

Figure 6.37 show the measurement of RF power. In this RF power may be directly converter into heat. Water acts as the load and RF power may be used to heat an element as long transmission line water being used as a coolant. The RF power may be absorbed directly in the calorimeter fluid. This system should have no RF leakage either by radiation or through lossy joints. The power radiated is given by the relation,

$$P = 4.18 \times \text{Mass} \times \text{Specific Heat} \times \Delta T$$

Where ΔT is the temperature difference and the power is in watts.

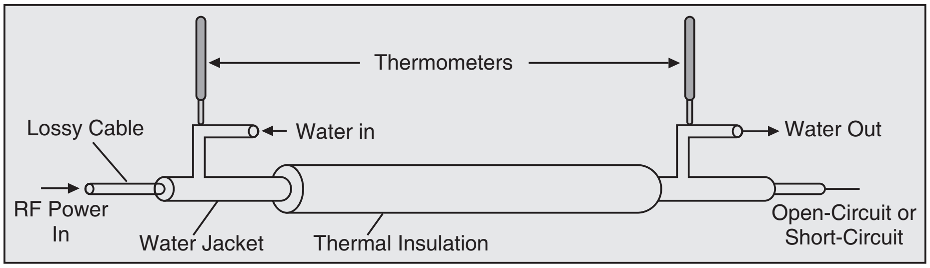


Fig. 6.37.

In this method of power measurement, the FR portion of the calorimeter system must be designed to provide a proper transformation of impedance. This is usually done by a tapered section. The length of cable should be sufficient to provide an attenuation of 10 db or more at the operating frequency so that the reflected wave will be down by 20 dbs corresponding to 100 W of power. Thus the load virtually absorbs almost all the RF power. The cable is available with standard impedance of 50 Ω. Therefore there is no impedance matching problem. The water acts as the load and directly absorbs the power from the source.

SUMMARY

1. The electronic instruments generally have higher sensitivity, faster response and greater flexibility than mechanical or electrical instruments in indicating, recording and, where required, in controlling the measured quantity.
2. The deflection type instruments with a scale and movable pointer are called analog instruments.
3. Digital instruments are those which use logic circuits and techniques to obtain a measurement and then display it in numerical-reading (digital) form.
4. An electronic voltmeter uses rectifiers, amplifiers and other circuits to generate a current proportional to the voltage being measured.
5. Transistor voltmeter Circuits (Direct Couple Amplifier) is a dc couple amplifier with an indicating meter.
6. AC Analog voltmeters are one of the most popular electronic measuring instruments in use today. They are used to measure the rms voltage of the many waveforms commonly found in electronics.
7. The D' Arsonval meter movement can be used for measuring alternating quantities provided a rectifier is added to the measuring circuit.
8. The general purpose of the multirange ac voltmeter is for measuring ac voltage for different ranges.
9. Peak responding voltmeters are also designed to indicate the rms value of a sine wave.
10. The difference between average responding meter and this meter is the use of storage capacitors with the rectifying diode.
11. The true rms reading voltmeter indicated the rms value of any waveform by using an rms detect
12. Electronics Voltmeter using an IC Op-Amp
13. Electronic voltmeter are frequently constructed to act as multipurpose instruments so that they can be used to measure current as well as voltage.
14. When alternating current is to be measured a rectifier is used to change the alternating current to a corresponding direct current, which is then measured by a TVM.

15. The operating principle of the ramp type DVM is based on measurement of the time taken by the DVM for a linear ramp voltage to rise from 0 V to the level of the input voltage, or to decrease from level of the input voltage to zero.
16. In successive approximation type DVM, the comparator compares the output of digital to analog converter with the unknown voltage.
17. A digital multimeter (DMM) displays the quantity measured as a number, which eliminates parallax errors.

GLOSSARY

AC electronics voltmeter: An AC electronics voltmeter is used to measure AC voltage. The PMMC meter movement is used for measurement AC voltage by inserting a rectifier in the measuring circuit.

AC coupled peak responding voltmeters: The positions of diode and capacitor are interchanged with reference to D.C coupled peak responding voltmeters. The capacitor still charges to the peak value of the ac input.

AC Voltmeter using full wave rectifier: The full-wave rectifier has been combined in series with a dc meter movement.

AC Voltmeter using half wave rectifier: The half-wave rectifier has been combined in series with a dc meter movement.

D.C Coupled peak responding voltmeters: DC coupled peak responding voltmeters the capacitor charges to the total peak voltage above ground reference.

Digital Multimeter: The information from analog input signal through the various analog signal conversion circuits which convert the measured quantity to a dc voltage equivalent. Then the ADC convert the dc value to digital form and display unit display the value.

Digital Voltmeter (DVM): A digital voltmeter is also called digital electronic voltmeter, it measure and display dc or ac voltages as discrete number instead of a pointer deflection on a continuous scale. It requires analog to digital converter (ADC) to converter the analog value into digital value.

Electronics Voltmeter: In an electronics voltmeter the measured alternating voltage is rectified using a diode rectifier or decoder and a rectified direct current is produced which is the measure of the original alternating voltage.

Transistor voltmeter Circuits: An AC electronics voltmeter is used to measure AC voltage. The PMMC meter movement is used for measurement AC voltage by inserting a rectifier in the measuring circuit.

True RMS reading voltmeter: This instrument produces a meter indication by sensing waveform heating power, which is proportional to the square of theRMS value of the voltage.

DESCRIPTIVE QUESTIONS

1. What is digital instrument? Explain.
2. What are the essentials of an electronic instrument? Explain each of them briefly.
3. State the advantages of electronics instruments.
4. What are electronics voltmeters? Explain.
5. What are the advantages of electronics voltmeters?
6. Discuss in detail the principle of operation of electronics voltmeter with the help of a circuit diagram *(GBTU/MTU, 2004-05)*
7. What are the advantages of true rms reading voltmeter?
8. Write a short note on true rms reading voltmeter. *(GBTU/MTU, 2008-09)*
9. Draw a circuit of true rmsmeter and explain its working. *(GBTU/MTU, 2007-08)*
10. Define solid state voltmeter.
11. Explain transistor voltmeter in detail.
12. Explain rectifier type ac voltmeter
13. Describe AC voltmeter using rectifier with diagram. *(GBTU/MTU, 2008-09)*

14. Explain briefly the principle on which the digital meters works.
15. What is the function of a digital voltmeter?
16. State the advantages of digital voltmeters.
17. State the characteristic features of DVMs.
18. List the application of DVMs.
19. Give the classification of digital voltmeters.
20. Explain the working of ramp-type DVM.
21. Discuss the working of dual-slope integrating DVM.
22. Draw the block diagram and its working of an integrating type DVM. *(GBTU/MTU, 2006-07)*
23. With the help of a block diagram, describe briefly the working of a successive approximation digital voltmeter.
24. Describe a digital multimeter with the help of a block diagram.
25. Explain the operation of a basic digital multimeter?
26. What principle does a digital frequency meter operate?
27. Enlist the different types of frequency meter. Explain anyone in detail. *(Nagpur University, Summer 2010)*
28. Draw and explain the basic circuit of digital frequency meter. *(Nagpur University, Summer 2010)*
29. Explain the term loading in voltmeter and five the method to remove the adverse effect of loading. *(GBTU/MTU, 2009-10)*
30. Explain the principle of electronics voltmeter. *(GBTU/MTU, 2010-11)*
31. Explain how an electronic analog voltmeter can be used to measure alternating current. *(GBTU/MTU, 2010-11)*
32. Explain various specification of digital multimeter which are important while selecting for any applications. *(GBTU/MTU, 2009-10)*
33. Draw the block diagram of dual slope type digital multimeter and explain its working. *(GBTU /MTU, 2009-10)*
34. Compare the various techniques used in digital volt meter in tabular format with parameter such as circuit complexity, stability, accuracy, noise effect and operating speed. *(GBTU/MTU, 2009-10)*
35. Explain the working of integration type DVM. *(GBTU/MTU, 2010-11)*
36. Write a short note on electronic multimeter. *(Nagpur University, Summer 2011)*
37. Explain the true RMS voltmeter with neat sketch. *(Nagpur University, Summer 2010)*
38. Enlist various types of digital voltmeters and explain any one. *(Nagpur University, Summer 2011)*
39. Define the Q-factor of a coil. Explain with a circuit diagram construction and principle of operation of a basic Q-meter. *(GBTU/MTU, 2010-11)*
40. Explain the Q-meter with suitable diagram. Also mention various source of error in Q-meter. *(GBTU/MTU, 2009-10)*

MULTIPLE CHOICE QUESTIONS

1. An average response rectifier type electronic ac voltmeter has a dc voltage of 10 V applied to it. The meter reading will be,
(*a*) 7.1 V (*b*) 10 V (*c*) 11.1 V (*d*) 22.2 V

2. True rms responding voltmeter use,
(*a*) Thermistors. (*b*) RTDs. (*c*) LVDTS. (*d*) Thermocouple.

3. Measuring and balancing thermocouple are used in a,
(*a*) Peak responding voltmeter.
(*b*) Peak-to-peak responding voltmeter.
(*c*) Avarage responding voltmeter.
(*d*) rms responding voltmeter.

4. Transistor voltmeter ,
(*a*) Cannot measure ac voltage.
(*b*) Cannot be designed to measure resistance as well as voltage.
(*c*) Cannot measure high frequency voltage.
(*d*) Can measure ac voltage.

5. Electronic voltmeter provides more accurate reading in high resistance circuits as compared to non-electronic voltmeter because of ,
(*a*) High V/ohm rating.
(*b*) High Ohm/V rating.
(*c*) How meter resistance.
(*d*) High resolution.

6. True rms reading voltmeter uses two thermocouple in order ,
(*a*) To increase sensitivity.
(*b*) That the second thermocouple cancels out the no-linear effects of the first thermocouple.
(*c*) To prevent drift in the dc amplifier.
(*d*) All of the above.

7. Digital instrument are those which,
(*a*) have numerical readout.
(*b*) use LED or LCD displays.
(*c*) have a circuitry of digital design.
(*d*) use deflection types meter movement.

8. The essential elements of an electronic instrument are,
(*a*) Transducer.
(*b*) signal conditioner.
(*c*) indicating device.
(*d*) all of these.

9. Electronics voltmeters which use rectifier employ negative feedback. This is done,
(*a*) To increase the overall gain.
(*b*) To improve stability.
(*c*) To improve nonlinearity of diodes.
(*d*) None of the above.

10. In a digital frequency meter, the Schmitt trigger is used for,
(*a*) Sinusoidal waveforms into rectangular pulses.
(*b*) Scaling of sinusoidal waveforms.
(*c*) Providing time base.
(*d*) None of the above.

ANSWERS

1. (*c*) **2.** (*d*) **3.** (*d*) **4.** (*d*) **5.** (*b*) **6.** (*b*)
7. (*c*) **8.** (*d*) **9.** (*c*) **10.** (*a*)

Chapter 7

Cathode Ray Oscilloscopes

Outline

Objectives

After completing this chapter, you should be able to:

- Know the purpose of oscilloscope
- Describe the construction and operation of CRO and CRT.
- Analyze the electrostatic focus and deflection sensitivity.
- Explain how waveform signal is displayed on CRO screen.
- Describe the function of sweep generator.
- Know how voltage, current, time period, frequency and phase measured with CRO.

- Draw the Lissajous Figures
- Calculate the frequency and phase with Lissajous Figures.
- Know the difference between different types of probes.

7.1 Introduction

A cathode ray oscilloscope or simply CRO or oscilloscope is one of the extremely useful and the most versatile tool used in the sciences, medicine, engineering and telecommunication industry. These are commonly used to observe the exact wave shape of an electrical signal. In addition to the amplitude of the signal, an oscilloscope can show distortion, the time between two events (such as pulse width, period, or rise time) and relative timing of two related signals.

General purpose oscilloscopes are used for maintenance of electronic equipment and laboratory work. Special purpose oscilloscopes may be used for such purposes as analyzing aircraft cockpit instruments, automotive ignition system or to display the waveform of the heartbeat. In electronics engineering/telecommunication industry, the cathode ray oscilloscopes are used extensively for design, build and test of electronic circuits. The engineers and technicians studythe wave shapes of alternating currents and voltages as well as for measurement of voltage, current, power and frequency. The oscilloscope allows the user to observe the amplitude of electrical signals as a function of time on the screen.

Originally all oscilloscopes used cathode ray tubes(CRTs) as their display element and linear amplifiers for signal processing. However, modern oscilloscopes have LCD or LED screens, fast analog-to-digital converters and digital signal processors. Some oscilloscopes use storage CRTs to display single events for a limited time. These days oscilloscope peripheral modules are available for general purpose laptop or desktop personal computers which allows the laptop or desktop computers to be used as test instruments.

Two to three decades ago, the oscilloscopes were quite bulky and were generally bench top devices. But most modern oscilloscopes are lightweight, portable instruments that are compact enough to be easily carried by an engineer or a technician. Special purpose oscilloscopes may be rack mounted or permanently mounted into a custom instrument housing.

Oscilloscope allows us to observe the constantly varying signal, usually as a two-dimensional graph of one or more electrical potential differences using the vertical or '*Y*' axis, plotted as a function of time, (horizontal or '*X*' axis). Although an oscilloscope displays voltage on its vertical axis, any other quantity that can be converted to a voltage can be displayed as well. In most instances, oscilloscopes show events that repeat with either no change or change slowly.

Whatever is the type of an oscilloscope, whether CRT or LCD or LED screen, its front panel normally has control sections divided into Vertical, Horizontal, and Trigger sections. There are also display controls and input connectors.

In this chapter, we shall study the general purpose oscilloscopes. Special purpose oscilloscopes are covered in Chapter 8.

7.2 Cathode-Ray Oscilloscope

As mentioned in the last article, the cathode ray oscilloscope (CRO) is generally referred to as an oscilloscope or simply scope. It is a basic electronic test instrument that allows observations of constantly varying signal voltages usually as a two-dimensional graph of one or more electrical potential differences as shown in Fig. 7.1. It allows an electronic engineer to 'observe' the signal in various parts of the electronic circuit.

By '*observing*' the signal waveforms, the engineers or technicians can correct errors, understand mistakes in the circuit design and thus make suitable adjustments. The circuit symbol of an oscilloscope is shown in Fig. 7.2.

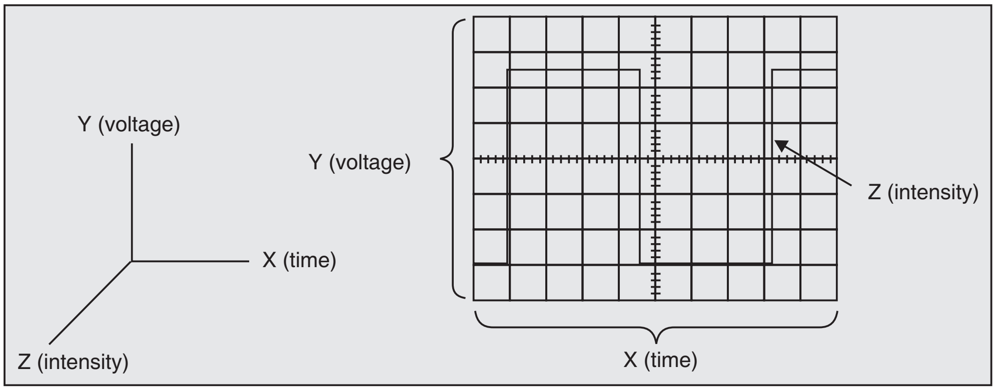


Fig. 7.1.

An oscilloscope can display and measure many electrical quantities like ac/dc voltage, time, phase relationships, frequency and a wide range of waveform characteristics like rise-time, fall-time and overshoot etc. Non-electrical quantities like pressure, strain, temperature and acceleration etc. can also be measured by using different transducers to first convert them into an equivalent voltage.

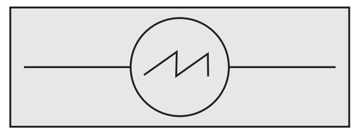


Fig. 7.2. Circuit Symbol for an Oscilloscope

7.3 Block Diagram of CRO

Fig. 7.3 shows the block diagram of a CRO. As seen in the diagram, it consists of the following major sub-systems:

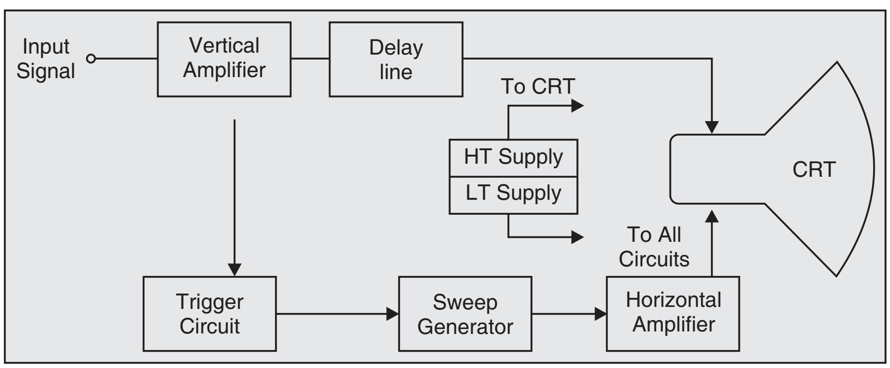


Fig. 7.3. Block Diagram of CRO.

1. **Display.** In all the modern oscilloscopes it is usually LCD panel. In the old oscilloscopes the display was a cathode ray tube or CRT. The display whether LCD panel or CRT is laid out with both horizontal and vertical reference lines referred to as the graticule. In addition to the screen, most display sections are equipped with three basic controls, a focus knob, an intensity knob and a beam finder button.
2. **Cathode Ray Tube (*CRT*).** This is the cathode ray tube which emits electrons that strikes the phosphor screen internally to provide a visual display of signal. It displays the quantity being measured.
3. **Vertical amplifier.** It amplifies the signal waveform to be viewed.
4. **Delay Line.** It is used to delay the signal for some time in the vertical sections.

5. **Horizontal amplifier.** This is used to amplify the sawtooth voltage which is then applied to the *X*-plates.
6. **Sweep generator.** Produces sawtooth voltage waveform used for horizontal deflection of the electron beam.
7. **Trigger circuit.** Produces trigger pulses to start horizontal sweep. It converts the incoming signal into trigger pulses so that the input signal and the sweep frequency can be synchronized.
8. **High and low.** Voltage power supply.

Two voltages are generated in CRO

(***a***) The low voltage supply is from +300 to 400 V.

(***b***) The high voltage supply is from –1000 to –1500 V.

7.4 Operation Control of Oscilloscope

The operating controls of a basic oscilloscope are shown in Fig. 7.4. The different terminals provide.

1. Horizontal Amplifier Input
2. Vertical Amplifier Input
3. Synchronous Input
4. *Z*-Axis Input
5. External Sweep Input.

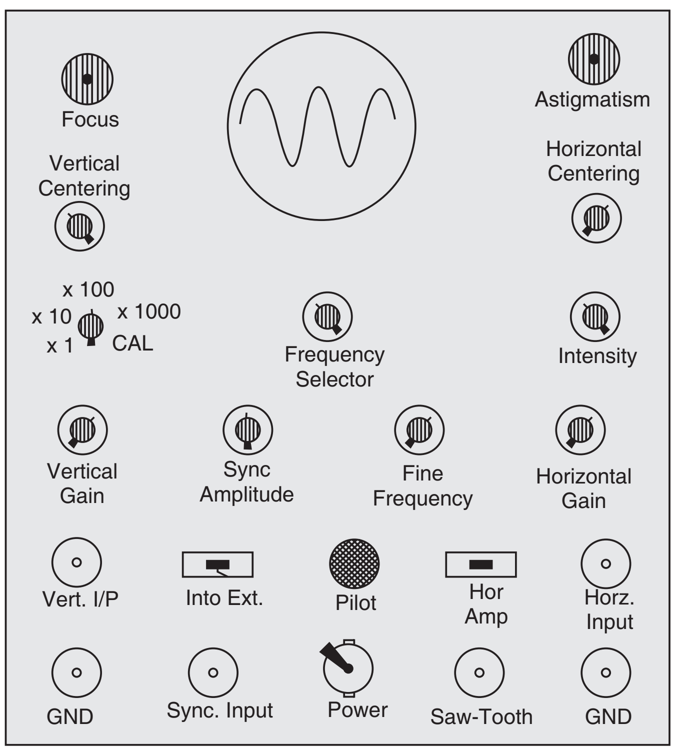


Fig. 7.4.

As seen from this diagram, different controls permit the following adjustment.

1. **Intensity.** For correct brightness of the trace on the screen. This adjusts trace brightness. Slow traces on CRT scopes need less, and fast ones, especially if they don't repeat very

often, require more. On flat panels, however, trace brightness is essentially independent of sweep speed, because the internal signal processing effectively synthesizes the display from the digitized data.

2. **Focus.** For sharp focus of the trace. This control adjusts CRT focus to obtain the sharpest, most-detailed trace. In practice, focus needs to be adjusted slightly when observing quite-different signals, which means that it needs to be an external control. Flat-panel displays do not need a focus control; their sharpness is always optimum.
3. **Horizontal centering.** For moving the pattern right and left on the screen. The horizontal position control moves the display sidewise. It usually sets the left end of the trace at the left edge of the graticule, but it can displace the whole trace when desired. This control also moves the *X*-*Y* mode traces sidewise in some 'scopes, and can compensate for a limited DC component as for vertical position.
4. **Vertical centering.** For moving the pattern up and down on the screen. The vertical position control moves the whole displayed trace up and down. It is used to set the no-input trace exactly on the center line of the graticule, but also permits offsetting vertically by a limited amount. With direct coupling, adjustment of this control can compensate for a limited DC component of an input.
5. **Horizontal gain (also Time/div or Time/cm).** For adjusting pattern width. This section controls the time base or "sweep" of the instrument. The primary control is the Seconds-per-Division (Sec/Div) selector switch. Also included is a horizontal input for plotting dual *X*-*Y* axis signals. The horizontal beam position knob is generally located in this section.
6. **Vertical gain (also volt/div or volt/cm).** For adjusting pattern height. This controls the amplitude of the displayed signal. This section carries a Volts-per-Division (Volts/Div) selector knob, an AC/DC/Ground selector switch and the vertical (primary) input for the instrument. Additionally, this section is typically equipped with the vertical beam position knob.
7. **Sweep frequency.** For selecting number of cycles in the pattern.
8. **Sync. Voltage amplitude.** For locking the pattern. The different switches permit selection of:
   (***a***) sweep type
   (***b***) sweep range
   (***c***) sync. type

A CRO can operate upto 500 MHz, can allow viewing of signals within a time span of a few nanoseconds and can provide a number of waveform displays simultaneously on the screen. It also has the ability to hold the displays for a short or long time (of many hours) so that the original signal may be compared with one coming on later.

7.5 Working of CRO

In the past, CRO consists mainly of a vacuum tube which contains a cathode, anode, grid, *X* & *Y*-plates, and a fluorescent screen. When the cathode is heated (by applying a small potential difference across its terminals), it emits electrons. Having a potential difference between the cathode and the anode (electrodes), accelerate the emitted electrons towards the anode, forming an electron beam, which passes to fall on the screen. When the fast electron beam strikes the fluorescent screen, a bright visible spot is produced. The grid, which is situated between the electrodes, controls the amount of electrons passing through it thereby controlling the intensity of the electron beam. The *X* & *Y*-plates are responsible for deflecting the electron beam horizontally and vertically.

A sweep generator is connected to the *X*-plates, which moves the bright spot horizontally across the screen and repeats that at a certain frequency as the source of the signal. The voltage to be studied is applied to the *Y*-plates. The combined sweep and *Y* voltages produce a graph showing the variation of voltage with time.

7.6 Applications of a CRO

As stated earlier, no other instrument in electronic industry is as versatile as a CRO. In fact, a modern oscilloscope is the most useful single piece of electronic equipment that not only removes guess work from technical troubleshooting but makes it possible to determine the trouble quickly. Some of its uses are as under:

(a) In Radio Work

1. to trace and measure a signal throughout the RF, IF and AF channels of radio and television receivers.
2. it provides the only effective way of adjusting FM receivers, broadband high-frequency RF amplifiers and automatic frequency control circuits;
3. to test AF circuits for different types of distortions and other spurious oscillations;
4. to give visual display of wave shapes such as sine waves, square waves and their many different combinations;
5. to trace transistor curves
6. to visually show the composite synchronized TV signal
7. to display the response of tuned circuits etc.

(b) Scientific and Engineering Applications

1. measurement of ac/dc voltages,
2. finding B/H curves for hysteresis loop,
3. for engine pressure analysis,
4. for study of stress, strain, torque, acceleration etc.,
5. frequency and phase determination by using Lissajous Figures,
6. radiation patterns of antenna,
7. amplifier gain,
8. modulation percentage,
9. complex waveform as a short-cut for Fourier analysis,
10. Standing waves in transmission lines etc.

7.7 Cathode Ray Tube (CRT)

It is the 'heart' of an oscilloscope and is very similar to the picture tube in a television set.

Construction

The cross-sectional view of a general-purpose electrostatic deflection CRT is shown in Fig. 7.5. Its four major components are:

1. an electron gun for producing a stream of electrons,
2. focusing and accelerating anodes-for producing a narrow and sharply-focused beam of electrons,
3. horizontal and vertical deflecting plates-for controlling the path of the beam,
4. an evacuated glass envelope with a phosphorescent screen which produces bright spot

As shown, a CRT is a self-contained unit like any electron tube with a base through which leads are brought out for different pins.

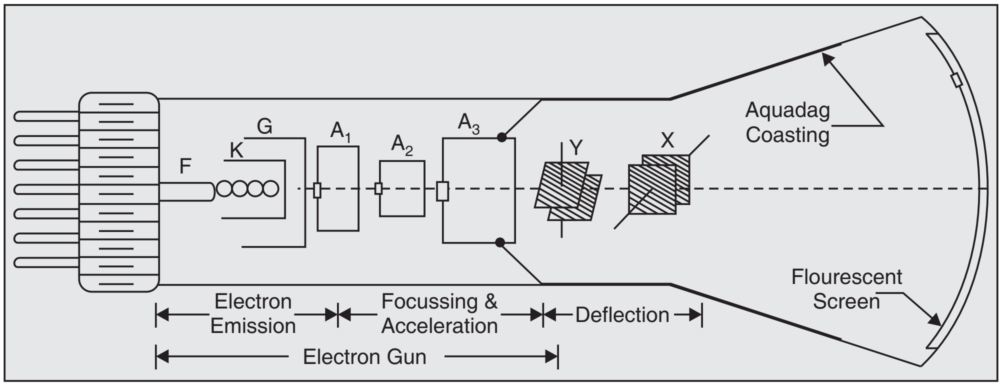


Fig. 7.5. Cathode Ray Tube

1. Electron Gun Assembly

The electron gun assembly shown in Fig. 7.6. It consists of an indirectly-heated cathode K, a control grid G, a pre-accelerator anode A_1, focusing anode A_2 and an accelerating anode A_3. We will discuss each part of electron gun one by one in following:

(*a*) Cathode *K*. The sole function of the electrons gun assembly is to provide a focused beam of electrons which is accelerated towards the fluorescent screen. The electrons are given off by thermionic emission from the cathode. The electron gun assembly consists of an indirectly-heated cathode K. A heated cathode emits electrons, which are accelerated to the first accelerating anode through a small hole in the control grid.

(*b*) Control Grid. The control grid is a metallic cylinder with a small aperture in line with the cathode and kept at a negative potential with respect to K. The number of electrons allowed to pass through the grid aperture (and, hence, the beam current) depends on the amount of the control grid bias. Since the intensity (or brightness) of the spot S on the screen depends on the strength of beam current, the knob controlling the grid bias is called the ***intensity control***.

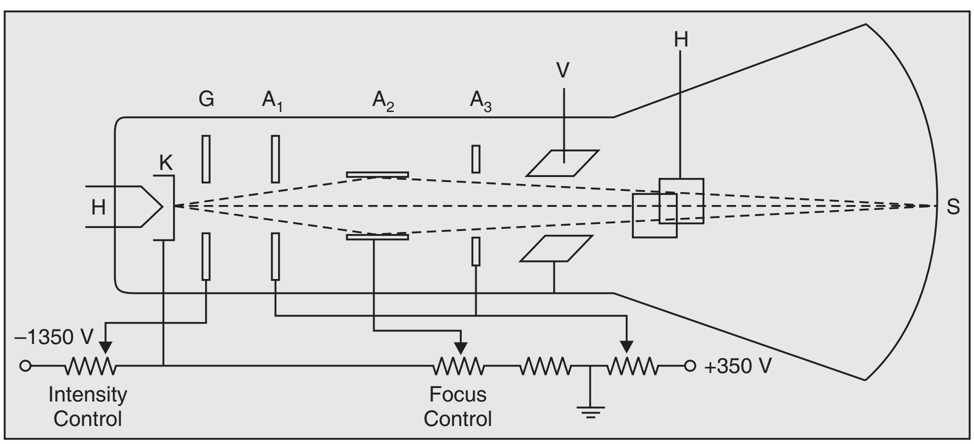


Fig. 7.6.

(*c*) Accelerating Anode. The anodes A_1 and A_3 are the accelerating anode. The Anode A_1 is the pre-accelerating anode. The pre-accelerating anode is a hollow cylinder that is at a potential a few hundred volts more positive than the cathode so that the electron beam will be accelerated in the electric field. Both the anode is at positive potential with respect to K. These anodes operate to accelerate the electron beam.

(***d***) **Focusing Anode.** The focusing anode ensures that electrons leaving the cathode in slightly different directions are focused down to a narrow beam and all arrive at the same spot on the screen. The cylindrical focusing anode A_2, being at negative potential, repels electrons from all sides and compresses them into a fine beam. The knob controlling the potential of A_2 provides the focus control.

2. Deflecting Plates

Two sets of deflecting plates are used for deflecting the thin pencil-like electronic beam both in the vertical and horizontal directions. Deflecting plates are:

(***a***) **Vertical Deflection Plates:** These plates move the electron beam up and down the screen. The input signal is applied to these plates.

(***b***) **Horizontal Deflection Plates:** These plates move the electron bean by electrostatic attraction and repulsion, horizontally across the CRT screen.

The first set marked *Y* (nearer to the gun) is for vertical deflection and *X*-set is for horizontal deflection. When no potential is applied across the plates, beam passes between both sets of plates undeflected and produces a bright spot at the centre of the screen.

If upper *Y*-plate is given a positive potential, the beam is deflected upwards depending on the value of the applied potential. Similarly, the beam (and hence the spot) deflects downwards when lower *Y*-plate is made positive. However, if an ***alternating*** voltage is applied across the *Y*-plates, the spot keeps moving up and down thereby producing a vertical luminous trace on the screen due to persistence of vision. The maximum displacement of the spot from its central position is equal to the amplitude of the applied voltage.

The screen spot is deflected horizontally if similar voltages are applied to the *X*-plates. The dc potentials on the *Y*-and *X*-plates are adjustable by means of ***centering controls***.

It must be remembered that the signal to be displayed on the screen is always applied across the *Y*-plates. The voltage applied across *X*-plates is a ramp voltage i.e. a voltage which increases linearly with time. It has a sawtooth wave-form as shown in Fig. 7.7. It is also called horizontal time-base or sweep voltage. It has a sweep time of T_{sw}.

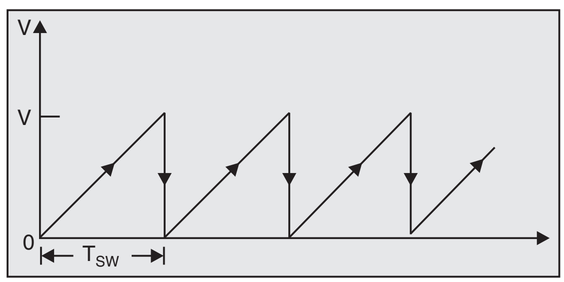


Fig. 7.7

3. Glass Envelope

It is funnel-shaped having a phosphor-coated screen at its flared end. It is highly-evacuated in order to permit the electron beam to traverse the tube easily. The inside of the flared part of the tube is coated with a conducting graphite layer called Aquadag which is maintained at the same potential as A_3. The bombarding electrons striking the phosphor release secondary-emission electrons, thus keeping the screen in a state of electrical equilibrium. These secondary-emission low velocity electrons are collected by aquadag, which is electrically connected to the secondary anode.

Functions of Aquadag are:

(***i***) It accelerates the electron beam after it passes between the deflecting plates

(***ii***) Collects the electrons produces by secondary emission when electron beam strikes the screen.

Hence, it prevents the formation of negative charge on the screen.

4. Graticules

The graticule is a grid of squares that serve as reference marks for measuring the displayed trace. It is the calibrated horizontal and vertical marks are placed on the cathode ray tube screen to facilitate the use of the oscilloscope. It is a grid of lines that serves as a scale when making time and amplitude measurements. The accuracy of these marks depends on how close the graticule marks can be placed to the actual phosphor to eliminate parallax. These are three types:

(*a*) **External Graticule.** This is scribed on a Plexiglas plastic and fixed to the screen. The distance between the marks on the graticule and the actual phosphor coating could be nearly 1 cm, which caused measurement errors if not used carefully.

(*b*) **Internal Graticule.** The graticule lines are etched (marked) on the inner surface of the front glass of the cathode ray tube. The distance of separation of phosphor and the graticule is nearly zero and parallax errors are practically nonexistent.

(*c*) **Projected Graticule.** It provides flexibility which can include additional features such as legends on the glass.

7.8 Screens for CRTs

When the electron beam strikes the screen of the CRT, a spot of light is produced. The screen material on the inner surface of the CRT that produces this effect is the phosphor. The phosphor absorbs the kinetic energy of the bombarding electrons and reemits energy at a lower frequency in the visual spectrum. The property of some crystalline materials, such as phosphor or zinc oxide, to emit light when stimulated by radiation is called fluorescence. Fluorescent materials have second characteristic, called phosphorescence, which refers to the property of the material to continue light emission even after the source of excitation is cut off.

The screen itself is coated with a thin layer of a fluorescent material called phosphor. This material determines the color and persistence of the trace, both of which are indicated by the phosphor. When struck by high-energy electrons, it glows. In other words, it absorbs the kinetic energy of the electrons and converts it into light-the process being known as ***fluorescence***. That is why the screen is called ***fluorescent screen***.

The color of the emitted light depends on the type of phosphor used. The trace of colors in electrostatic CRTs for oscilloscopes is blue, green and blue green. Persistence is expressed as short, medium and long. This refers to the length of time the trace remains in the screen after the signal has ended. The phosphor of the oscilloscope is designated as follows:

$$P_1 = \text{Green medium}$$
$$P_2 = \text{Blue green medium}$$
$$P_5 = \text{Blue very short}$$
$$P_{11} = \text{Blue short}$$

These designations are combined in the type number. Like 5GP1 is a 5 inch tube with a medium persistence green trace.

7.9 Electrostatic Focusing

In a cathode ray tube number of electrons is projected by the gun in the form of electron beam towards the screen. But due to variation of energy the electrons diverge and cannot produce spot on the screen. So we use electrostatic focusing method for projection of electron beam.

In electrostatic focusing two parallel deflecting plates are used. These are spaced at a distance d from each other. The plates are at potential difference V_d due to this potential difference electric field E exist between the two plates. The electrons from the cathode are accelerated towards the anode by the potential V_d as shown in Fig. 7.8.

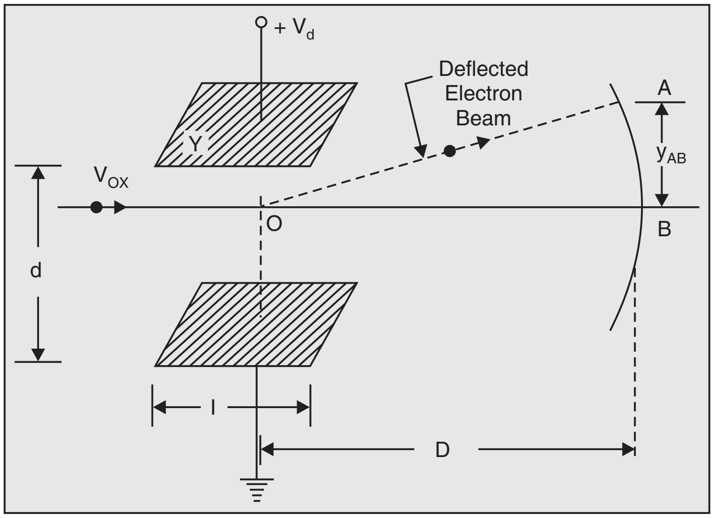


Fig. 7.8

where m = mass of electron

e = Charge on electron

v_{ox} = Velocity of electron coming out of electron gun

V_a = Accelerating voltage

d = distance between Y plates

l = length of each Y plates

D = distance from point O to screen

V_d = Deflecting voltage

Y_{AB} = Deflection on the screen

The loss of potential energy ($P.E$) when electron moves from cathode to accelerating anode

$$P.E = eV_a$$

The kinetic energy

$$K.E = \frac{1}{2}\, m\, v_{ox}^2$$

where the mass of electron is $m = 9.109 \times 10^{-31}$ kg

Equating the kinetic and potential energy,

$$eV_a = \frac{1}{2}\, m\, v_{ox}^2$$

The above equation gives the velocity of electron in the X direction when it enters the deflecting plates.

The electric field in the Y direction,

$$E_y = \frac{V_d}{d}$$

Force on the electron in Y direction,

$$F_y = eE_y = \frac{eV_d}{d}$$

Acceleration of electron,

$$F_y = ma_y$$

$$a_y = \frac{F_y}{m} = \frac{eE_y}{m}$$

As there is no initial velocity in the Y direction the displacement y at any instant t in the Y direction is,

$$y = \frac{1}{2} a_y t^2 = \frac{1}{2} \frac{eE_y}{m} t^2 \qquad \ldots(i)$$

The velocity in X direction

$$x = v_{ox} t$$

$$t = \frac{x}{v_{ox}}$$

Substituting the value of t in equation (i),

$$y = \frac{1}{2} \frac{eE_y}{m} \left(\frac{x}{v_{ox}} \right)^2 = \frac{1}{2} \frac{eE_y}{m (v_{ox})^2} x^2$$

The above equation is an equation of a parabola. The slope at any point (x, y) is given by,

$$\frac{dy}{dx} = \frac{dy}{dx} \left[\frac{1}{2} \frac{eE_y}{m (v_{ox})^2} x^2 \right] = \frac{eE_y}{m (v_{ox})^2} x \qquad \ldots(ii)$$

From the Fig 7.8,

$$\tan \theta = \left. \frac{dy}{dx} \right|_{x = l} \qquad \ldots(iii)$$

Substituting the value of dy/dx from equation (ii) to equation (iii) we get,

$$\tan \theta = \frac{eE_y}{m (v_{ox})^2} l = \frac{eV_d}{md (v_{ox})^2} l \qquad \ldots(iv)$$

$$\because \qquad E_y = \frac{V_d}{d}$$

After leaving the deflection plates the electrons travel in a straight line. The straight line of travel of electrons is tangent to the parabola at x = l and the tangent intersects the X axis at point O. The location of the point is given by

$$x = \frac{y}{\tan \theta} = \frac{\frac{1}{2} \frac{eE_y}{m (v_{ox})^2} l^2}{\frac{eE_y}{m (v_{ox})^2} l} \frac{l}{2} \qquad \ldots(v)$$

The deflection y_{AB} on the screen is given by,

$$y_{AB} = D \tan \theta$$

Substituting the value of tan θ from equation (iv) we get,

$$y_{AB} = D \frac{eV_d}{md (v_{ox})^2} l \qquad \ldots(vi)$$

Substituting the value of $v_{ox} = \sqrt{\frac{2 eV_a}{m}}$ in equation (vi) we get,

$$y_{AB} = D \frac{eV_d}{md} l \cdot \frac{m}{2 eV_a} = \frac{DV_d l}{2 dV_a} \qquad \ldots(vii)$$

Equation (*vii*) shows that the vertical deflection Y_{AB} is proportional to the deflection voltage V_d. This direct proportionality indicates that CRT may be used as a linear voltage-indicating device.

Deflection Sensitivity

Fig. 7.8 shows the upward deflection of an electron beam when it passes between the vertical or *Y*-plates of a CRT. The beam deflects upwards because the upper *Y*-plate has been made positive with respect to the lower plate. Reversing the polarity of the applied voltage would, obviously, cause the beam to deflect downwards.

The vertical deflection of the beam from equation (*v*) is

$$y = \frac{DV_d\, l}{2\, dV_a}$$

where V_A is the accelerating voltage applied to the electrons which make up the electron beam.

The deflection sensitivity of a CRT is definition as the vertical deflection of the beam on the screen per unit deflecting voltage.

$$S = \frac{y}{V_d}$$

Using the above equation, we get

$$S = \frac{lD}{2\, dV_a}$$

The deflection factor which is defined as the reciprocal of deflection sensitivity is given by $G = 1/S$.

Substituting the value of *S* from above

$$G = 2 \,.\, \frac{d}{l} \,.\, \frac{V_a}{D} \text{ Volt/metre}$$

The sensitivity can be increased by decreasing the value of accelerating voltage, V_a.

7.10 Electromagnetic Focusing

The electromagnetic method of focusing depends on the theory that when an electron enters a constant magnetic fields perpendicular to its path, it is deflected and moves in a circular path. The magnetic field produced is parallel to the axis of the circle. The electrons moving to the axis are not affected by the magnetic field, while electrons having a component of velocity away from the axis move in a spiral path which finally brings them back to the axis. The axis of the electromagnetic coil coincides with the electron beam axis.

Fig. 7.9 shows the magnetic focusing. The electromagnetic coil surrounds the tube such that the lines of magnetic field are uniformly distributed and are parallel to the axis of tube. The electrons moving parallel to the tube axis are not affected by the magnetic field. While the electrons moving at an angle to the axis experience a force. The direction of the force is perpendicular both to the direction of motion of the electron and to the magnetic field. Thus, two forces act on the electron, one that attractive force of the anode causing it to move forward and another due to magnetic field causing the side motion. Thus the electron moves in a spiral path which finally returns to the axis of the tube.

Let us consider an electron having an initial velocity of 'v' m/s along the tube axis *OA* at point *O* and assume that there is a uniform magnetic field of flux density *B* in Wb/m^2 covering an axis distance l as shown in Fig. 7.10.

Then the force acting on the electron entering the field is $e.B.v$ in a direction perpendicular to the path which is an arc of radius *R* given by,

$$R = \frac{mv}{eB}$$

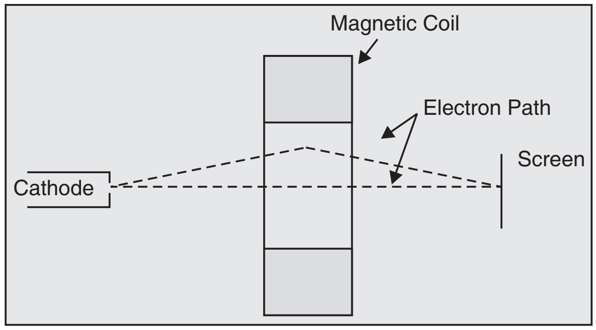


Fig. 7.9. Magnetic Focusing

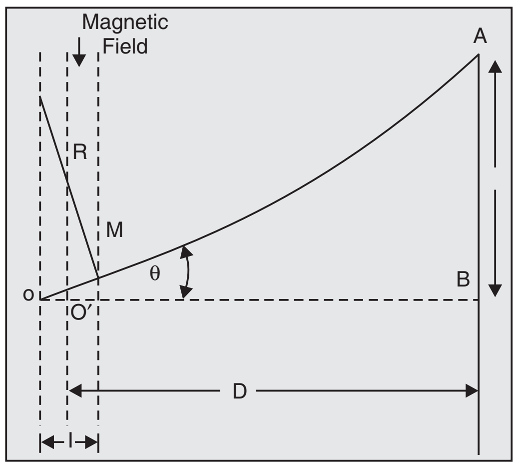


Fig. 7.10.

The electron emerges from the field and moves in a direction inclined at an angle θ to the axis and strikes the screen at *A*. If the total angular deflection θ is very small, then

$$\text{Arc OM} = l$$

and angular deflection,

$$\theta = \frac{l}{R} = \frac{leB}{mv}$$

In most practical cases *L* is very much larger than *l* so that little error will be caused in assuming that straight line *MA*', if projected backward, will pass through the centre *O*' of the region of the magnitude field. Then

$$d \approx D \tan \theta \approx L\,\theta$$

Substituting value of θ we get,

$$d = D\,\frac{leB}{mv}$$

Now substituting the value of $v = \sqrt{\frac{2\,eV_a}{m}}$ in the above equation

$$d = D\,lB\,\sqrt{\frac{e}{2\,mV_a}}$$

This expression is again approximate as it neglects the variations of field at the edges.

The magnetic field deflection sensitivity S is define as the deflection (in meter) on the screen caused by unit magnetic flux density, is given by

$$S = \frac{d}{B} = Dl\sqrt{\frac{e}{2\,mV_a}}$$

Alternatively, the sensitivity S is defined as the deflection, in mm, on the screen when 1 mA current flows through the deflection coil. This is expressed in mm/mA.

Example 7.1. *In a CRT, the distance between the plates is 1 cm, the length of the deflecting plates is 4.5 cm and the distance of the screen from the centre of the plates is 33 cm. If the accelerating voltage is 300 V and deflecting voltage is 50 V, find*

(i) *Velocity of electron reaching the field*
(ii) *Deflection produced on the screen*
(iii) *Deflection sensitivity*

Solution. Given: d = 1 cm = 1 × 10^{-2} m, l = 4.5 cm = 4.5 × 10^{-2} m, D = 33 cm = 33 × 10^{-2} m, v_a = 300 V and V_d = 50 V.

(*i*) *Velocity of electron reaching the field*

We know that the velocity of electron,

$$v_{ox} = \sqrt{\frac{2\,eV_a}{m}}$$

$$= \sqrt{\frac{2\times 1.6\times 10^{-19}\times 300}{9.107\times 10^{-31}}} = 1.0267 \times 10^{7} \text{ m/s } \textbf{Ans.}$$

(*ii*) *Deflection produced on the screen*

We know that the deflection,

$$y_{AB} = \frac{DV_d\,l}{2\,dV_a}$$

$$= \frac{4.5\times 10^{-2}\times 50\times 33\times 10^{-2}}{2\times 1\times 10^{-2}\times 300} = 0.1237 \text{ m } \textbf{Ans.}$$

(*iii*) *Deflection sensitivity*

We know that the sensitivity,

$$S = \frac{y}{V_d} = \frac{0.1237}{50} = 2.474 \times 10^{-3} \text{ m/V } \textbf{Ans.}$$

Example 7.2. *In a cathode ray tube having electric deflection system, the deflecting plates are 2 cm long and have a uniform spacing of 4 mm between them. The fluorescent screen is 25 cm away from the center of the deflection plates. Calculate the deflection sensitivity, if the potential of the final anode is.*

(i) *1000 V*
(ii) *2000 V*
(iii) *3500 V*

Solution. Given: l = 2 cm = 2 × 10^{-2} m, d = 4 cm = 4 × 10^{-2} m, D = 25 cm = 25 × 10^{-2} m and v_a = 1000 V.

We know that the sensitivity is given by,

$$S = \frac{y}{V_d} = \frac{l\,D}{2\,dV_a}$$

(*i*) V_a = 1000 V

$$S = \frac{2\times10^{-2}\times25\times10^{-2}}{2\times4\times10^{-3}\times1000} = 6.25 \times 10^{-4} \text{ m/V } \textbf{Ans.}$$

(*ii*) V_a = 1000 V

$$S = \frac{2\times10^{-2}\times25\times10^{-2}}{2\times4\times10^{-3}\times2000} = 3.125 \times 10^{-4} \text{ m/V } \textbf{Ans.}$$

(*iii*) V_a = 1000 V

$$S = \frac{2\times10^{-2}\times25\times10^{-2}}{2\times4\times10^{-3}\times3500} = 1.7857 \times 10^{-4} \text{ m/V } \textbf{Ans.}$$

Example 7.3. *An electrostatically deflected CRT has plane parallel deflecting plates which are 2.5 cm long and 0.5 cm apart. The distance of the screen from the centre of the plates is 20 cm. The accelerating voltage is 2500 V. Calculate the deflecting voltage required to get the corresponding deflection of 4 cm on the screen, and the velocity of the electron beam entering the field.*

Solution. Given: y = 4 cm = 4×10^{-2} m, D = 2.5 cm = 2.5×10^{-2} m, l = 20 cm = 20×10^{-2} m, d = 0.5 cm = 0.5×10^{-2} m and v_a = 2500 V.

We know that the deflecting voltage is,

$$y = \frac{DV_d\, l}{2\,dV_a}$$

$$4 \times 10^{-2} = \frac{2.5\times10^{-2}\times V_d\times20\times10^{-2}}{2\times0.5\times10^{-2}\times2500}$$

$$V_d = 200 \text{ V } \textbf{Ans.}$$

We also know that velocity of the electron beam,

$$v_{ox} = \sqrt{\frac{2eV_a}{m}}$$

$$= \sqrt{\frac{2\times1.6\times10^{-19}\times2500}{9.107\times10^{-31}}} = 2.9638 \times 10^{7} \text{ m/s } \textbf{Ans.}$$

7.11 Effect of Beam Transit and Frequency

The plate voltage V_d is constant during the motion of the electrons through the deflection field. If the voltage applied to the vertical deflecting plates changes during the transit time of the electrons through the horizontal plates, the deflection sensitivity gets decreased

$$\text{Transit time, } t_1 = \frac{l}{v_{ox}}$$

The transit time impose a limitation of the upper frequency limit. An upper limiting frequency is defined as that frequency at which the transit time is equal to one quarter of the period of the voltage applied to vertical plates.

$$\text{Upper limiting frequency, } f_c = \frac{1}{4t_1} = \frac{v_{ox}}{4l}$$

The frequency range of the oscilloscope can be increased by subdividing the deflecting plates in a number of sections in the path of the electron beam.

7.12 Normal Operation of CRO

The signal to be viewed or displayed on the screen is applied across the *Y*-plates of a CRT. But to see its waveform or pattern, it is essential to spread it out horizontally from left to right. It is achieved by applying a sawtooth voltage wave (produced by a time base generator) to *X*-plates. Under these conditions, the electron beam would move uniformly from left to right thereby graphic vertical variations of the input signal versus time. Due to repetitive tracing of the viewed waveform, we get a continuous display because of persistence of vision. However, for getting a stable stationary display on the screen, it is essential to synchronize the horizontal sweeping of the beam (sync) with the input signal across *Y*-plates. The signal will be properly synced only when its frequency equals the sweep-generator frequency.

In general, for proper synchronization of time-base with the signal, the condition is

$$T_{sw} = n\ T_s$$

where T_s the time-period of the signal and n is an integer.

If $n = 1$, then $T_{sw} = T_s$ i.e. time-periods of the sweep voltage and input signal voltage are equal, then one cycle of the signal would be displayed as shown in Fig. 7.11(*a*).

On the other hand, if T_{sw} is twice T_s, then two cycles of the signal voltage would be displayed as shown in Fig. 7.11(*b*) obviously, three full cycles of the input voltage would be spread out on the screen when $T_{sw} = 3T_s$.

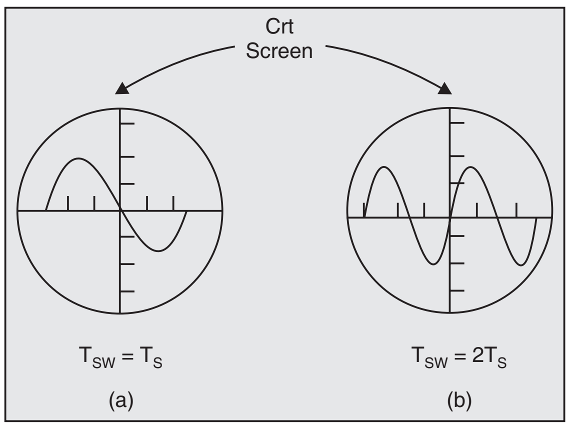


Fig. 7.11.

Internal Synchronization

The periodic sawtooth voltage which is applied to *X*-plates for horizontal sweep (or scan) of the beam across the screen is usually provided by the unijunction relaxation oscillator. When the sawtooth voltage falls abruptly to zero, the beam experiences no horizontal deflection and hence flies back almost instantly to the original (central) position.

The usual method of synchronizing the input signal is to use a portion of the input signal to trigger the sweep generator so that the frequency of the sweep signal is locked or synchronized to the input signal. It is called internal sync. because the synchronization is obtained by internal wiring connection as shown in the block the diagram of Fig. 7.12.

7.13 Oscilloscope Amplifiers

The voltage applied to the inputs of an oscilloscope is very small to cause any noticeable deflection of the electron beam in the screen. Therefore before applying any voltage direct to the plates, the input voltages are first feed to the amplifier which increases their magnitude.

The amount of amplification which each amplifier provides is selected by the sensitivity controls of the oscilloscope. To make the oscilloscope versatile, the sensitivity control is designed to be a wide range of discrete amplification levels. These levels are calibrated to produce the level of amplification specified by the control setting. Oscilloscope amplifiers are of following two types:

1. Vertical Amplifier
2. Horizontal Amplifier

We will discuss each amplifier one by one in the following pages.

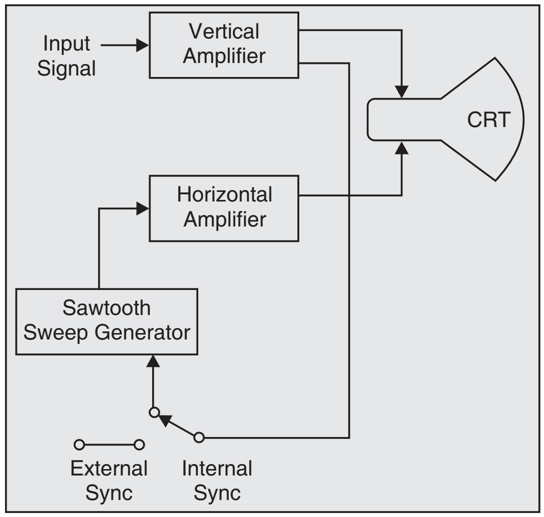


Fig. 7.12.

7.14 Vertical Amplifier

The vertical amplifier is the principle factor in determining the sensitivity and bandwidth of an oscilloscope. The block diagram of vertical deflection is shown in Fig. 7.13. The input signal is not so strong to provide the measurable deflection on the screen. Vertical amplifier stage is used to amplify the input signals.

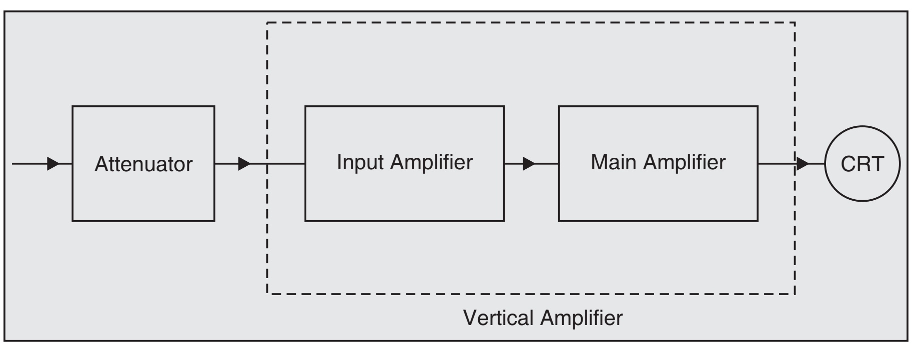


Fig. 7.13. Vertical Deflection

The input signal is feeds an input attenuator. After which follows the vertical amplifier. The amplifier stages used are generally wide band amplifiers so as to pass faithfully the entire band of frequencies to be measured. The amplifier can be designed for stability.

7.15 Attenuators

An **attenuator** is an electronic device that reduces the amplitude or power of a signal without distorting its waveform.

The voltage at the input terminal of the vertical amplifier is quite low in amplitude so it deflected off the CRT screen. So high input signals may be applied. An attenuator network is placed between the vertical input terminal and the input terminal of the vertical amplifier.

The purpose of the attenuator is to reduce the amplitude of the vertical input signal before applying it to the vertical amplifier. An attenuator is a simple resistive voltage divider connected to an amplifier with a 10 pF input capacitance. If the impedance of the amplifier is high, the input impedance of the attenuator is relativity constant, immaterial of the switch setting of the attenuator.

The input impedance, as seen by the amplifier, changes greatly depending on the setting of the attenuator. Because of this, the RC time constant and frequency of the amplifier are dependent on the setting of the attenuator. There are two types of attenuators, uncompensated and compensated attenuators. Each attenuators are discuss as following:

1. Uncompensated Attenuators

Fig. 7.14. shows the circuit diagram of an uncompensated attenuator. The resistive divider circuit is connected to an amplifier. The equivalent input capacitance is 10 pF. It the input impedance of the amplifier is high, the input impedance to the attenuator is relatively constant irrespective of the switch setting of the attenuator. The input impedance, as seen by the amplifier, changes largely depending on the attenuator setting. This makes the RC time constant and the frequency response of the amplifier dependent on the setting of the attenuator, which is highly undesirable.

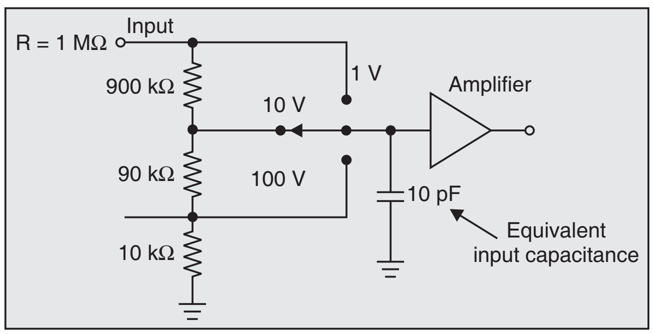


Fig. 7.14.

2. Compensated Attenuators

Compensated attenuator is used in the oscillator having frequency range more than 100 MHz. It used both resistive and capacitive voltage dividers. High frequency response is improves by capacitive voltage divider. RC compensated attenuator is required to attenuate all frequencies equally. For oscilloscope where the frequency ranges extend to 100 MHz and beyond, more complex input dividers are required. A compensated attenuator is shown in Fig. 7.15.

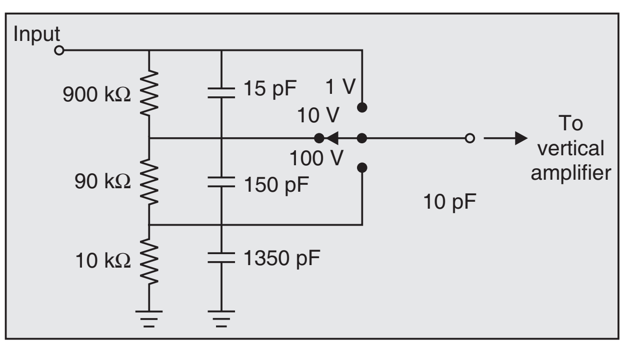


Fig. 7.15. Attenuator

7.16 Horizontal Deflection Amplifier

The oscilloscopes deflect the horizontal portion of the trace at a constant rate relative to time. This is referred to as linear sweep. The horizontal deflection system consists of

1. **Trigger Circuit.** The trigger circuit insures that the horizontal sweep starts at the same point of the vertical input signal.
2. **Sweep Generator or Time Base Generator.** The detail of the sweep generator is discuss in next article
3. **Horizontal Amplifier**

The function of the horizontal amplifier is given below:

1. The function of the horizontal amplifier is to amplify the signal applied to the *X*-plates.
2. When the oscilloscope is being used in the ordinary mode of operation to display a signal applied to the vertical input, the horizontal amplifier will amplify the sweep generator input.
3. When the oscilloscope is being used in the *X-Y* mode, the signal applied to the horizontal input terminal will be amplified by the horizontal amplifier.

7.17 Sweep Generator

In such circuits, either the output voltage (or the output current) is a linear function of time, over a specified time interval. This circuit is also known as ***time base circuits*** or ***time base generators***. These circuits are extremely important in most of the electronic systems. A linear time base voltage is required on the deflection plates of cathode ray oscilloscope, to sweep the electron beam, from left to right across the screen. Similarly, a linear time base current waveform is required in the deflection coils of a television receiver. Because of the sweep application, the circuits are also sometimes known as ***sweep circuits*** (or sweep generators).

Fig. 7.16 (*a*) shows a typical time base signal. Here the voltage starts from some initial value as indicated by point *A* in the Figure. Then it increases linearly with time to a maximum value indicated by point *B* in the Figure. After this, the voltage returns back to its initial value as indicated by point *C* in the Figure.

The time, required by the voltage from its initial value to reach its maximum value, is known as sweep time and is designated by the symbol T_s. Similarly,the time taken by the voltage to its initial value is called a restoration time and is designated by the symbol T_r. The restoration time is also known as return time or the flyback time.

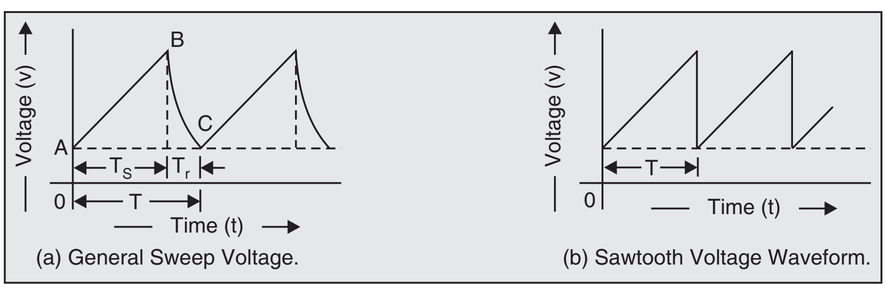


Fig. 7.16. Sweep Waveforms.

In most of the applications, the shape of the waveform during the restoration time, as well as the restoration time itself, is of no importance. However, in certain applications, it is desired that the restoration time is very short in comparison with the time occupied by the linear portion of the waveform (*i.e.,* $T_r << T_s$). In that case, the restoration time is extremely short and a new voltage is initiated at the instance the previous one is terminated. The waveform, in such a case, is as shown in Fig. 7.16 (*b*) and is known as sawtooth waveform. It is customary to refer to waveforms shown in Fig. 7.16 (*a*) and (*b*) as sweep waveforms even in applications not involving the deflection of an electron beam.

It will be interesting to know that the circuits, which generate time base signals, do not ordinarily provide sweep voltages that are precisely linear. A most useful way of expressing the deviation from linearity is the slope error or sweep-speed error which is given by the relation,

$$e_S = \frac{\text{Difference in slope at the beginning and end of sweep}}{\text{Initial value of slope}}$$

There is one another term called 'sweep speed', which is used to compare the performance of different sweep generating circuits. In all these circuits, a capacitor is an essential element. The charging and discharging of a capacitor generates a sweep voltage. Suppose a capacitor (C) is charged by a constant current (I). Then the voltage across the capacitor at any time (v_C) is given by the relation,

$$v_C = \left(\frac{I}{C}\right) t$$

The rate of change of capacitor voltage with time is known as sweep speed. Thus

$$\text{Sweep speed} = \frac{dv_C}{dt} = \frac{d}{dt}\left(\frac{I}{C}\right) t = \frac{I}{C}$$

The sweep speed is required to be constant in most of the applications.

7.18 Types of Time Base Circuits

A time-base circuit is a circuit which generates a saw-tooth waveform. It causes the spot to move in the horizontal and vertical direction linearly with time. When the vertical motion of the spot produced by the Y-plates due to alternating voltage, is superimposed over the horizontal sweep produced by X-plates, the actual waveform is trace on the screen. Following two types of time base circuits are important from the subject point of view:

1. *Free running time base generator.* A circuit, in which the periodic sawtooth waveform is generated, without the application of any signal, is called a free running time base generator. Such a circuit is required to display a periodic waveform. It may be noted that in a free running time base generator, the sweep time (T_s) must be larger than the period of the waveform to be displayed.

2. *Triggered time base generator.* A circuit, in which the linear waveform with a prescribed duration of time is generated by the application of a trigger signal, is called a triggered time base generator. Such a circuit is required to display widely separated narrow-width pulser or a waveform which may not be periodic but may occur at irregular intervals.

The operation of the circuit may be understood from the condition, that the switch (S) is initially assumed to be closed. At this instant, the capacitor voltage and hence the output voltage (v_O) is zero, when the switch (S) is opened, the capacitor voltage starts towards the supply voltage (V) in accordance with the equation,

$$V_S = V\,(1 - e^{-t/RC}) \qquad ...(i)$$

However, the capacitor is never allowed to charge to a voltage equal to the supply voltage. It is because of the fact that after a time interval (T_S), when the sweep voltage has attained the value (V_S), the switch (S), again closes. The resulting sweep voltage waveform is as shown in Fig. 7.17 (b). The sweep-speed error for the exponential sweep circuit is given by the relation,

$$e_S = \frac{V_S}{V}$$

It is evident from the above relation that smaller the value of sweep voltage (V_S), lower will be the value of sweep-speed error and hence higher is the value of linearity. Due to this reason, the exponential charging sweep circuit is used only in those applications, which require lower sweep voltages (usually of the order of volts or tens of volts). If $t/RC << 1$, then we can expand equation (i) as follows:

$$v_S = \frac{V \cdot t}{R \cdot C}\left(1 - \frac{t}{2\,RC} + \frac{t^2}{6\,R^2C^2} \ldots\right)$$

$$= \frac{V \cdot t}{R \cdot C} \qquad \text{...(Retain first term and neglect others)}$$

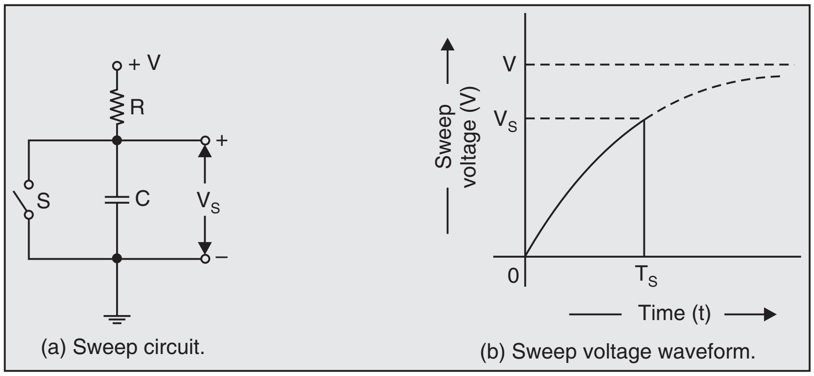


Fig. 7.17.

Since $v_S = V_S$ when $t = T_S$, therefore

$$V_S = \frac{V \cdot T_S}{R \cdot C}$$

or

$$\frac{V_S}{V} = \frac{T_S}{R \cdot C}$$

sweep-speed error,

$$e_S = \frac{V_S}{V} = \frac{T_S}{R \cdot C} = \frac{T_S}{\tau}$$

where τ is the time constant and is equal to $(R \cdot C)$. It is obvious from this relation that for good linearity (*i.e.,* smaller sweep-speed error), the time constant (τ) must be very large as compared to sweep duration (T_S).

7.19 Sweep Circuit

Fig. 7.18 (*a*) shows the basic circuit of a transistor switch sweep circuit. This circuit requires a gating waveform (*vi*) as shown in Fig. 7.18 (*b*). It may be obtained from a monostable multivibrator (*i.e.,* one shot) or an astable multivibrator. If the 'gating' waveform is obtained from a monostable multivibrator, the sweep generated by the circuit is called *triggered sweep* and the circuit is known as *triggered voltage time base generator*. However, if the 'gating' waveform is obtained from an astable multivibrator, the sweep generated is called ***free running sweep*** and the circuit is known as ***free running voltage time base generator***.

Initially, the transistor is biased ON and operates in the saturation region. Thus when there is no input (*i.e.,* $v_i = 0$), the output voltage is zero. (Actually its value is equal to $V_{CE\,(sat)}$). When the 'gating' pulse (*i.e.,* a negative pulse) is applied, the transistor turns OFF. As a result of this, the capacitor voltage rises to a target value V_{CC} with a time constant $R_C \cdot C$. The charging curve ignoring $V_{CE\,(sat)}$ is governed by relation,

$$v_o = V_{CC}\left(1 - e^{-\frac{t}{CR_C}}\right)$$

If $t/R_C \cdot C << 1$, the above equation may be expanded into a power series in $t/R_C \cdot C$. Then retaining only the first term of the power series, the output voltage,

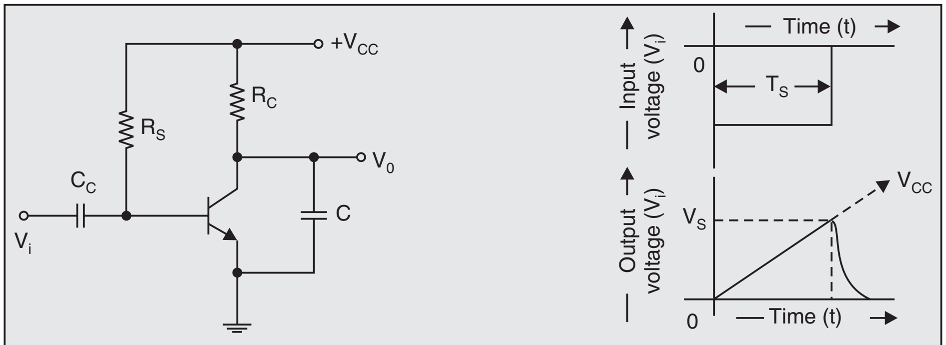
$$v_o(t) = V_{CC}\ \frac{t}{R_C \,.\, C} \qquad ...(i)$$

At $t = T_s$, the output voltage,

$$v_o\,(T_S) = V_{CC} \cdot \frac{T_S}{R_C \,.\, C} = V_S \qquad ...(ii)$$

The equation (*i*) represents an approximately linear waveform. The slope error or sweep-speed error or such a waveform is given by the relation,

$$e_S = \frac{V_S}{V_{CC}} = \frac{T_S}{R_C \,.\, C}$$



(a) Basic transistor switch sweep circuit. (b) Associated input and output waveforms.

Fig. 7.18.

It is evident from the above relation that the output or sweep voltage level (V_s) must be a small fraction of the supply voltage (V_{CC}) and this is not a desirable feature, if a certain sweep voltage level is desired. This shortcoming can be remedied by the Miller sweep and the Bootstrap sweep circuits.

It may be noted that the transistor switch if OFF only for the gating time (T_s). At the end of time T_s, the capacitor discharges, and the voltage is again zero. It is also possible to generate a negative-going sweep using transistor switch. But in that case, we have to use a PNP transistor instead of a NPN transistor in the sweep circuit.

7.20 Delay Line

Both the horizontal sweep and vertical deflection information should arrive at the CRT at the same time. If they do not, the scope cannot display the voltage information properly. Since the delays in the horizontal path are longer, vertical information reaches the CRT before the horizontal information. The solution to the problem is to put a calibrated delay into the vertical path so that both horizontal and vertical signals reach the CRT at the same time.

The delay line is used to delay the signal for some time in the vertical section. The horizontal signal (time base, or sweep voltage) is initiated or trigger by a portion of the output signal applied to the vertical CRT plates. Signal processing in the horizontal channel consists of generating and shaping a trigger pulse that starts the sweep generator. The output is then feed to the horizontal amplifier and then to the horizontal deflection plates. This whole process takes time about 80 ns or more.

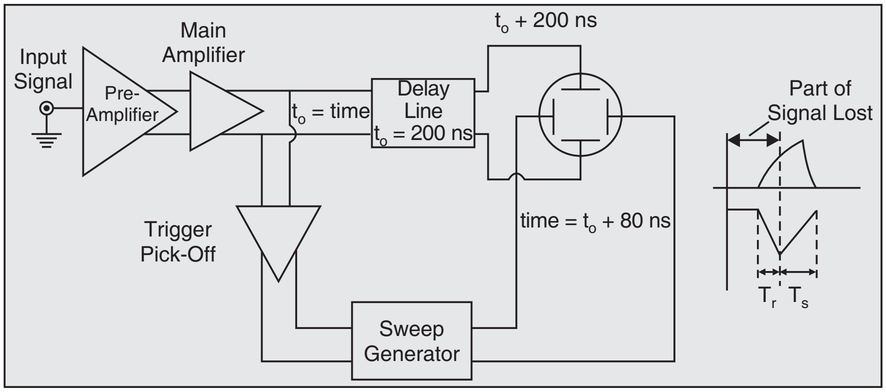


Fig. 7.19. Delay Line Circuit.

To display the waveform, the signal for the vertical CRT plates must be delayed by at least the same amount of time. This is the function of the vertical delay circuit. From Fig. 7.19 we observe that a 200 ns delay has been added to the vertical channel so that the signal voltage to the CRT plates is delayed by 200 ns, and the horizontal sweep is started prior to the vertical deflection.

There are two kinds of delay line:

1. The lumped-parameter delay line
2. The distributed-parameter delay line.

We will explain each delay line one by one in coming article.

7.21 Lumped-Parameter Delay Line

Fig. 7.20 shows the lumped-parameter delay line, it also called *T*-section. This type of delay line consists of a number of cascaded symmetrical *L*-*C* networks.

The *T*-section is terminated in its characteristic impedance Z_o, then the impedance looking back into the input terminals is also Z_o. This condition of termination provides the *T*-section the characteristics of a low-pass filter whose attenuation and phase shift are a function of frequency, and whose passband is defined by the frequency range over which the attenuation is zero. The upper limit of passband is known as the cut-off frequency of the filter and is given by,

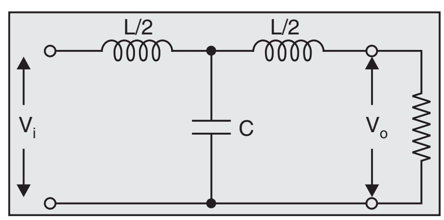


Fig. 7.20.

$$f_o = \frac{1}{\pi \sqrt{LC}}$$

It the frequency of input signal is much less than cut-off frequency then the output signal will be the reproduction of the input signal but delayed by some amount of time.

$$t_s \approx \frac{1}{\pi f c} = \sqrt{LC}$$

where t_s is the time delay for a single *T*-section. There are numbers of *T*-section cascaded so the total delay time,

$$t_d = nt_s = n\sqrt{LC}$$

where *n* is the number of cascaded *T*-sections.

When the frequency of the input signal increases then the cut-off frequency of the lumped-parameter delay line poses the amplitude and phase distortion problem. The input step-voltage (high-frequency component) gives an output voltage that suffers from transient response distortion in the form of over-shoot and ringing. This type of response can be improved to more closely resemble the original step-voltage input by modifying the design of the filter sections into *m*-derived sections.

It is important to match the delay line as closely as possible to its characteristic impedances Z_o, at both input and output ends. This requirement often leads to complex termination circuitry in an effort to optimize the balance between amplitude and phase distortion and to have better transient response.

A practical delay line circuit in an oscilloscope is driven by a push-pull amplifier and then consists of a symmetrical arrangement of cascaded filter sections as shown in Fig. 7.21. Optimum response of the delay line needs precise proportioning of the *L* and *C* components in each section, the variable capacitors must be carefully adjusted to be effective.

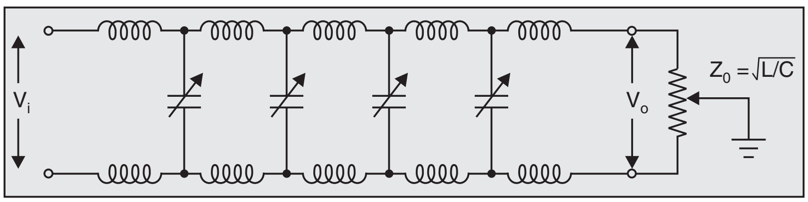


Fig. 7.21.

7.22 Distributed-Parameter Delay Line

Fig. 7.22 consists of a specially manufactured coaxial cable with a high value of inductance per unit length. The straight center conductor of the normal coaxial cable is replaced with a continuous coil of wire, wound in the form of a helix on a flexible inner core. The outer conductor is made of braided insulated wire, electrical connected at the ends of the cable in order to reduce eddy currents.

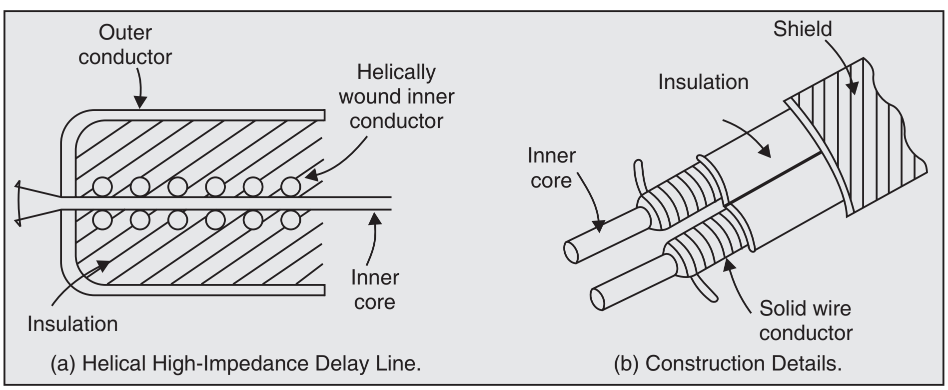


Fig. 7.22.

The inductance of the delay line is caused by the inner coil, and it equal to that of a solenoid with '*n*' turns per meter. The inductance is increased by winding the helical inner conductor on a ferromagnetic core having the effect of increasing the delay time and the characteristics impedance. The capacitance of the delay line is that of two coaxial cylinders separated by polyethylene insulation. The capacitance is increased by using a thinner dielectric spacing between the inner and outer conductors.

The coaxial delay line is advantages because if does not require the carefully adjustment of lumped parameter line and it occupies much less space.

7.23 Measurement of Voltage

Cathode Ray Oscilloscope (CRO) is primary a voltage-measuring instrument. Once we have measured the voltage, other quantities can be calculated. CRO is a voltage dependent instrument and can be used for the measurement of voltages at any frequency within the range of the operation of the CRO. Fig. 7.23. shows the display of voltage.

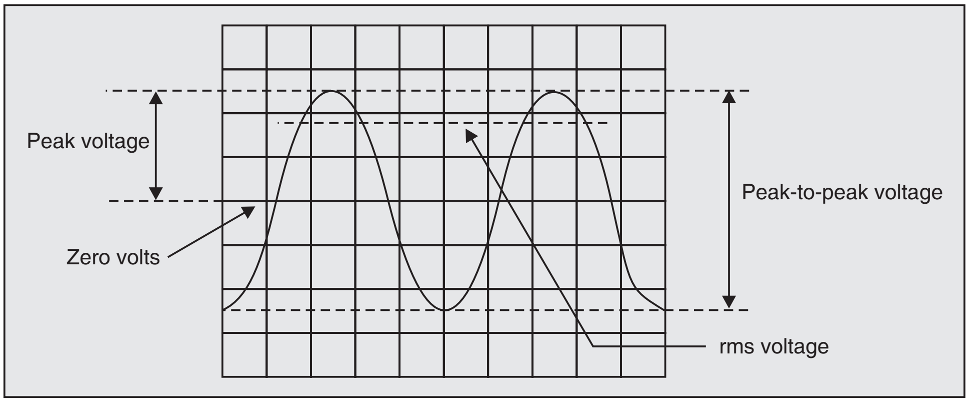


Fig. 7.23.

To measure the voltages

1. The input voltage is applied on the vertical deflection plates
2. An appropriate sweep is applied to the horizontal plates.
3. The amplitude attenuator is than adjusted such that the signal is displayed comfortably on the screen.
4. The amplitude trace of the waveform is then observed on the screen.
5. The position of the attenuator knob gives the volts/cm position or volts/ division.
6. The peak to peak voltage of the input signal is measured by multiplying this position value with the number of centimeters the signal is occupying in the vertical direction.
7. The peak to peak voltage of the signal is given by

$$V_{p-p} = \left(\frac{\text{volts}}{\text{div.}}\right) \times \text{(number of divisions)}$$

$$\text{Amplitude } V_{\max} = \frac{V_{p-p}}{2}$$

$$\text{R.M.S value, } V_{\text{r.m.s}} = \frac{V_{p-p}}{2\sqrt{2}}$$

Example 7.4. *The waveform shown in Fig. 7.24 is observed on the screen of an oscilloscope. If the vertical attenuation is set to 0.5 V/div, determine the peak to peak amplitude of the signal.*

(GBTU/MTU, 2006-07)

Solution. Given: Volts/div = 0.5 V and number of divisions along the vertical axis = 3,

We know that the peak to peak voltage,

$$V_{p-p} = \left(\frac{\text{volts}}{\text{div}}\right) \times \text{no.of div}$$

$$= 0.5 \text{ V} \times 3 = 1.5\ V_{p-p}$$ **Ans.**

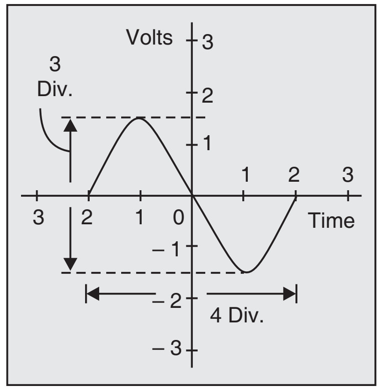


Fig. 7.24.

Example 7.5. *Fig 7.25 shows the waveform of a sinusoidal voltage observed on CRO. The vertical attenuation selected is 2 mV/div. Calculate the amplitude and r.m.s value of the sinusoidal voltage.*

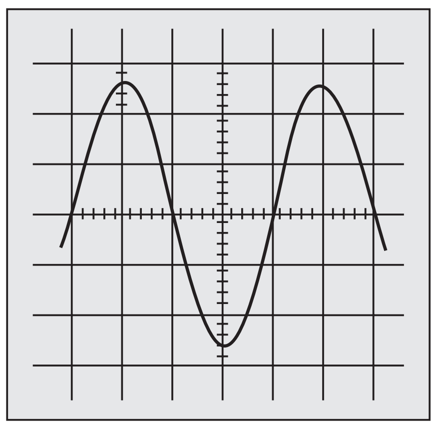


Fig. 7.25.

Solution. Given: Volts/Division = 2 mV/div

It can be observed that the one part is subdivided into 5 units.

$$1 \text{ subdivision} = \frac{1}{5} = 0.2 \text{ units}$$

It can also be observed that positive peak of signal corresponds to two full divisions and three subdivisions.

Thus positive peak is,

$$\text{Positive Peak} = (2 \text{ full divisions}) + (3 \text{ subdivisions} \times \text{value of 1 subdivision})$$
$$= 2 + 3 \times 0.2 = 2.6 \text{ divisions}$$

Similarly for negative peak,

$$\text{Negative Peak} = 2.6 \text{ divisions}$$

Then peak-to-peak voltage

$$V_{p-p} = 2.6 + 2.6 = 5.2 \text{ divisions}$$

$$V_{p-p} = \text{Number of divisions} \times \frac{\text{volts}}{\text{divison}}$$

$$= 5.2 \times 2 \text{ mV} = 10.4 \text{ mV}$$

We know that the amplitude of the waveform is given by,

$$V_p = \frac{V_{p-p}}{2} = \frac{10.4}{2} = 5.2 \text{ mV } \textbf{Ans.}$$

We also know that the rms value of the waveform,

$$V_{\text{r.m.s.}} = \frac{V_m}{\sqrt{2}}$$

$$= 5.2/\sqrt{2} = 3.6769 \text{ mV } \textbf{Ans.}$$

7.24 Measurement of Current

Current cannot be measured directly with a CRO. To measure the current, a known resistance is taken and the potential drop across the resistance is determined with the help of measurement of potential at both ends of the resistor. The voltage across resistance is displayed on CRO and measured as shown in Fig. 7.26. The voltage divided by the considered resistance value gives the amount of current flowing in the device.

$$I = \frac{V_{\text{measured}} \text{ on } CRO}{R}$$

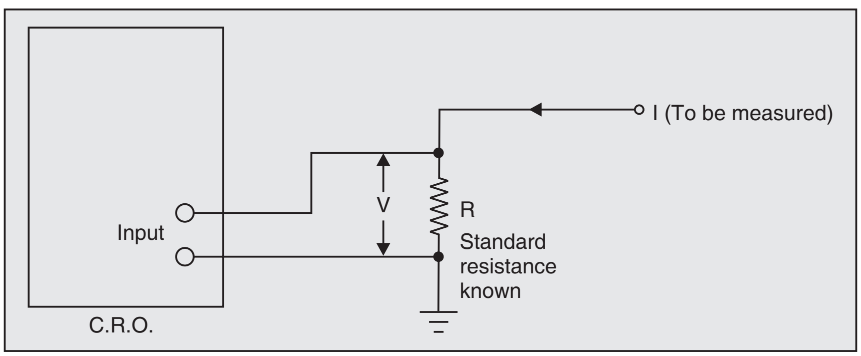


Fig. 7.26.

7.25 Measurement of Time period

The waveform is displayed on the screen such that one complete cycle is visible on the screen. Note the time/division on the front panel. Then the period of the waveform can be obtained as,

$$T = \frac{\text{Time}}{\text{Division}} \times \text{number of divisions occupied by one cycle}$$

Frequency without Lissajous pattern,

$$f = \frac{1}{T}$$

Example 7.6. *If the time/div control is set to 2 μs/div when the waveform in Fig. 7.27, is displayed on the CRT screen, determine the frequency of the signal.*

(GBTU/MTU, 2006-07)

Solution: The period of the signal is calculated using the equation,

$$T = \left(\frac{\text{time}}{\text{div}}\right) \times \left(\frac{\text{No. of div}}{\text{cycle}}\right)$$

$$= 2\mu\text{s} \times 4 = 8 \ \mu\text{s}$$

Frequency is given by

$$f = \frac{1}{T} = \frac{1}{8\,\mu s} = 125 \text{ kHz } \textbf{Ans.}$$

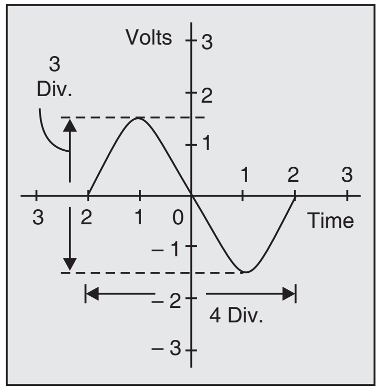


Fig. 7.27.

7.26 Lissajous Figures

Lissajous Figures (or patterns) are named in honour of the French scientist who first obtained them geometrically and optically. They illustrate one of the earliest uses to which the CRO was put.

Lissajous patterns are formed when two sine waves are applied simultaneously to the vertical and horizontal deflecting plates of a CRO. The two sine waves may be obtained from two audio oscillators as shown in Fig. 7.28. Obviously, in this case, a sine wave sweeps a sine-wave input signal. The shape of the Lissajous pattern depends on the frequency and phase relationship of the two sine waves.

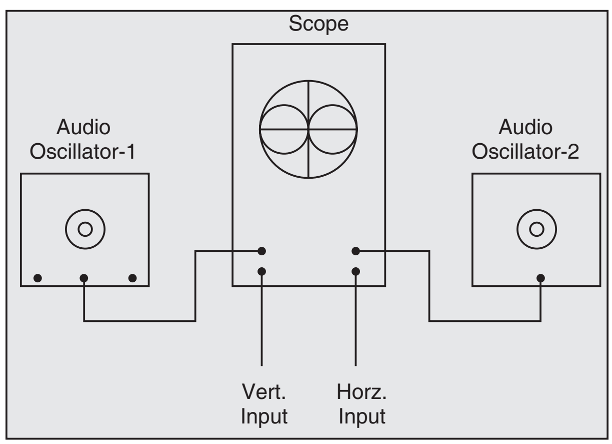


Fig. 7.28.

Two sine waves of the ***same*** frequency and amplitude may produce a straight line, an ellipse or a circle depending on their phase difference as shown in Fig. 7.29.

In general, the shape of Lissajous Figures depends on

(*i*) Amplitude

(*ii*) Phase difference

(*iii*) Ratio of frequency of the two waves.

Consider the two signals applied having same amplitude and frequency with phase difference of Ø between them,

$$e_1 = E_m \sin \theta$$
$$e_1 = E_m \sin (\theta + \phi)$$

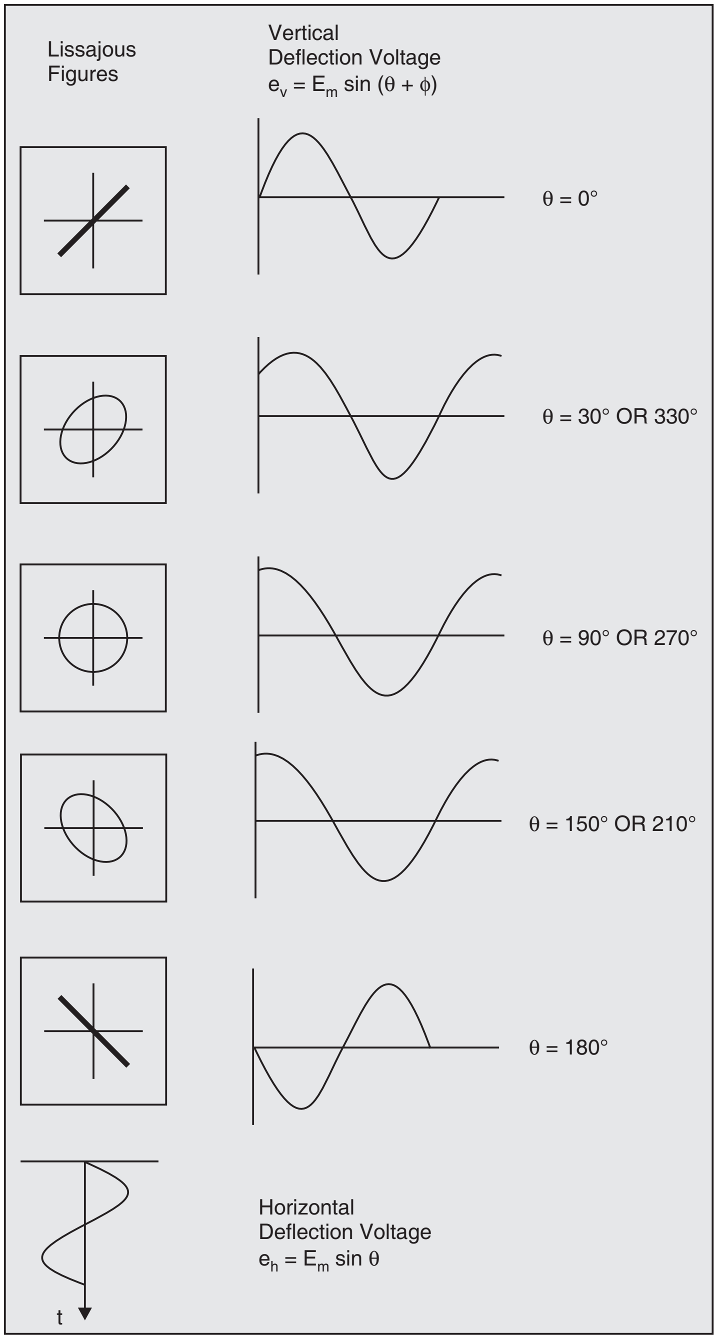


Fig. 7.29.

Straight Line

1. The straight line is formed when the two voltages are in phase with each other or 180° out of phase with each other.

2. The straight line formed angle 45° with horizontal when the magnitude of voltages are equal.
3. An increase in vertical deflection voltage causes the line to have an angle greater than 45°with the horizontal.
4. A grater horizontal voltage makes the angle less than 45 ° with the horizontal.

Circle

When the magnitudes of two voltages are equal and the phase difference between them is either 90° or 270°

Ellipse

The ellipse is formed when voltage are not equal and or out of phase.

7.27 Used of Lissajous Figures

Lissajous Figures is used as:

(*i*) determining an unknown frequency by comparing it with a known frequency
(*ii*) checking audio oscillator with a known-frequency signal
(*iii*) checking audio amplifiers and feedback networks for phase shift.

7.28 Frequency Determination with Lissajous Figures

The unknown signal is applied across one set of deflecting plates and a known signal across the other. By studying the resultant Lissajous pattern, unknown frequency can be found.

Depending on the frequency ratio, the various patterns obtained are shown in Fig. 7.30. The ratio of the two frequencies is given by

$$\frac{f_V}{f_H} = \frac{\text{No. of points of horizontal tangency}}{\text{No. of points of vertical tangency}}$$

In Fig. 7.30 (*a*), there is one point of tangency along the horizontal as well as vertical axis. Hence, $f_H = f_V$ i.e. the signals have the same frequency.

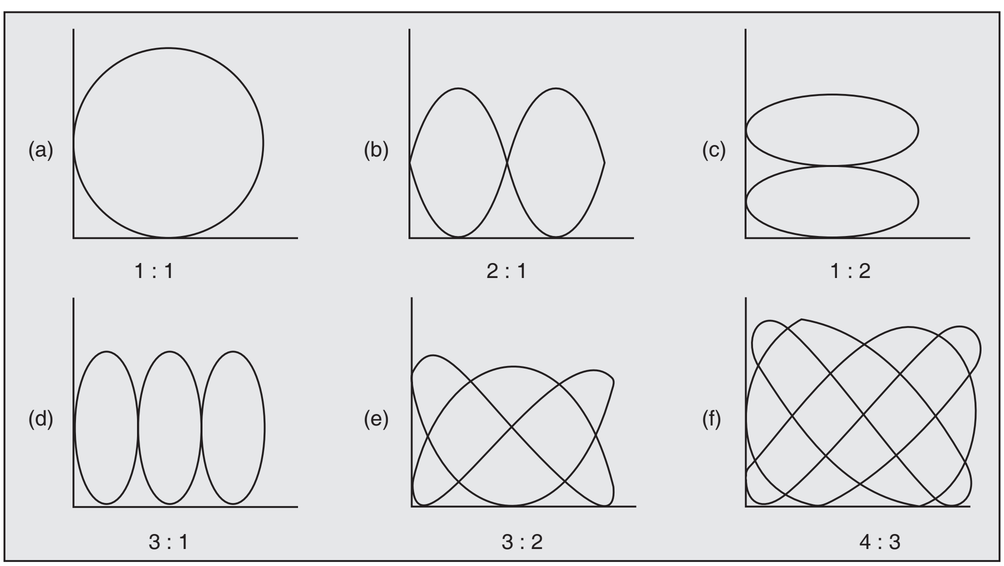


Fig. 7.30.

The ratio of frequencies when open ended Lissajous patterns are obtained can also be found by treating the open ends as half tangencies as shown in Fig. 7.31.

$$\frac{f_V}{f_H} = \frac{\text{No. of points of horizontal tangency} + \frac{1}{2}}{\text{No. of points of vertical tangency}}$$

For Fig. 7.31 we get,

$$\frac{f_V}{f_H} = \frac{2 + \frac{1}{2}}{1} = \frac{5}{2}$$

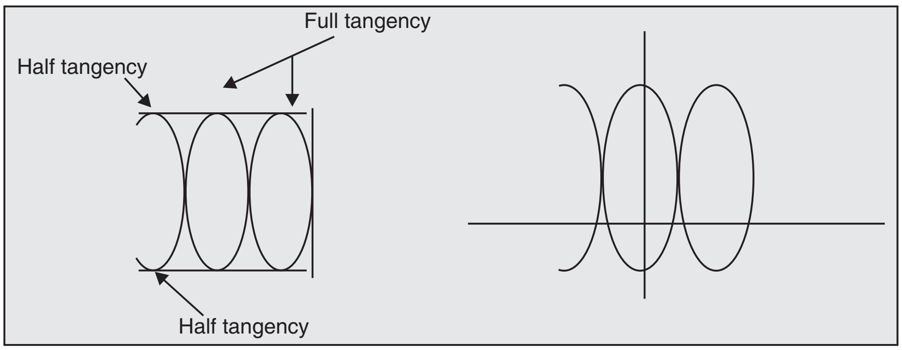


Fig. 7.31.

It should be noted that this method of frequency determination has limitations and is being discarded gradually because low-cost digital frequency counters are available in the market. The two main limitations of this method are as under:

(*i*) the numerator and denominator of the frequency ratio must be whole numbers,

(*ii*) the maximum ratio of frequencies that can be used is 10 : 1. Beyond that, the Lissajous patterns become too complex to analyse.

Example 7.7. *Fig. 7.32 shows the Lissajous pattern obtained on the CRO screen by applying horizontal signal of frequency 1 kHz. Determine the unknown frequency of vertical signal.*

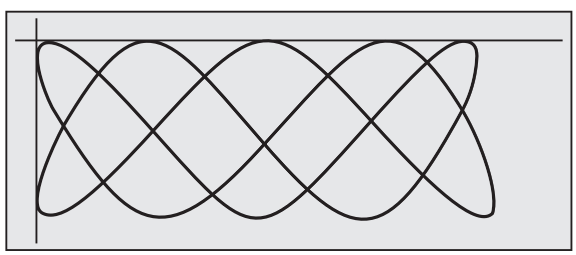


Fig. 7.32.

Solution. Given: f_H = 1 kHz, number of vertical tangencies = 2 and number of horizontal tangencies = 5

We know that

$$\frac{f_V}{f_H} = \frac{\text{Number of horizontal tangencies}}{\text{Number of vertical tangencies}}$$

$$\frac{f_V}{f_H} = \frac{5}{2}$$

$$f_V = \frac{5}{2} \times 1 \text{ kHz} = 2.5 \text{ kHz}$$ **Ans.**

Example 7.8. *A Lissajous pattern on the oscilloscope is stationary having 8 vertical maximum values and 6 horizontal maximum values. Calculate the frequency of vertical input if the frequency of horizontal input is 1800 Hz.*

Solution. Given: f_H = 1800 kHz, number of vertical tangencies = 8 and number of horizontal tangencies = 6

We know that,

$$\frac{f_H}{f_V} = \frac{\text{Number of horizontal tangencies}}{\text{Number of vertical tangencies}}$$

$$\frac{f_V}{1800} = \frac{6}{8}$$

$$f_V = \frac{6}{8} \times 1800 = 2400 \text{ Hz } \textbf{Ans.}$$

7.29 Phase Determination with Lissajous Figures

A Lissajous pattern is obtained on CRO with an unknown phase difference ϕ. This pattern which is in the form of an ellipse,provides a simple means of finding phase difference between two voltages. The gains of the vertical amplifiers are adjusted so that the ellipse fits exactly into a square marked by the lines on the graticule.

If the major axis lies in first and third quadrants

If the major axis of the ellipse lies on the first and third quadrants, its slope is positive as shown is Fig. 7.33. Then the phase angle is either between 0° and 90° or between 270° and 360°.The sine of the phase angle between the voltages is given by

$$\sin \phi = \frac{Y_1}{Y_2} = \frac{X_1}{X_2}$$

$$\phi = \sin^{-1} \frac{Y_1}{Y_2}$$

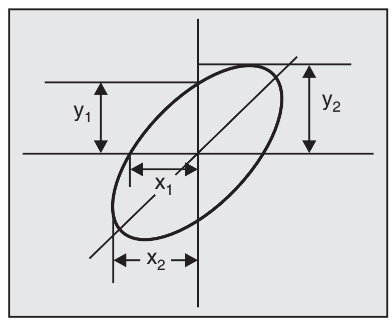


Fig. 7.33.

If the major axis in lies in second and forth quadrants

If the major axis of the ellipse lies on the second and forth quadrants, its slope is negative as shown in Fig. 7.34. Then the phase angle is either between 90° and 180° or between 180° and 270°. The sine of the phase angle between the voltages is given by

$$\sin \phi = \frac{Y_1}{Y_2}$$

$$\phi = 180° - \sin^{-1} \frac{Y_1}{Y_2}$$

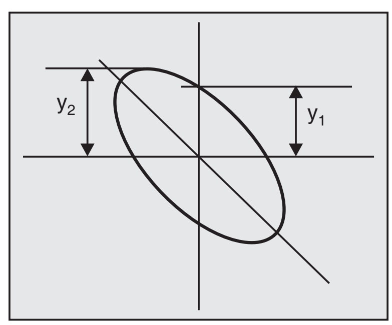


Fig. 7.34.

Example 7.9. *The Lissajous Figure obtained on the CRO is shown in Fig. 7.35. Find the phase difference between the two waves applied.*

Solution.

From the Lissajous Figure shown in Fig 7.35, we know that

$$Y_1 = 8 \text{ units}$$
$$Y_2 = 10 \text{ units}$$

We know that if the major axis lies in first and third quadrants then phase difference is given by,

$$\phi = \sin^{-1} \frac{Y_1}{Y_2}$$

$$= \sin^{-1} \frac{8}{10} = 53.13° \textbf{ Ans.}$$

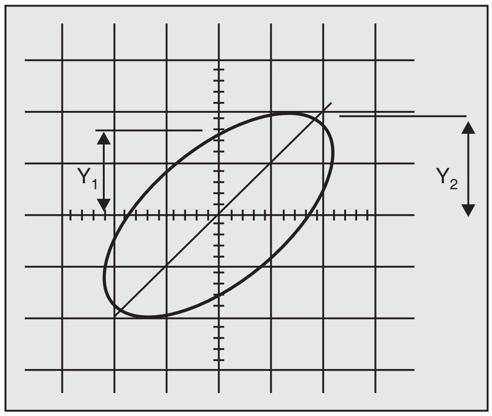


Fig. 7.35.

7.30 Spot Wheel Method of Display

CRO is not a precision instrument for measuring frequency of an alternating voltage because the accuracy depends directly on the accuracy of calibrated scale of variable frequency source, which is usually a few per cent. It is used for rough estimate of frequency or when voltage waveform is so complex that a frequency counter not operates reliably. Lissajous pattern method becomes more and more complicated with the increase in the ratio of the two frequencies. In such cases, spot wheel method of display is used. Refer to Fig. 7.36.

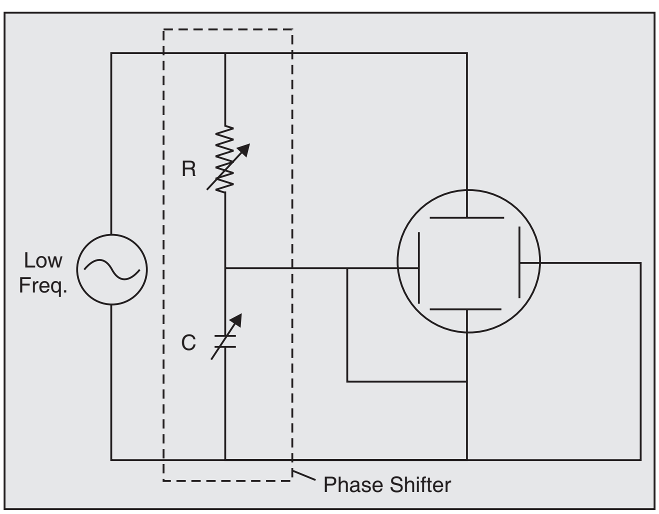


Fig. 7.36. Basic Circuit.

In this method, an intensity modulated circular or elliptical display is produced on the CRT screen. The lesser of the two frequencies under comparison is applied to the CRT deflection plates through the resistance capacitance (*R*-*C*) phase shifter as shown in Fig. 7.36 and the higher frequency is applied to the control grid of the CRT as shown in Fig. 7.37.

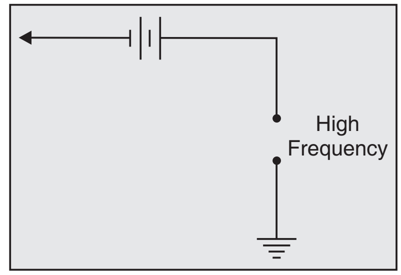


Fig. 7.37. Input Circuit to the Control Grid.

Consequently, the pattern appears as a series of alternate bright and dark spots as shown in Fig. 7.38, where the ratio of the high to low frequencies is given by the number of bright spots. In Fig 7.38, the frequency is 20:1 as there are 20 blank pattern.

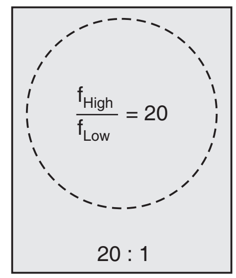


Fig. 7.38. Spot Wheel Pattern.

If two sinusoidal signals are equal in magnitude but 90° out of phase are applied to the vertical and horizontal deflecting plates, a circle is formed. In a case if single sinusoidal signal is applied to a phase shifting circuit, it is possible to have two outputs, equal in magnitude and 90° out of phase.

If the voltages across resistor *R* and capacitor *C* are equal then the pattern obtained is a circle. When the applied voltages are unequal, the pattern obtained is an elliptical.

Variation in grid-cathode potential causes the change in the density of the electron stream within the CRT and determines the intensity. When the CRT grid bias attains cut-off potential, there is no electron steam and florescence at the screen cannot occur. This property is used in comparing two frequencies, provided their ratio is an integer. Grid bias must be sufficient so that the negative peaks of the sinusoidal wave cut off the electron beam. It is not necessary that high-frequency signal be sinusoidal, it can be a square wave too.

7.31 Gear Wheel Method

In the Lissajous pattern large numbers of loop makes their counting difficult. Fig. 7.39 shows a test method that makes use of a modulated ring pattern in place of looped figure and allows a higher count. This pattern is known as a gear wheel or toothed wheel. By multiplying the known frequency by the number of teeth in the pattern we determine the unknown frequency.

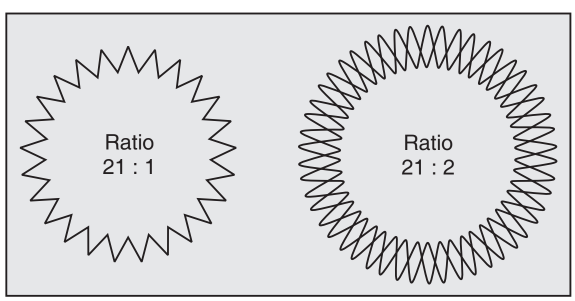


Fig. 7.39. Gear Wheel Pattern.

Circuit diagram is shown in Fig. 7.40. A phase shift of 90° between the horizontal and vertical channels of the oscilloscope, required to give a ring or circle pattern with the known frequency f_v, is introduced by *R*-*C* phase shift network.

A voltage from unknown frequency modulates the ring. With the equal voltage across *R* and *C* circle pattern will be obtained,while with unequal voltages it will be an ellipse pattern. To avoid distortion the unknown frequency must be large than known frequency and the amplitude of the unknown frequency must be smaller than that of unknown frequency.

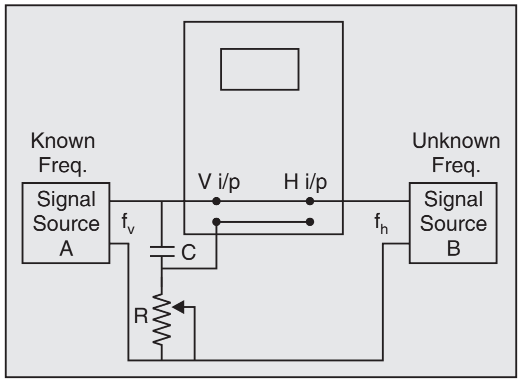


Fig. 7.40. Gear Wheel Method of Frequency Measurement.

7.32 Electronic Switch

The electronic switch is a device that enables two signals to be displayed simultaneously on the screen by a single gun CRT. The block diagram of electronic switch is shown in Fig. 7.41. As shown each signal is applied to a separate gain control and gate stage. The gate stages are alternately biased to cut off by square wave signals from the square wave generator. Therefore only one gate stages is in a condition to pass its signal at any given time.

The outputs of the both stages are applied directly to the oscilloscope input. Where R_1 and R_2 are gain controls used to adjust the amplitudes of channels A and B.

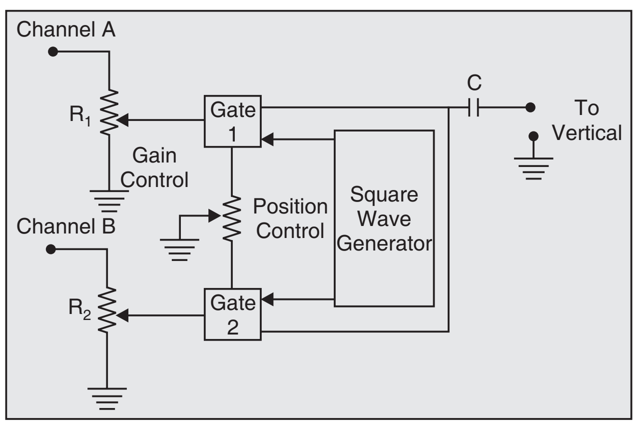


Fig. 7.41. Electronic Switch.

The circuit diagram of electronic switch is shown in Fig. 7.42. Q_1 and Q_2 are amplifiers and Q_3 and Q_4 are the switches. The input signal 1 is applied to Q_1 through gain control R_1 and the input signal 2 is applied to Q_2 through gain control R_2. The square wave generator alternately biases first Q_3 and then Q_4 to cut off. When Q_3 is conducts and transmits signal 1 to the output terminals.

When the square wave generator switching frequency is much higher than either signal frequency, bits of each signal are alternately presented to the oscilloscopes vertical input to reproduce the two signals on the screen.

The traces can be moved up or down by the position control R_5. The traces can be overlapped for easy comparison. The heights of the individual signals can be adjusted by means of gain controls R_1 and R_2. The sweep signal produced by this design is very linear and can be calibrated in time per cm or inch, so that accurate time and frequency can be measured.

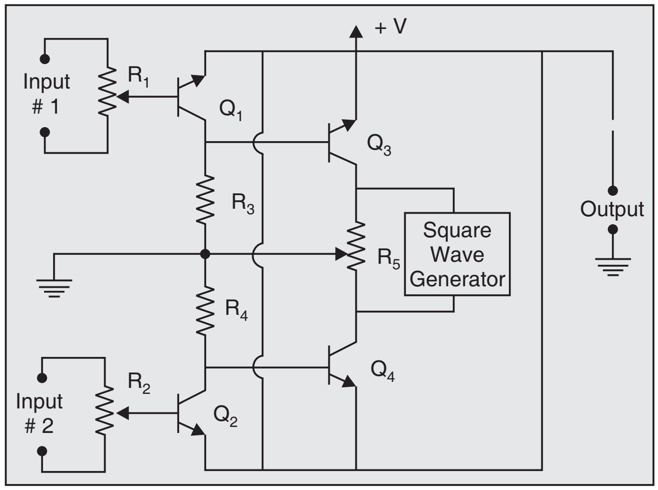


Fig. 7.42.

7.33 Oscilloscope Probes

A probe is a conductor used to establish a connection between the circuit under test and the measuring instrument. While connecting the test circuit, the probe does not alter, load or disturbs the circuit and signal conditions to be analysed.

The probe should have high impedance. The probe bandwidth should be as high as possible. It should be about 10 times the bandwidth of the oscilloscope. The ideal probe offers the following key attributes:

(*a*) Ease of connection
(*b*) Absolute signal fidelity
(*c*) Zero signal source loading
(*d*) Complete noise immunity

General diagram of probe is shown in Fig. 7.43.

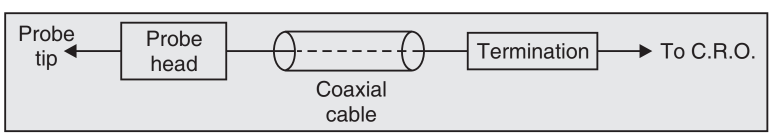


Fig. 7.43.

The probe tip is the signal sensing circuit. It may be passive or active. It consists of the resistors and capacitors if passive and in active it consists of active components like FET source follower circuit.

Fig. 7.44 shows a 60 MHz bandwidth oscilloscope probe *x*1/*x*10. A two position slide switch allows attenuation of either × **1** or × **10** to be selected.

The probe cable is a special coaxial type (with a resistive center conductor to damp out ringing), with quite-effective shielding. Its capacitance is greater than that of an open wire, and in some cases, such a probe is satisfactory. The probes are of many types, they are given below:

1. Direct probe
2. Isolation Probe

3. High impedance or 10: 1 Probe
4. Active Probes
5. Current Probe
6. Differential Probes

Now we will know discuss the each type of probes in detail.

Fig. 7.44.

7.34 Direct Probe 1:1

The simplest types of probe are the test lead. Test leads are simply convenient lengths of wire for connecting the CRO input to the point of observation. At the end of CRO, they usually terminate with lugs, banana tips or other tips to fit input jacks of the scope, and at the other end has a crocodile clip or any other convenient means for connection to the electronic circuit.

The CRO has high input impedance and high sensitivity. So the test leads should be shielded to avoid hum pickup, unless the scope is connected to low impedance high level circuits.

Direct probe is shown in Fig. 7.45. While using the shielded probe, the shunt capacitance of the probe and cable is added to the input impedance and capacitance of the oscilloscope and acts to lower response of the oscilloscope to high impedance and high frequency circuits.

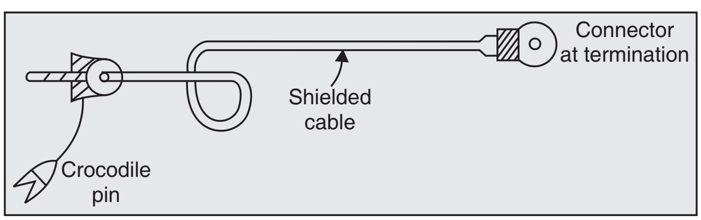


Fig. 7.45. Direct Probe.

7.35 Isolation Probe

The input capacitance of the scope and the stray capacitance of the test lead are very high. It causes the sensitive circuit to break into oscillation when CRO is connected. This effect can be prevented by an isolation probe. The isolation probe is made by placing a carbon resistor in series with test lead as shown in Fig. 7.46.

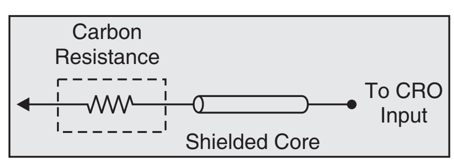


Fig. 7.46. Isolation Probe

An isolation probe is employed to avoid the undesirable circuit loading effect of the shielded probe. This probe causes a slight change in the amplitude of the waveform and a slight change in the wave shape. To avoid this possibility, a high impedance compensated probe, called a low capacitance probe or a 10:1 probe is used.

7.36 High Impedance or 10: 1 Probe

This probe is also known as passive voltage probe. The basic function of this probe is to increase the input impedance and reduce the effective input capacitance of an oscilloscope. This probe head uses a resistor and a capacitor combination. The resistance R_1 is shunted by an adjustable capacitor C_1. This capacitor is called compensating capacitor.

A co-axial cable connects the probe head to the CRO input as shown in Fig. 7.47. Let C_2 be the probe cable equivalent capacitance. The input resistance and capacitance of CRO can be referred to as R_{in} and C_{in}. The typical values of R_{in} and C in are 1 MΩ and 20 pF.

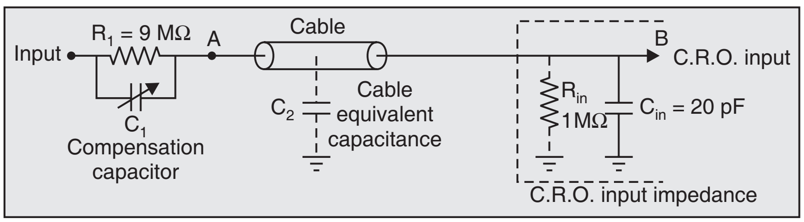


Fig. 7.47. High impedance

The equivalent circuit of the probe is shown in Fig. 7.48.

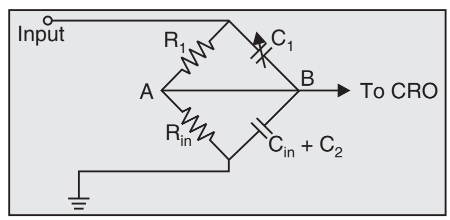


Fig. 7.48.

The compensating capacitor is adjusted to get balanced bridge condition,

$$R_1 X_{(C_{in}+C_2)} = R_{in} X_{(C_1)}$$

$$\frac{R_1}{\omega(C_{in}+C_2)} = \frac{R_{in}}{\omega C_1}$$

$$R_1 C_1 = R_{in}(C_{in}+C_2)$$

Therefore, A and B will be equipotential. Thus the probe acts as a potential divider consisting of R_1 and R_{in} across the input. Thus the attenuator factor is

$$\frac{R_1+R_{in}}{R_{in}} = \frac{9+1}{1} = 10$$

Hence this probe is also called 10 × probe. Thus effectively input resistance increases by a factor of 10 while the input capacitance decreases by a factor of 10.

Example 7.10. *Calculate the value of compensating capacitance for 10:1 probe with input impedance of CRO equal to 1 MΩ, in parallel with 35 pF capacitance as shown in Fig. 7.49.*

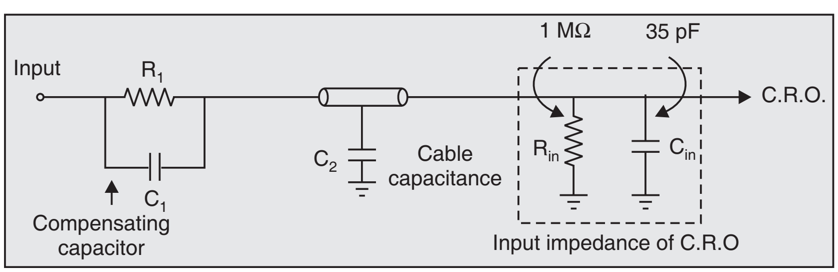


Fig. 7.49.

Solution. Given: a 10:1 probe.

The attenuation factor is given by

$$\frac{R_1 + R_{in}}{R_{in}} = 10$$

or $$R_1 = 9\ R_{in}$$

We know that,

$$R_1\ C_1 = R_{in}\ (C_{in} + C_2)$$

Neglecting C_2,

$$R_1\ C_1 = R_{in}\ C_{in}$$

$$C_1 = \frac{R_{in} C_{in}}{R_1} = \frac{R_{in} C_{in}}{R_1} = \frac{R_{in} \times 35}{9\ R_{in}}$$

$$= 3.88 \text{ pF } \textbf{Ans.}$$

7.37 Active Probe

The active probes are used for connecting fast rising and high frequency signals. These probes are very useful for small signal measurements as their attenuation factor is very small. The block diagram of the active probe is shown in Fig. 7.50. As seen from this figure, the active probe consists of an active element like FET source follower circuit and BJT emitter follower circuit along with a co-axial cable termination.

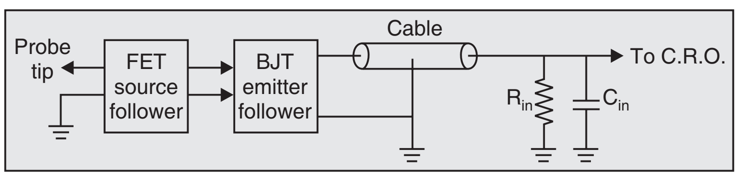


Fig. 7.50. Active Probe.

FET is used as an active element to amplify the signal. The voltage gain of FET source follower is unity but it provides a power gain due to which input impedance increases. The output impedance of FET source follower is very low and hence eliminates the loading effect.

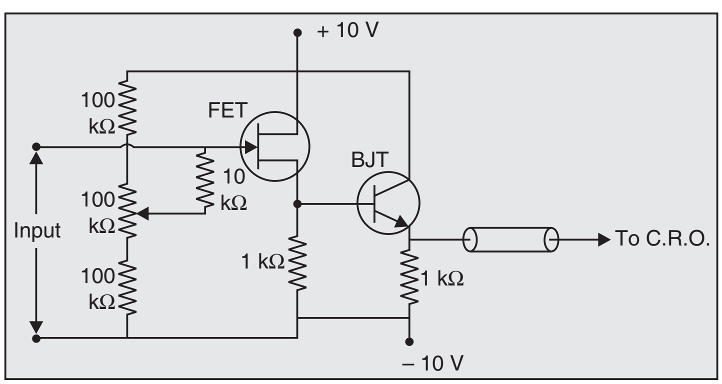


Fig. 7.51.

Instead of connecting cable directly to CRO from FET stage, one more stage of BJT emitter follower is introduced as shown in Fig. 7.51. This emitter follower drives the cable and helps further in solving the problems of improper impedance matching.

These probes are more expensive and bulky than passive probes, but they are useful for small signal measurements, because their attenuation is less. Active probes have limited use because the FET probe effectively becomes an attenuator probe. So the oscilloscopes are typically used with 10:1 attenuator probe.

7.38 Current Probe

This probe provides a method of inductively coupling the signal to the CRO input. The direct electrical connection between the test circuit and CRO is not necessary. This probe can be clamped around a wire carrying an electrical current without any physical contact to the probe. Thus the magnitude of current with a frequency range from d.c to 50 MHz can be measured using this probe.

The current sensor consists of two parts: A conventional transformer for transforming alternating current to voltage, and a Hall effect device for converting direct current to a voltage.

The current probe is shown in Fig. 7.52. A magnetic core with a removable piece is used as the coupling element for the current probe. The wire carrying the current to be measured is inserted in the center of the magnetic core and acts as a primary of a transformer. The core is the ferrite *U* shaped and work as secondary of the transformer. Because of the electromagnetic induction principle, whenever current flows through primary, the e.m.f gets induced in the secondary. This is fed to the CRO input via termination circuitry.

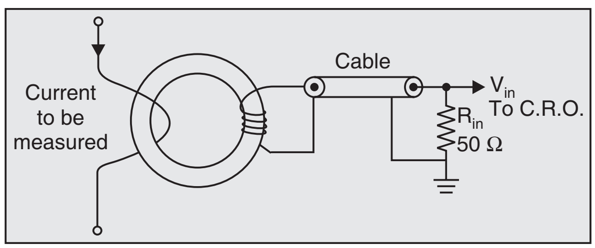


Fig. 7.52. Current Probe.

When d.c current flows through the wire, it will not appear at the secondary. In addition to this flux in core may increase causing the saturation of the core which is undesirable. This provides inaccurate measurements. To avoid this problem Hall Effect sensor and a feedback amplifier is added to the probe.

7.39 Differential Probes

This is a type of active probe shown in Fig. 7.53. It has two inputs, positive and negative. It has a separate ground lead and it drives single terminated 50 Ω cable to transmit its output to one oscilloscope channel. This output voltage signal is proportional to the difference between the voltages appearing to the input terminals. There is a restriction that the two input signals must be within a few volts from ground so that signals can stay within the dynamic range of the probe.

The output is proportional to the difference between the two inputs and hence the name, differential probe. It rejects the common mode signal but still some error voltage results proportional to common mode signals like noise. The common mode rejection power can be measured by connecting both the input simultaneously to the same input. The rejection is best for d.c and at low frequencies. But at high frequencies the rejection is poor.

Such probes can handle the signals which are typically less than a few volts only. The peaks above certain amplitude will be clipped in such probes. This probe is bulky, expensive, having less dynamic range and requires external power supply.

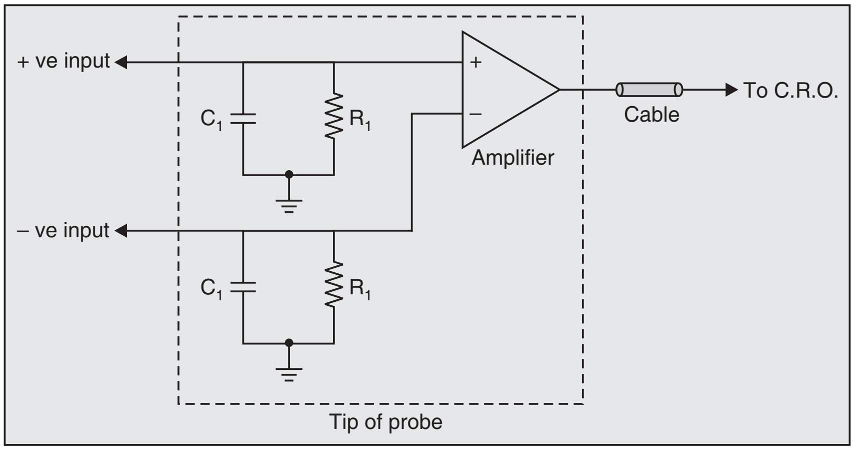


Fig. 7.53. Differential Probe.

7.40 Oscilloscope Specifications and Performance

The oscilloscope specifications are necessary when choosing a particular oscilloscope for a particular application. It is necessary to look in detail at the specifications list to see whether the instrument meets its requirements. The oscilloscope specifications and performance are given below:

1. Bandwidth. The bandwidth specification tells you the frequency range the oscilloscope accurately measures. As signal frequency increases, the capability of the oscilloscope to accurately respond decreases. By convention, the bandwidth tells you the frequency at which the displayed signal reduces to 70.7% of the applied sine wave signal. (This 70.7% point is referred to as the "–3 dB point," a term based on a logarithmic scale.)

2. Rise Time. Rise time is another way of describing the useful frequency range of an oscilloscope. Rise time may be a more appropriate performance consideration when you expect to measure pulses and steps. An oscilloscope cannot accurately display pulses with rise times faster than the specified rise time of the oscilloscope.

3. Vertical Sensitivity. The vertical sensitivity indicates how much the vertical amplifier can amplify a weak signal. Vertical sensitivity is usually given in millivolts (mV) per division. The smallest voltage a general purpose oscilloscope can detect is typically about 2 mV per vertical screen division.

4. Sweep Speed. For analog oscilloscopes, this specification indicates how fast the trace can sweep across the screen, allowing you to see fine details. The fastest sweep speed of an oscilloscope is usually given in nanoseconds/div.

5. Gain Accuracy. The gain accuracy indicates how accurately the vertical system attenuates or amplifies a signal. This is usually listed as a percentage error.

6. Time Base or Horizontal Accuracy. The time base or horizontal accuracy indicates how accurately the horizontal system displays the timing of a signal. This is usually listed as a percentage error.

7. Sample Rate. On digital oscilloscopes, the sampling rate indicates how many samples per second the ADC (and therefore the oscilloscope) can acquire. Maximum sample rates are usually given in megasamples per second (MS/s). The faster the oscilloscope can sample, the more accurately it can represent fine details in a fast signal. The minimum sample rate may also be important if you need to look at slowly changing signals over long periods of time. Typically, the sample rate changes with changes made to the sec/div control to maintain a constant number of waveform points in the waveform record.

8. ADC Resolution (Or Vertical Resolution). The resolution, in bits, of the ADC (and therefore the digital oscilloscope) indicates how precisely it can turn input voltages into digital values. Calculation techniques can improve the effective resolution.

Record Length. The record length of a digital oscilloscope indicates how many waveform points the oscilloscope is able to acquire for one waveform record. Some digital oscilloscopes let you adjust the record length. The maximum record length depends on the amount of memory in your oscilloscope. Since the oscilloscope can only store a finite number of waveform points, there is a trade-off between record detail and record length. You can acquire either a detailed picture of a signal for a short period of time (the oscilloscope "fills up" on waveform points quickly) or a less detailed picture for a longer period of time. Some oscilloscopes let you add more memory to increase the record length for special application.

SUMMARY

1. An oscilloscope can display and also measure many electrical quantities like ac/dc voltage, time, phase relationships, frequency and a wide range of waveform characteristics like rise-time, fall-time and overshoot etc.
2. This is the cathode ray tube which emits electrons that strikes the phosphor screen internally to provide a visual display of signal. It displays the quantity being measured.
3. CRT is the 'heart' of an oscilloscope and is very similar to the picture tube in a television set.
4. Vertical amplifier amplifies the signal waveform to be viewed. It is the principle factor in determining the sensitivity and bandwidth of an oscilloscope.
5. Delay Line is used to delay the signal for some time in the vertical sections
6. The main function of the Horizontal amplifier is to amplify the sawtooth voltage which is then applied to the *X*-plates.
7. The graticule is a grid of squares that serve as reference marks for measuring the displayed trace.
8. An attenuator is an electronic device that reduces the amplitude or power of a signal without distorting its waveform.
9. The trigger circuit insures that the horizontal sweep starts at the same point of the vertical input signal.
10. A time-base circuit is a circuit which generates a saw-tooth waveform. It causes the spot to move in the horizontal and vertical direction linearly with time.
11. The delay line is used to delay the signal for some time in the vertical section.
12. Lissajous patterns are formed when two sine waves are applied simultaneously to the vertical and horizontal deflecting plates of a CRO.
13. The straight line is formed when the two voltages are in phase with each other or 180 ° out of phase with each other.
14. The circle is formed when the magnitudes of two voltages are equal and the phase difference between them is either 90°or 270°
15. The ellipse is formed when voltage are not equal and or out of phase.
16. The electronic switch is a device that enables two signals to be displayed simultaneously on the screen by a single gun CRT.
17. A probe is a conductor used to establish a connection between the circuit under test and the measuring instrument.
18. The oscilloscope specifications are necessary when choosing a particular oscilloscope for a particular application.

GLOSSARY

Attenuator: An attenuator is an electronic device that reduces the amplitude or power of a signal without distorting its waveform.

Cathode Ray Tube (*CRT*): This is the cathode ray tube which emits electrons that strikes the phosphor screen internally to provide a visual display of signal. It displays the quantity being measured.

Deflecting Plates: Deflecting plates are used for deflecting the thin pencil-like electronic beam both in the vertical and horizontal directions

Delay line: Delay line is used in the vertical path so that both horizontal and vertical signals reach the CRT at the same time.

Electronic Switch: The electronic switch is a device that enables two signals to be displayed simultaneously on the screen by a single gun CRT.

Frequency Determination with Lissajous Figures: The ratio of the two frequencies is given by

$$\frac{f_V}{f_H} = \frac{\text{No. of points of horizontal tangency}}{\text{No. of points of vertical tangency}}$$

Graticules: The graticule is a grid of squares that serve as reference marks for measuring the displayed trace.

Horizontal amplifier: This is used to amplify the sawtooth voltage which is then applied to the X-plates.

Oscilloscope Probes: A probe is a conductor used to establish a connection between the circuit under test and the measuring instrument.

Lissajous patterns: Lissajous patterns are formed when two sine waves are applied simultaneously to the vertical and horizontal deflecting plates of a CRO.

Sweep generator: Sweep generator produces sawtooth voltage waveform used for horizontal deflection of the electron beam.

Time Base Circuits: A time-base circuit is a circuit which generates a saw-tooth waveform. It causes the spot to move in the horizontal and vertical direction linearly with time.

Trigger circuit: This circuit produces trigger pulses to start horizontal sweep. It converts the incoming signal into trigger pulses so that the input signal and the sweep frequency can be synchronized. It insures that the horizontal sweep starts at the same point of the vertical input signal

Vertical amplifier: It amplifies the signal waveform to be viewed.

NUMERICAL PROBLEMS

1. The deflection sensitivity of an oscilloscope is 35 V/cm. If the distance from the deflection plates to the CRT screen is 16 cm, the length of the deflection plates is 2.5 cm, and the distance between the deflection plates is 12 cm. What is the acceleration anode voltage?

(**Ans.** 583 V)

2. In a cathode ray tube the distance between the deflecting plates is 1.0 cm, the length of the deflecting plates is 4.5 cm and the distance of the screen from the centre of the deflecting plates is 33 cm. If the accelerating voltage supply is 300 volt, calculate deflecting sensitivity of the tube.

(**Ans.** 2.48 mm/V)

3. An electrically deflected cathode ray tube has a final anode voltage of 2000 V and parallel deflection plates of 1.5 cm long and 5 mm apart. If the screen is 50 cm from the center of the deflecting plates, find:

(*i*) Beam velocity.

(*ii*) The deflection sensitivity.

(*iii*) The deflection factor of the tube.

(**Ans.** (*i*) 26.5095×10^6 m/s, (*ii*) 3.75×10^{-4} m/V, (*iii*) 2666.67 V/m

4. An electrically deflected CRT has an accelerating voltage of 900 V and parallel deflecting plates of 1.5 cm long and 0.5 cm apart. If the screen is 40 cm away from the centre of the plates, calculate

(*i*) Beam speed

(*ii*) Deflection sensitivity of tube

(*iii*) Deflection factor of tube

Assume charge of electron as 1.6×10^{-19} *C* and mass of electron as 9.1×10^{-31} kg.

(**Ans.** (*i*) 17.8×10^6 m/s (*ii*) 0.67 mm/V, (*iii*) 1.5 V/mm)

5. Voltage E_1 is applied to the horizontal input and E_2 to the vertical input of a CRO. E_1 and E_2 have same frequency. The trace on the screen is an ellipse. The slope of major axis is negative. The maximum vertical value is 3 divisions and the point where the ellipse across the vertical axis is 2.6 divisions. The ellipse is symmetrical about horizontal and vertical axis. Determine the possible phase angle of E_2 with respect to E_1.

(**Ans.** 120° or 210°)

6. A Lissajous pattern on an oscilloscope is stationary and has 5 horizontal tangencies and 2 vertical tangencies. The frequency of horizontal input is 1000 Hz. Determine the frequency of vertical input.

(**Ans.** 2500 Hz)

7. A Lissajous pattern is obtained on a CRO screen when sinusoidal voltages are applied to the two sets of deflecting plates. The Figure makes 3 tangencies with the horizontal and 5 tangencies with the vertical. If the frequency of the horizontal signal is 2 kHz, find the frequency of the vertical signal.

(**Ans.** 1.2 kHz)

DESCRIPTIVE QUESTIONS

1. What are the major blocks of the oscilloscope, and what does each do?
2. What are the major components of a CRT?
3. Discuss briefly, the basic block diagram of cathode ray oscilloscope.

   (GBTU/MTU, 2008-09)
4. What does the terms phosphorescence mean?
5. Explain in detail the principle of operation of a single beam CRO.
6. Draw the basic block diagram of an oscilloscope and explain the functions of each block.
7. How is the electron beam focused on to a fine spot on the face of the CRT?
8. Why are the operating voltages of a CRT arranged so that the deflection plates are nearly at ground potential?
9. Derive the expression for acceleration, velocity and displacement of a charged particle placed in an electric field.
10. Derive the expression for the deflection in an electrostatic deflection system. Hence obtain the expression for magnetic deflection sensitivity.
11. How is the vertical axis of an oscilloscope deflected? How does it differ from the horizontal axis?
12. How do the *X*-shift and *Y*-shift function?
13. Why is a delay line used in the vertical section of an oscilloscope?
14. What are the advantages of dual trace over dual beam CROs for multiple trace?
15. What are the advantages of dual trace over dual beam CROs for multiple trace?
16. How does alternate sweep compare with chopped sweep? When would one method be selected over the other?
17. What is the function of the electronic switch?
18. How does the sampling CRO increase the apparent frequency response of an oscilloscope?
19. Will the waveform displayed on the CRT screen of a sampling oscilloscope be at a higher frequency than the actual input signal?
20. Explain the functions of various controls on the front panel of a CRO.
21. With the help of a circuit diagram explain the working of a triggered sweep generator.
22. What is oscilloscope probe compensation and how is its adjusted? What effects are noted when the compensation is not correctly adjusted?

23. What are the advantages of using an active probe?

24. What is the need for a time base generator?

25. Describe how the following measurement can be made with the use of a CRO

(*i*) Frequency

(*ii*) Phase angle

(GBTU/MTU, 2008-09)

26. Explain the following measurements on CRO.

(*i*) Voltage measurement

(*ii*) Current measurement

(*iii*) Time period measurement

(*iv*) Frequency measurement

27. How is magnitude and phase measured on a CRO for two different waves?

28. Explain the method of Lissajous pattern used for the frequency measurement.

29. Explain the use of a CRO for frequency measurement.

30. What is delayed sweep CRO? Explain in brief.

31. State the function of an Attenuator in CRO.

32. What is the basic principle of signal display in CRT? Also state why sweep generator is called time base generator?

(VTU, Dec. 2007)

33. State the function and explain the working of a 10:1 probe for a CRO.

(GBTU/MTU, 2006-07)

34. Why delay lines are required in a CRO?

(Mumbai University, June 2007)

35. What is the purpose of triggering of circuit in CRO?

(PTU, May 2007)

36. How CRO is used for measurement of electrical quantities?

(PTU, Dec 2008)

37. With the help of suitable diagram, describe the working of cathode ray tube.

(P.T.U, May 2010)

38. Name the main components of a CRO.

(PTU, Dec 2008)

39. Enumerate application of CRO for measurement of electrical quantities.

(PTU, May 2009)

40. With respect of CRO explain the function of the following terms briefly:

1. Intensity
2. Triggering
3. Delay Line
4. Blanking

(Mumbai University, June 2006)

41. Explain the function of various controls on the front panel of a CRO.

(Mumbai University, June 2007)

42. Why is delay line used in the vertical section of the oscilloscope?

(Mumbai University, June 2009)

43. Draw and explain the block diagram of a general purpose CRO.

(Mumbai University, June 2009)

44. Describes various types of sweep used in CRO.

(Mumbai University, Dec 2008)

45. What are Lissajous patterns? How are they used for measurement of frequency and phase angle?

(Mumbai University, June 2007)

46. Explain with neat sketches, working principle of CRO.

(GBTU/MTU, 2010-11)

47. Define active and passive CRO probes along with three comparison in tabular format.

(GBTU/MTU, 2009-10)

48. Discuss the loading and measurement effects on CRO probes.

(GBTU/MTU, 2009-10)

49. Discuss the specifications of CRO and probes for any particular laboratory application.

(GBTU/MTU, 2009-10)

50. With suitable block diagram, explain general purpose CRO.

(Nagpur University, Summer 2010)

51. Describe different types of sweeps used in CRO.

(Nagpur University, Summer 2010)

52. Draw the block diagram of CRO and explain each block in details.

(Nagpur University, Summer 2011)

MULTIPLE CHOICE QUESTIONS

1. In a CRT the focusing anode is located
   (*a*) Between pre-accelerating and accelerating anodes
   (*b*) After pre-accelerating anode
   (*c*) None of the above.

2. The source of emission of electrons in a CRT is
   (*a*) PN function diode
   (*b*) A barium and strontium oxide coated cathode
   (*c*) Accelerating anodes
   (*d*) Post-accelerating anodes

3. Post acceleration is needed in a CRO if the frequency of the signal is:
   (*a*) Less than 1 MHz (*b*) More than 1 MHz
   (*c*) More than 10 MHz (*d*) More than 10 Hz

4. The deflection of an electron beam on a CRT screen is 10 mm, Suppose the pre-accelerating anode voltage is halved and the potential between deflecting plates is doubled, the deflection of the electron beam will be:
   (*a*) 80 mm (*b*) 40 mm
   (*c*) 20 mm (*d*) 10 mm

5. If the distance of screen from a CRT to centre of deflection plates is 15 cm. The length of deflection plates is 2 cm, the distance between plates is 1 cm and the accelerating voltages is 500 V, the deflection sensitivity is:
   (*a*) 33.2 V/cm (*b*) 0.03 cm/V
   (*c*) 66.4 V/cm (*d*) 0.015 cm/V

6. The horizontal amplifier should be designed for
   (*a*) High frequency signals with a fast rise time
   (*b*) High amplitude signals with a slow rise time

(*c*) High amplitude signals with a fast rise time
(*d*) Low amplitude signals with a fast rise time

7. P1 phosphor material is used for display in CRTs for:
(*a*) Photographic applications
(*b*) General purpose applications
(*c*) Television applications
(*d*) All of the above

8. An aquadag is used in a CRO to collect:
(*a*) Primary electrons
(*b*) Secondary emission electrons
(*c*) Both primary and secondary emission electrons
(*d*) None of the above

9. A thin aluminum film is usually deposited on the non viewing side of the phosphor because,
(*a*) Its acts as a heatsink and prevents phosphor burn
(*b*) The lighter scatter from the phosphor is reduced
(*c*) It does not allow the screen to be negatively charged
(*d*) All of the above

10. During the retrace time, the electrons forming the horizontal beam.
(*a*) Move from left to right on the screen
(*b*) Move from right to the left on the screen
(*c*) Move from bottom to top of screen
(*d*) Move from top to bottom of screen

11. A vertical amplifier for a CRO can be designed for:
(*a*) Only a high gain
(*b*) Only a broad bandwidth
(*c*) A constant gain times bandwidth product
(*d*) All of the above

12. In an oscilloscope, when the unknown signal applied to the vertical plates is being synchronized with the sweep signal applied to horizontal plates, the pattern seen on the CRO screen moves towards the right. It means that,
(*a*) The frequency of the signal is lower than of the sweep signal
(*b*) The frequency of the signal greater than of the sweep signal
(*c*) The frequency of the signal is equal to the frequency of sweep signal
(*d*) None of the above.

13. The sine wave output of a function generator is fed to both the horizontal (X) and vertical (Y) inputs of a CRO. What will be the pattern on the cathode ray screen?
(*a*) Circle
(*b*) An ellipse
(*c*) A straight line with 45° slope
(*d*) Sinusoidal

(UPSC Engg. Service. 2006)

14. Which one of the following is the correct statement? Active probe used in a CRO,
(*a*) Is bulk then passive ones
(*b*) Cannot measure small signals
(*c*) Cannot couple high frequency signals
(*d*) Can attenuate more

(UPSC Engg. Service. 2006)

15. A circle is found on the screen of a CRO when 2 time varying signals of same frequency and same magnitude are applied to X and Y plates of the CRO. What is the relative phase difference?
(*a*) 0°
(*b*) 90°
(*c*) 180°
(*d*) 45°

(UPSC Engg. Service. 2007)

16. A compensated probe of a CRO contains which of the following ?
(*a*) An amplifier
(*b*) *R-O* network
(*c*) Only resistive network
(*d*) Only capacitive network

(UPSC Engg. Service. 2008)

17. A 1000 Hz sinusoidal voltage is connected to both *X* and *Y* inputs of a CRO. Which of the following waveforms is seen on CRO?

(*a*) Sine Wave (*b*) Circle (*c*) Ellipse (*d*) Straight Line

(UPSC Engg. Service. 2011)

18. While measuring the phase difference between the signals $V_1(t) = 10 \sin \omega t$ and $V_2(t) = 10 \sin (\omega t + \theta)$, the Lissajous pattern observed on CRO was a circle. The value of θ is,

(*a*) 2 MHz (*b*) 1 MHz (*c*) 4 kHz (*d*) 2 kHz

(UPSC Engg. Service. 2001)

19. The *X* and *Y* inputs to a CRO are respectively $10 \cos (100t + \theta)$ and $10 \sin (\omega t + \theta)$ the resulting Lissajous pattern is,

(*a*) A straight line inclined at an angle θ (*b*) A horizontal line

(*c*) An ellipse with axis making an angle θ (*d*) A circle

(UPSC Engg. Service. 2003)

20. Voltages $V_Y = 100 \sin 1000\, t$ and $V_X = 50 \sin 1000\, t$ are connected to *Y* and *X* terminals of a CRO, respectively. What is the shape of the figure seen on the CRO?

(*a*) A circle (*b*) A straight line (*c*) An ellipse (*d*) A parabola

(UPSC Engg. Service. 2005)

ANSWERS

1. (*a*)	**2.** (*b*)	**3.** (*c*)	**4.** (*b*)	**5.** (*b*)	**6.** (*b*)
7. (*b*)	**8.** (*b*)	**9.** (*d*)	**10.** (*b*)	**11.** (*c*)	**12.** (*a*)
13. (*c*)	**14.** (*c*)	**15.** (*a*)	**16.** (*d*)	**17.** (*d*)	**18.** (*c*)
19. (*d*)	**20.** (*b*)				

Chapter 8

Special Oscilloscopes

Outline

Objectives

After completing this chapter, you should be able to:

- List the different types of oscilloscopes.
- Explain the operation and use of time delayed oscilloscope.
- Understand the operation and use of dual trace and dual beam oscilloscope.
- Differentiate between dual trace and dual beam oscilloscope.
- Draw the block diagram of digital storage oscilloscope and describe its operation.
- Explain the operation of sampling oscilloscope.
- Explain the operation of digital phosphor oscilloscope and its applications.

8.1 Introduction

We have already discussed in the last chapter that oscilloscope is a type of electronic test instrument that allows observation of constantly varying signal voltages, usually as a two-dimensional graph of one or more electrical potential differences using the vertical axis, plotted as a function of time. Oscilloscopes are commonly used tools in engineering especially electronics engineering. General purpose instruments are used for maintenance of electronic equipment and laboratory work. Special-purpose oscilloscopes may be used for special purposes such as analyzing an automotive ignition system, or to display the waveform of the heartbeat as an electrocardiogram.

Originally all oscilloscopes used cathode ray tubes as their display element and linear amplifiers for signal processing, (commonly referred to as CROs) however, modern oscilloscopes have LCD or LED screens, fast analog-to-digital converters and digital signal processors. Although not as common, some oscilloscopes used storage CRTs to display single events for a limited time.

Broadly speaking, oscilloscopes are mainly of two types: analog and digital. An analog oscilloscope works by applying the measured signal voltage directly to an electron beam moving across the oscilloscope screen. We have already discussed the analog oscilloscope in the previous chapter. The fastest analog scopes can display frequencies up to about 1 GHz. Analog oscilloscopes are preferred when it is important to display rapidly varying signals in real time. The digital oscilloscope uses fast analog-to-digital converters to convert the voltage being measured into digital form and digital signal processors for signals processing.

8.2 Types of Oscilloscope

The oscilloscope may also be classified more conveniently as listed below:

1. Delayed Time Base Oscilloscope
2. Dual Beam Oscilloscope
3. Dual Trace Oscilloscope
4. Digital Storage Oscilloscope
5. Sampling Oscilloscope
6. Digital Phosphor Oscilloscope
7. Digital Readout Oscilloscope
8. High Frequency Oscilloscope

All these types of oscilloscopes are discussed one by one in the following pages.

8.3 Delayed Time Base Oscilloscope

In this oscilloscope, the input signal of the vertical plates is delayed by some finite time with delay circuit. The signal before the delay circuit is applied to the trigger time base circuit to the horizontal section as shown in Fig. 8.1. This allows the study of all leading or lagging edges of a pulse type waveform.

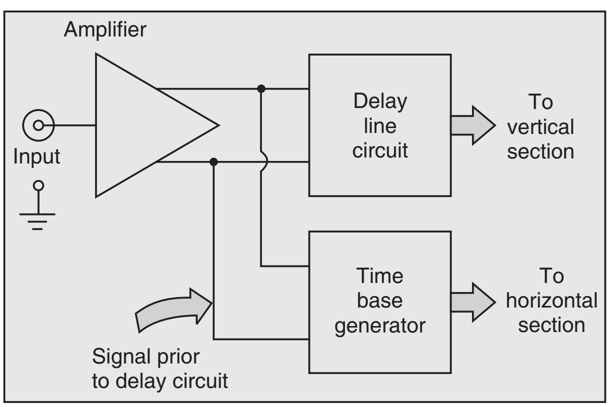


Fig. 8.1. Delayed Time Base

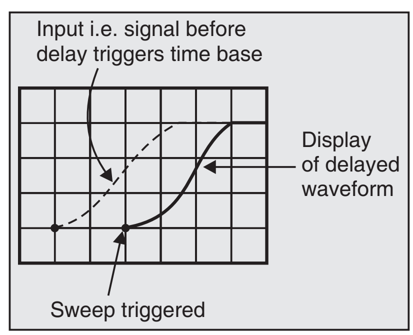


Fig. 8.2. Display of Delayed Waveform

The triggering of time base input signal sweep starts in time. In vertical section the sweep is triggered and delayed waveform is displayed as shown in Fig. 8.2.

The delayed time base oscilloscope uses two time base generators. One is normal time base while the other one is an additional time base generator. The additional time base generator is superimposed on the additional time base generator output. Due to this additional time base the waveform can be brightened when oscilloscope is running on a normal time base.

The block diagram of delayed time base oscilloscope is shown in Fig. 8.3. As seen in the figure, it uses main time base and delayed time base circuit.

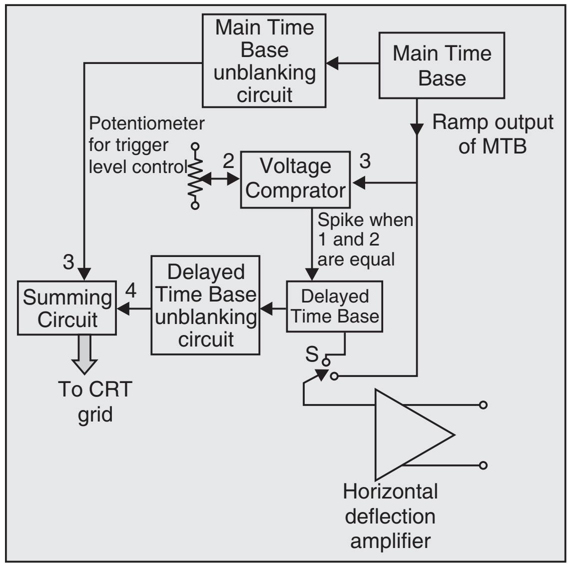


Fig. 8.3. Block Diagram of Delayed Time Base Oscilloscope

The normal time base circuit is for main time base circuits which works the same as in other oscilloscopes. The main time base unblanking circuit produces an unblanking pulse which is applied to CRT grid to turn on an electron beam in the CRT during the sweep time. The ramp output of the main time base is applied to the vertical comparator and to the horizontal deflection amplifier through the switch. The other input to the voltage comparator is derived from the potentiometer whose level is adjustable.

When the levels of ramp output of main time base and trigger level set by potentiometer are equal then the voltage comparator produce a negative or positive output spike at that instant. This spike triggers the delayed time base circuit.

The main time base and delayed time base unblanking circuit produces an unblanking pulse during the ramp time of delayed time base. The unblanking pulse from these is applied to the summing circuit and then applied to the CRT.

8.4 Applications of Delayed Time Base Oscilloscope

Following are some of the important applications of a delayed time base oscilloscope, which are important from the subject point of view:

1. It is used to extend any part of the waveform on the entire screen of the oscilloscope and make it bright to analyse the desired portion of the waveform.
2. The rising and falling edges of the pulses are investigated with delayed time based oscilloscope.

8.5 Dual Beam Oscilloscope

The two beams could be produced by two independent electron gun assemblies, or by a single gun and a splitter plate to slice the beam in half. With an oscilloscope using this type of dual trace operation, is known as a **dual beam oscilloscope**.

The dual beam CRO uses two complete separate electron beams. The dual-beam analog oscilloscope can display two signals simultaneously. A special dual-beam CRT generates and deflects two separate beams.

Fig. 8.4 shows the block diagram of dual beam oscilloscope. The dual beam oscilloscope has .two separate electron beams, and therefore two completely separate vertical channels. The dual beam oscilloscope uses two complete separate electron beams, two sets of vertical amplifier and a single horizontal amplifier.

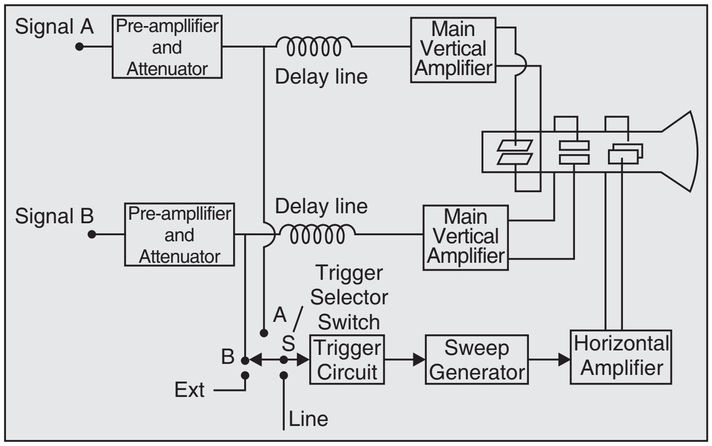


Fig. 8.4. Block diagram of dual beam Oscilloscope

From the block diagram we find that for the two separate input signals, A and B, we have two separate channels and two vertical deflection plates. Each channel consists of a preamplifier and an attenuator. A single channel consists of a delay line, main vertical amplifier and a set of vertical deflection plates. The horizontal plates sweep both the beams across the screen at the same rate. The sweep channel can be triggered internally by the channel A and Channel B.

The two channels may use the common time base system or independent time base systems. The independent time base allows different rates for the two channels but increases the size and weight of the system. Fig. 8.5 shows the dual beam oscilloscope with separate time base system.

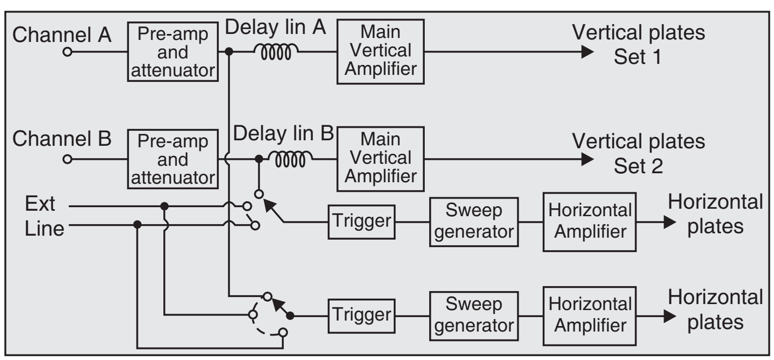


Fig. 8.5. Dual beam oscilloscope with separate time base system

The dual beam oscilloscopes are widely used, and are more versatile than the single beam type. They have the advantage that two waveforms can be displayed simultaneously. This enables waveforms to be compared, in terms of their amplitudes, shape, phase angle or frequency.

8.6 Dual Trace Oscilloscope

The dual trace oscilloscope has one cathode ray gun with an electronic switch, which switches two signals to a single vertical amplifier.

To display two waveforms, the single beam must somehow be shared between the two traces. Dual trace oscilloscopes almost invariably offer a front panel selectable choice of alternate and chopped modes as well as between traces.

Sometimes it is necessary to compare the two or more voltage waveforms to analyse the electronic circuits and systems. It can be done by using the two or more oscilloscopes but it is difficult to trigger the sweep of each oscilloscope precisely at the same time. This problem is solved by the use of dual trace or multitrace oscilloscopes. In this method the same electron beam is used to generate two traces which can be deflected from two independent vertical sources.

Fig. 8.6 shows the block diagram of a dual trace oscilloscope. As seen from this diagram, the single electron beam split into two by an electronic switch. There is one control for focus and another for intensity. The two signals are displayed simultaneously. Each channel has its own calibrated input attenuator and positioning control, so that the amplitude of each signal can be independently adjusted. After pre-amplification the two channels combine at an electronic switch. The electronic switch passes one channel at a time into vertical amplifier.

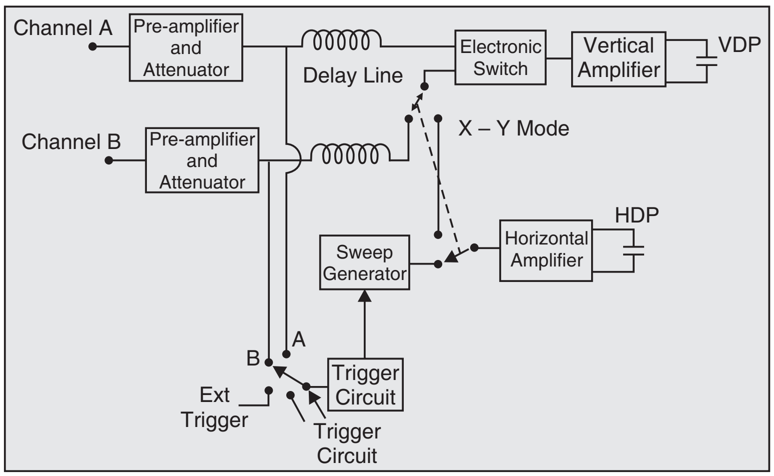


Fig. 8.6. Block diagram of dual Trace Oscilloscope

Fig. 8.7 shows a dual trace oscilloscope MODEL OS-3030 by ABRA. It has a bandwidth of 30 MHz and vertical sensitivity of 1mV/Div.

Fig. 8.7.

8.7. Operating Modes of Dual Trace Oscilloscope

There are two common operating modes for the electronic switch, called alternate and chop mode.

1. Alternate Mode

When the switch is in alternate position the electronic switch feeds each signal alternately to the vertical amplifier. The electronic switch alternately connects the main vertical amplifier to the channels A and B. In this mode the electronic switch alternates between channels A and B, letting each through for one cycle of the horizontal sweep.

The switching takes place at the start of each new sweep of the sweep generator. The switching rate of the electronic switch is synchronized to the sweep rate, so that the CRT spot traces the channel A signal on one sweep and the channel B signal on the succeeding sweep as shown in Fig. 8.8.

During the flyback and hold-off periods it displays blanked. The sweep speed is much greater than the decay time of the CRT phosphor. So the screen will show a stable display of both the waveform at channels A and B. The alternate mode cannot be used for displaying very low frequency signals. The display is not the actual representation of two events taking place simultaneously.

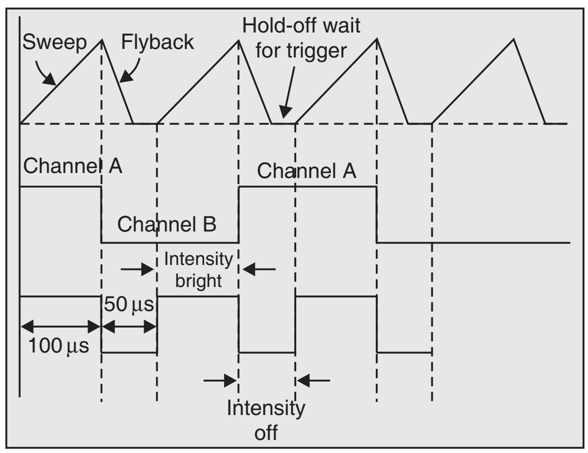


Fig. 8.8. Alternate Mode

2. Chop Mode

In chop mode the electronic switch free runs at a high frequency of the order of 100 kHz to 500 kHz. The switch successively connects small segments of A and B waveforms to the main vertical

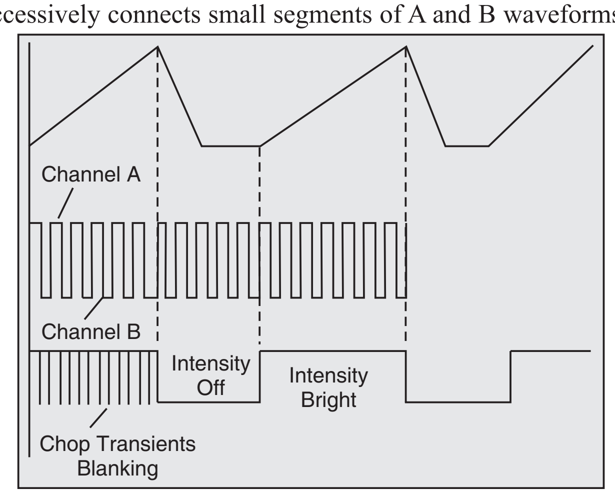


Fig. 8.9. Chop Mode

amplifier and displays on the screen as shown in Fig. 8.9. When the chopping rate is much faster than the horizontal sweep rate it will show a continuous line for each channel. If the sweep rate reaches the chopping rate then the individual segments will be visible.

8.8 Comparison of Dual Trace and Dual Beam Oscilloscopes

Table 8.1 shows comparison between the dual trace and dual beam oscilloscopes.

Table 8.1

	Dual Trace	*Dual Beam*
1.	One electron beam and one vertical amplifier are used to generate two traces.	Two electron beams and two vertical amplifier are used.
2.	Two signals are not displayed simultaneously in real time but appear to be displayed simultaneously.	The two signals are displayed simultaneously.
3.	Single beam is used to share between the two signals hence difficult to switch quickly between the traces	Two beams are used hence easy to switch between the traces.
4.	Two signals have different frequencies.	Two signals must have same frequency or their frequencies must be integer multiple of each other.
5.	Cannot operate at fast speeds because the two separate fast transient signals cannot be done.	It can operate at very fast speed.
6.	The cost is low due to single beam.	The cost is more due to two beams.
7.	Size and weight is less	Size and weight is more as compared to dual trace oscilloscope.

8.9 Digital Storage Oscilloscope (DSO)

The digital storage oscilloscope just like a normal oscilloscope is a "test and measurement" equipment. It makes use of A/D and D/A converters internally to take advantage of processing of signals in digital form. Fig. 8.10 shows the block diagram of a digital storage oscilloscope (DSO).

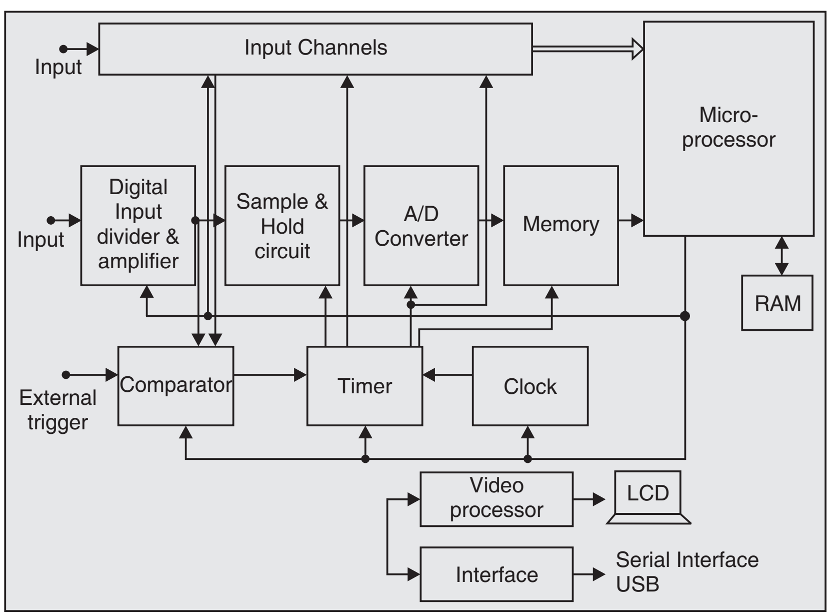


Fig. 8.10.

The DSO operation is controlled and operated by a comparator block in the microprocessor. The data acquisition system contains a sample-and-hold circuit and an A/D converter that takes the samples and digitizes the input signal at a rate determined by the clock. This digitized data will be stored in the memory. If the memory becomes full, the first stored data will be overwritten by the latest data. This data acquisition and storage process will happen till the external trigger receives at the comparator circuit. Once the trigger occurs, the data acquisition will be stopped and will not acquire any new data. At this point of time the saved data will be shown in the LCD.

Modes of Operation

The digital storage oscilloscope has the following mode of operation:

1. **Roll Mode:** This is used to observe the fast varying signal.
2. **Store Mode:** It is called refresh mode and is most commonly used.
3. **Hold or Save Mode:** This mode is also the commonly used mode.

Fig. 8.11 shows TDS1000B Series digital storage oscilloscopes. This model has 100 MHz bandwidth. It provides accurate real-time acquisition up to their full bandwidth. We can easily use USB flash drive to store screenshots and waveform data. The data can be inserted into your personal computer for importing to desk publishing or spreadsheet programs.

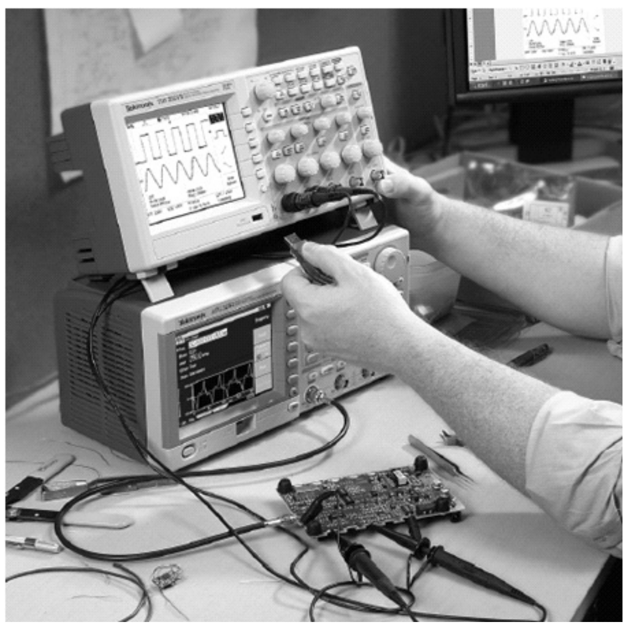


Fig. 8.11.

Advantages

The digital storage oscilloscope(DSO) has many advantages than that of normal oscilloscope. Some of the advantages are as listed below:

1. Since the DSO uses digital memory, it can store the waveforms for longer time. But in the normal CRO this cannot happen.
2. In the DSO, we can store and view the part or full waveforms before the actual trigger happens. But this is not possible in the conventional CRO.
3. In the DSO, the stored waveform can be positioned anywhere in the screen. We can actually adjust the vertical and horizontal scales of the waveform. This is not possible in the normal CRO.

4. Nowadays most of the DSOs can store as many waveforms in the memory and if needed we can take the printouts of the waveforms by connecting a normal standard printer to the DSO.

Disadvantages

The digital storage oscilloscope (DSO) has the following disadvantages:

1. DSOs are costly as compared to other oscilloscopes.
2. Slower compared to conventional oscilloscopes.

8.10 Applications of DSO

Following are some of the important applications of a DSO, which are important from the subject point of view:

1. Observation of single-pulse events: There are many phenomena which occur only once. Like occurrence of spike in any signal in a time due to some external effects, is only for the small instant of time. This can be easily recorded in the storage oscilloscope and analyzed when it required.
2. Observation of portion of waveform: The waveform recorded by storage oscilloscope is analyzed with greater detail.
3. Enlargement of waveform: Very small variation in the amplitude and frequency of the waveform is analyzed with this oscilloscope.
4. Mathematical operations: Waveform addition, subtraction, multiplication, integration, differentiation and feature comparison are possible with DSO.
5. As a measuring device: It can be used as multimeter, voltmeter, ammeter, ohmmeter, temperature meter etc.

8.11 Acquisition Methods

In digital storage oscilloscope it is necessary to capture the digital signal and store it. There are three different types of acquisition methods.

1. Real time sampling. In this method the response to single trigger event, a complete record of N samples, is simultaneously captured on each channel. From these samples recorded in a single acquisition cycle, the waveform is displayed on the screen of digital storage oscilloscope.
2. Random repetitive sampling. In this method repeated real time data acquisition cycles are performed. Each sample value is plotted independently on display as a dot. Interpolation between samples is not done. Each acquisition cycle produces random time interval between trigger point and sample clock.
3. Sequential repetitive sampling. In this method one sample per trigger event is captured at a carefully controlled time delay after the triggering pulses. This delay is increased by small amount after each point is captured. The single sample acquisition cycle is repeated till the entire waveform has been plotted.

8.12 Sampling Oscilloscope

As a matter of fact, high-frequency signals cannot be viewed by conventional oscilloscopes because its frequency range is limited by the gain-bandwidth product of its vertical amplifier. The sampling technique ‘slows down’ the signal frequency many thousands of times thereby making it easier to view it on the screen.

The sampling oscilloscopes are used for analyzing very high frequency signals. They are used for looking at repetitive signals which are higher than the sample rate of the oscilloscope. They capture the samples by assembling samples from several successive waveforms, and by combing them during the processing, they are able to build up a picture of the waveform. The oscilloscope specifications for these items may detail a frequency capability or bandwidth sometimes as high as 50 GHz. However these scopes are very expensive.

In order to display respectively signals whose frequencies are higher than the limits of high-frequency oscilloscopes sampling is used. In this technique, the signal is reconstructed from sequential samples of its waveform. These samples are obtained at slightly different points sequential samples of its waveform.

The sampling pulse generated within the oscilloscope turns on the oscilloscope measuring circuit for a brief instant. The vertical position of the electron beam is controlled by the resulting voltage observed at that point of the input waveform. The following pulse samples the waveform in its next cycle at a slightly different point. The horizontal position of the spot on the screen of the oscilloscope is meanwhile stepped forward very slightly, and the vertical position is determined by the new voltage value. As many as one thousand samples are taken to reconstruct one cycle as shown in Fig. 8.12. The sampling frequency may be as low as 1/100th of the input signal frequency i.e. ordinary oscilloscope having a bandwidth of 10 MHz can be used for observing input signal of frequency as high as 1,000 MHz as many as 1,000 samples are used to reconstruct the original waveform.

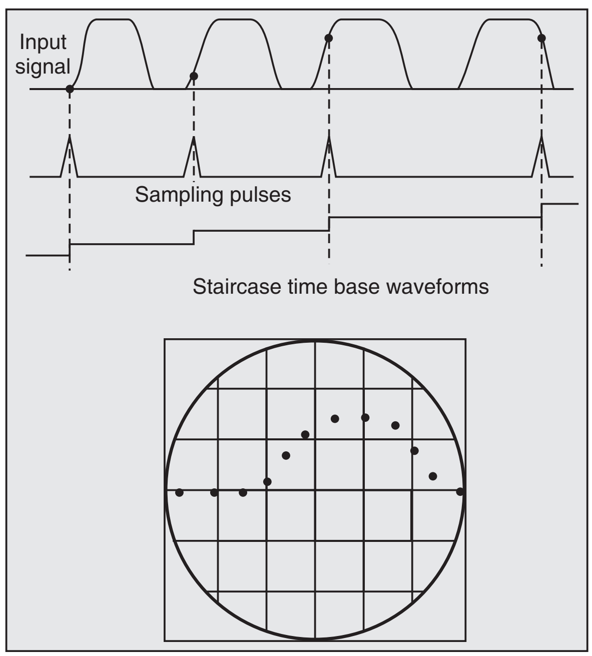


Fig. 8.12.

Fig. 8.13 shows the block diagram of sampling oscilloscope. The input waveform is applied to the sampling gate. The input waveform is sampled whenever a sampling pulse opens the sampling gate. The sampling must be synchronized with the input signal frequency.

At the beginning of each sampling cycle, the trigger pulse activates an oscillator and a linear ramp voltage is generated. This ramp voltage is applied to a voltage comparator. This comparator compares the ramp voltage to the staircase generator output voltage. When the two voltages are equal in amplitude, the staircase generator is allowed to advance one step and simultaneously a sampling pulse is applied to the sampling gate. At this moment, a sample of the input voltage is taken, amplified and applied to the vertical deflecting plates.

The resolution of the final image on the screen of the CRT is determined by the size of the steps of the staircase generator. The smaller the size of these steps and the larger the number of samples, the higher will be the resolution of the image.

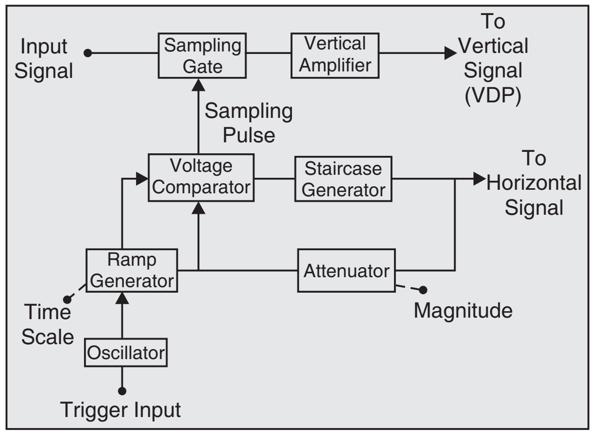


Fig. 8.13. Sampling Oscilloscope

Advantages

Some of the main advantages of sampling oscilloscopes are:

1. The waveform display is clear.
2. High speed electrical signals can be produced.
3. Very high frequency performance can be achieved.
4. The sampling techniques allow the design of the oscilloscope with wide bandwidth frequency.

Fig. 8.14 shows a 50 MHz bandwidth sampling oscilloscope Model TDS2001C manufacture by Tektronix. The model has 16 automated measurements and USB connectivity.

Fig. 8.14. Courtesy: Tektronix Corporation.

8.13 Digital Phosphor Oscilloscope (DPO)

Digital phosphor oscilloscope has unique acquisition and display characteristics for the accurately reconstruct the signal. The unique parallel processing architecture of digital phosphor oscilloscope permits higher level of signal visualization and is very much useful in detecting transient events. It uses color information to convey information about a signal.

Digital phosphor oscilloscope uses a purely electronic digital phosphor which is actually a continuous updating the database. Whenever the signal is captured the information is mapped into digital phosphor database. Each database consists of cells. This database has a separate cell of information for every single pixel in the scope's display. Each time a waveform is captured it is mapped into cells of the digital phosphor database. Each cell representing a screen location that is touched by the waveform gets reinforced with intensity information. Thus intensity information builds up in cells where the waveform passes most often. When the digital phosphor database is fed to the oscilloscope display, the display reveals intensified waveform areas in proportion to the signal frequency of occurrence at each point. Block diagram of digital phosphor oscilloscope is shown in Fig. 8.15 the display data get directly from the memory.

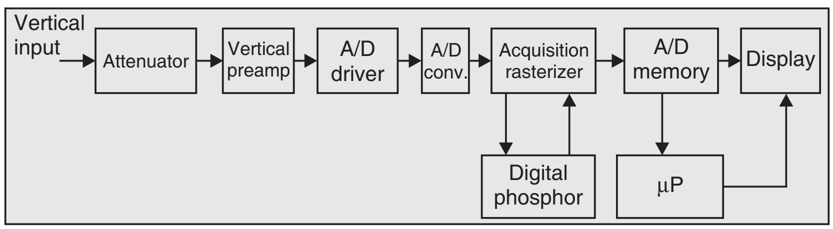


Fig. 8.15. Block diagram of digital phosphor oscilloscope.

Fig. 8.16 shows the Model DPO3052 by Tektronix. This instrument has 500 MHz bandwidth with 2 channels.

Fig. 8.16.

Advantages

The main advantages of digital phosphor oscilloscope are:

1. It has parallel processing architecture.
2. Speed of digital processing is more compared to digital signal processing.
3. More signal information for faster design and troubleshooting.

8.14 Applications of DPO

The main applications of digital phosphor oscilloscope are:

1. It is used for design and troubleshooting of various telecommunications
2. Video design and debug pulses.
3. Power measurements
4. Analyzing rate conditions set up/ holds timing violations, bus conflicts.
5. Embedded circuits design and debug.

8.15 Digital Read Out Oscilloscope

It consists of a high-speed laboratory CRO and an electronic counter, both contained in one cabinet. The counter measures the time. The input waveform is sampled and the sampling circuit advances the sampling position in fixed increment. This process is known as strobing. The equivalent time between each sample depends on the numbers of sample taken per cm and on the sweep time/ cm. e.g. if a sweep rate of 1 nano-sec/cm and a sampling rate of 100 sample/cm gives a time of 10 pico-sec/sample.

There are two modes of digital read out oscilloscope:

1. measuring voltage.
2. voltage to time conversion

1. Measuring Voltage

Fig 8.17 shows the block diagram of a digital readout oscilloscope for measuring voltage. In digital read out oscilloscope, two intensified portions of the CRT trace identify 0% and 100% zones position. Each zone can be shifted to any part of the display. Voltage divider taps between the 0% and 100% memory voltage are set for start and stop timing. The comparator senses the coincidence of any input waveforms with the selected percentage point. The number of clock pulses corresponding to the actual sample taken are read out digitally in a Nixie displays tube.

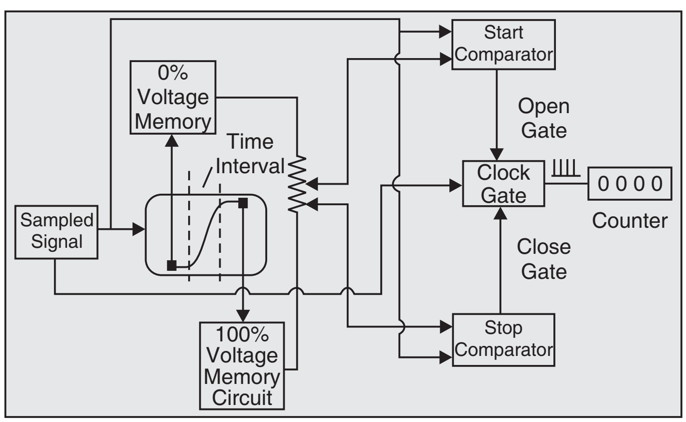


Fig. 8.17.

2. Voltage to Time Conversion

Fig 8.18 shows the block diagram of a digital readout oscilloscope for voltage to time conversion. As seen from this figure, a linear ramp generator produces a voltage. The gate is opened when the ramp voltage is equals to the 0% reference and the gate is closed when the ramp voltage is 100% reference. The CRT display is obtained by sampling the 0% reference voltage as chosen by the memory circuit. The number of clock pulses that activate the counter is directly proportional to the voltage between the selected references. The number of clock pulse is read out is display in Nixie tube in mV or volts.

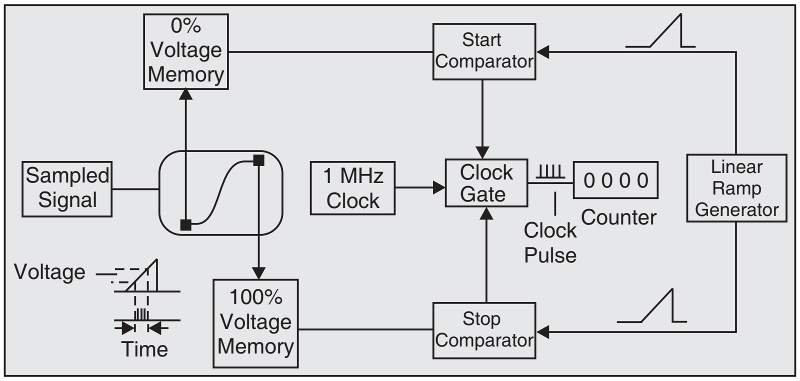


Fig. 8.18.

8.16 High Frequency Oscilloscope

The general purpose oscilloscope has a low frequency limit and is suitable for many engineering and science applications. However to measure or examine the signal whose frequency is very high (as in telecommunication industry), we need high frequency oscilloscope. The high frequency oscilloscope can display signals with frequencies up to 500 MHz. It uses high frequency CRTs and high frequency amplifiers. High-frequency design parameters include CRT writing speed, fast rise time, good high-frequency pulse response, and fast trigger capability.

In high frequency oscilloscope a series of vertical deflection plates are used. Because in a one pair of vertical deflection plates the electron beam does not get sufficient time to pick up the instantaneous level of the high frequency signal. At high frequencies the number of electrons striking the screen in a given time and the intensity of the beam is reduced. Due to high frequency it is necessary that an electron beam should get an additional deflecting force as shown in Fig. 8.19.

The vertical deflection plates are so shaped and spaced that an electron moving along CRT receives from each set of plates an additional deflection force in proper time sequence. When electron travels form one plate to other then some time gets lapsed called transit time of an electron. Thus synchronization is done by making the signal travel from one plate to the next plate at the same speed as the transit time of electrons. The signal is applied to each pair of plates and as the electron beam travels, the signal also travels through the delay times. The time delays are so arranged that the same electrons are deflected by the input signal. The electron beam picks up the level of input signal. The time delays between the plates are equal to the transit time of the electrons.

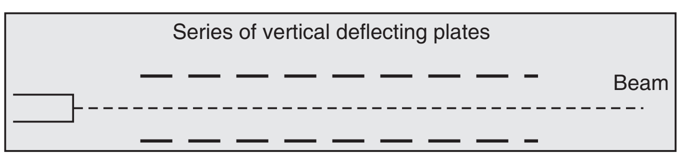


Fig. 8.19. Illustrating high frequency oscilloscope tube

8.17 Features of High Frequency Oscilloscope

Some of the main features of frequency amplifier are given below :

1. Vertical amplifier is designed to provide both high bandwidth and high sensitivity.
2. There are number of vertical deflecting plates in series are used to produce additional deflecting force needed by the electrons.
3. The low frequency cathode is replaced by high frequency cathode ray tube.
4. Time synchronization is achieved by the use of the delay lines between the vertical plates.
5. New special fluorescent material is used which increase the brightness of the display.

8.18 Mixed Domain Oscilloscopes (MDO)

Mixed Domain Oscilloscope (MDO) has been introduced in 2011. This oscilloscope has three kinds of inputs:

1. a small number (typically 4) of analog channels,
2. a large number (typically 16) of digital channels and
3. a dedicated RF input

The RF input distinguishes MDO from all other type of oscilloscopes currently available in the market. Measurements on all input types are acquired with a single time base, are viewed on a single display, and any combination of these signals can be used to trigger the oscilloscope.

An MDO combines the measurement capabilities and the use model of a Digital Storage Oscilloscope (DSO) with many of the measurement capabilities of a logic analyzer and a spectrum analyzer. It provides the ability to accurately time-correlate analog, digital, and RF signals with each other, and allows the user to see how the RF spectrum changes over time.

Applications

Mixed Domain Oscilloscope is used to characterize and debug wireless-enabled embedded systems and hunting noise sources.

8.19 Mixed-Signal Oscilloscopes

A mixed-signal osclloscope (or MSO) has two kinds of inputs:

1. 2 or 4 of analog channels, and
2. 16 digital channels.

These measurements are acquired with a single time base, they are viewed on a single display, and any combination of these signals can be used to trigger the oscilloscope.

An MSO combines all the measurement capabilities and the use model of a Digital Storage Oscilloscope (DSO) with some of the measurement capabilities of a logic analyser. MSOs typically lack the advanced digital measurement capabilities and the large number of digital acquisition channels of full-fledged logic analyzers, but they are also much less complex to use. Typical mixed-signal measurement uses include the characterization and debugging of hybrid analog/digital circuits like: embedded systems, analog-to-digital converters (ADCs), digital-to-analog converters (DACs), and control systems.

8.20 PC-Based Oscilloscopes (PCO)

A new type of "oscilloscope" called PC-based oscilloscope (PCO) has emerged recently. It consists of a specialized signal acquisition board (which can be an external USB or Parallel port device, or an internal add-on PCI or ISA card). The hardware itself usually consists of an electrical interface providing isolation and automatic gain controls, several high-speed analog-to-digital converters and some buffer memory, or even on-board Digital Signal Processor (DSPs). Depending on the exact hardware configuration, the hardware could be best described as a digitizer, a data logger or as a part of specialized automatic control system.

The PC which is usually a notebook (or desktop) computer provides the display, control interface, disc storage, networking and often the electrical power for the acquisition hardware. The viability of PC-based oscilloscopes depends on the current widespread use and low cost of standardized PCs. Since prices can range from as little as Rs 5,000 to as much as Rs 15,000 depending on their capabilities, such instruments are particularly suitable for the educational market, where PCs are common place but equipment budgets are often low.

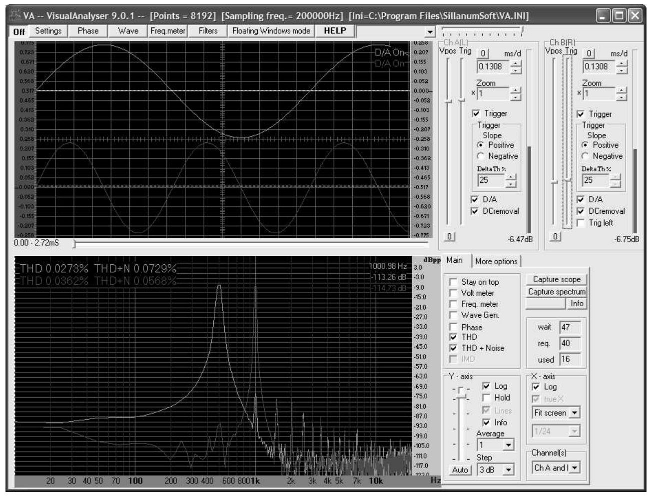


Fig. 8.20. Illustrating PC Based Oscilloscope

SUMMARY

1. Oscilloscopes can be classified in many ways. The biggest distinction is whether they are analogue or digital. There are a number of different types, and each one is suitable for different applications.
2. The dual beam CRO uses two complete separate electron beams. It can display two signals simultaneously.
3. In dual trace oscilloscope the single electron beam split into two by an electronic switch.
4. A digital oscilloscope uses an analog-to-digital converter to convert "the measured voltage" into digital information.
5. In digital storage oscilloscope it is necessary to capture the digital signal and store it. There are three different types of acquisition methods.
6. Sampling oscilloscopes are used for analyzing very high frequency signals.
7. Digital phosphor oscilloscope has unique acquisition and display characteristics to accurately reconstruct the signal.
8. Digital phosphor oscilloscope uses a purely electronic digital phosphor which is actually continuous updating of the database.
9. To measure or examine the signal whose frequency is higher than the 300 MHz high frequency oscilloscope is used.

GLOSSARY

Dual Beam Oscilloscope: The dual beam oscilloscope has two separate electron beams, and therefore two completely separate vertical channels.

Digital Phosphor oscilloscope: Digital phosphor oscilloscope uses the unique parallel processing architecture of permits higher level of signal visualization and is very much useful in detecting transient events.

Digital Read out Oscilloscope: It provides digital readout of the signal information such as voltage or time etc. in addition to the conventional CRT display.

Delayed Time Base Oscilloscope: In this oscilloscope, the input signal of the vertical plates is delayed by some time with delay circuit

Dual Trace Oscilloscope: The dual trace oscilloscope has one cathode ray gun with an electronics switch, which switches two signals to a signal vertical amplifier.

High Frequency Oscilloscope: In high frequency oscilloscope a series of vertical deflection plates are used.

DESCRIPTIVE QUESTIONS

1. List the different types of oscilloscopes.
2. What do you understand by delayed time base oscilloscope?
3. Explain the working of dual beam oscilloscopes.
4. Describe the dual trace oscilloscope with their operating mode.
5. Draw the block diagram of a dual trace digital oscilloscope.
6. Explain the alternate and chop mode.
7. What are the advantages of dual trace over dual beam CROs for multiple trace?
8. Differentiate between double beam CRO and dual trace CRO in detail. *(GBTU/MTU, 2006-07)*
9. Describe the construction and working of dual beam CRO using block diagram. *(GBTU/MTU, 2005-06)*
10. Explain sampling methods used in digital oscilloscopes.
11. Differentiate between analog oscilloscope, digital storage oscilloscope and digital phosphor oscilloscope.
12. Write specification of a digital oscilloscope.
13. Describe the principle of working and circuit diagram of a digital oscilloscope.
14. Discuss the advantages and disadvantages of analog and digital type of oscilloscope.
15. Explain the following features of an analog type storage oscilloscope.
    (*i*) Bistable persistence storage.
    (*ii*) Bistable storage.
    (*iii*) Fast storage.
16. Draw the block diagram of storage oscilloscope and explain the working of each block. *(GBTU/MTU, 2002-03)*
17. Explain the working principle of
    (*i*) Sampling CRO (*ii*) Storage CRO
    (VTU, May 2007)
18. Write the principle of dual trace oscilloscope. Also explain its various modes of operation. *(VTU, Dec. 2007, 2008)*
19. Write a brief note on CRO measurements. *(VTU, Dec. 2007)*
20. Write in brief about various CRO probes and their applications. *(VTU, Dec. 2008)*
21. State the advantages of sampling oscilloscope. Also draw the block diagram of sampling oscilloscope and explain. *(VTU, May 2009)*
22. Write a brief note on front panel controls of CRO. *(VTU, Dec 2007, 2009)*
23. Write short note on storage type oscilloscope. *(GBTU/MTU, 2008-09)*
24. How does the digital oscilloscope differ from the conventional storage oscilloscope using a storage cathode tube? *(GBTU/MTU, 2004-05)*
25. Explain the working of dual trace CRO and dual beam CRO. (Mumbai University, June 2007)
26. What is a sampling oscilloscope? What are its various applications?
27. How does the digital storage oscilloscope differ from a convention oscilloscope? Explain the principle, features and application of DSO. *(Mumbai University, June 2009)*
28. Draw and explain the block diagram of DSO. Describe the various modes of operation. *(Mumbai University, Dec 2008)*
29. Describe CRO probe and sampling oscilloscope. *(GBTU/MTU, 2010-11)*

30. Explain the three different mode of operation of digital storage oscilloscope.

(GBTU/MTU, 2009-10)

31. Explain the working of sampling oscilloscope with suitable diagram.

(GBTU/MTU, 2009-10)

MULTIPLE CHPOICE QUESTIONS

1. A dual-trace CRO has,

(*a*) One electron gun
(*b*) Two electron guns
(*c*) One electron gun and one-two pole switch
(*d*) two electron guns and one-two pole switch

2. In a digital oscilloscope the input signal are,

(*a*) Directly applied to the oscilloscope
(*b*) Multiplexed converted to digital form and stored and applied to oscilloscope
(*c*) Multiplexed converted to digital form and stored, converted to analog form and applied to oscilloscope
(*d*) Applied to amplifier, stored as analog signals, multiplexed, converted to digital form, stored in digital form, converted to analog form, and applied to CRO through an amplifier.

3. A vertical amplifier for a CRO can be designed for:

(*a*) Only a high gain
(*b*) Only a broad bandwidth
(*c*) A constant gain times bandwidth product
(*d*) All of the above

4. In an oscilloscope, when the unknown signal applied to the vertical plates is being synchronized with the sweep signal applied to horizontal plates, the pattern seen on the CRO screen moves towards the right. It means that,

(*a*) The frequency of the signal is lower than of the sweep signal
(*b*) The frequency of the signal greater than of the sweep signal
(*c*) The frequency of the signal is equal to the frequency of sweep signal
(*d*) None of the above.

5. An aquadag is used in a CRO to collect,

(*a*) Primary electrons
(*b*) Secondary emission electrons
(*c*) Both primary and secondary emission electrons
(*d*) None of the above

6. A dual trace CRO has,

(*a*) One electron gun
(*b*) Two electron guns
(*c*) One electron gun and one two-pole switch
(*d*) Two electron guns and one two-pole switch

(UPSC Engg. Service. 1999)

ANSWERS

1. (*c*) **2.** (*d*) **3.** (*c*) **4.** (*a*) **5.** (*b*) **6.** (*c*)

Chapter 9

Signal Generators and Analysers

Outline

Objectives

After completing this chapter, you should be able to:

- Describe the purpose of a signal generator.
- List the various types of signal generators.
- Draw the block diagram of an audio frequency and square wave generator and explain their working.
- Compare the signal generator and the function generator.
- Sketch the block diagram of a pulse generator and explain its working.
- Describe the construction and operation of wave analyzers.
- Draw the block diagram of spectrum analyser and explain its operation.
- Sketch the block diagram of harmonic analyser and explain its operation.

9.1 Introduction

A signal generator is an electronic device (or equipment) that generates repeating or non-repeating electronic signals (in either the analog or digital domains). It is generally used in designing, testing, troubleshooting, and electroacoustic devices and circuits. For example audio-frequency (AF) and radio-frequency (RF) signals are needed for the repair of radio, television and other electronic equipment. The waveform generated by various types of electronic devices range in complexity from simple fixed frequency sinusoidal waves to those produced by highly sophisticated devices such as those needed for testing complex telecommunication circuits and networks.

As discussed later in this chapter, there are many different types of signal generators with different purposes and applications. In general, no device is suitable for all possible applications.

The generation of signals is important in electronic system. The signal generator is used to provide known test condition for the performance evaluation of various electronic systems and for replacing missing signals in system.

For generating sinusoidal signals of known frequency we use oscillator. It is one of the basic and useful instruments used in electronic measurements. Since sinusoidal waveforms are encountered so frequently in electronic measurement work, the oscillator (Sinewave generator) represents the largest single category of signal generators. This device covers the frequency range from a few Hz to many GHz.

Many times we need non-sinusoidal waves such as rectangular waves, sawtooth waves, square wave etc. For generating non-sinusoidal wave we use multivibrators. It is a switching circuit, capable of storing binary numbers, counting pulses, synchronizing arithmetic operations and performing other essential functions used in digital systems.

9.2 Signal Generators

The signal generator, like an oscillator, is a source of sinusoidal signals but the signal generator is also capable of modulating its sinusoidal output with other signals. A signal generator is an instrument that provides a controlled output waveform or signal for use in testing, aligning or in measurements on other circuits or equipment. There are many different types of signal generators, with different purposes and applications (and at varying levels of expense); in general, no device is suitable for all possible applications. There are various types of signal generators, but the following characteristics are common to all types:

1. Low harmonic content
2. Stable operating frequency
3. Stable output amplitude
4. Low spurious output i.e. hum, noise, modulation etc.

Classification of Signal Generators

The signal generators can be classified into the following categories:

1. Audio generators
2. Function generators
3. Pulse generators
4. RF generators
5. Random Noise Generator
6. Frequency synthesizers
7. Other signal generators.

9.3 Basic Standard Signal Generator

The sine wave generator represents the largest single category of signal generator. This covers a frequency range from a few Hertz to Giga-Hertz. Fig. 9.1 shows the simplest form of sine wave generator.

Basic standard signal generator consists of two basic blocks an oscillator and an attenuator. The accuracy of the frequency, stability, and freedom from distortion depend on the design of the oscillator. The amplitude depends on the design of the attenuator.

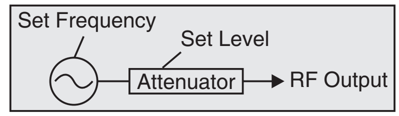


Fig. 9.1.

9.4 Standard Signal Generator

A standard generator produces known and controllable voltages. The block diagram of standard signal generator is shown in Fig. 9.2.

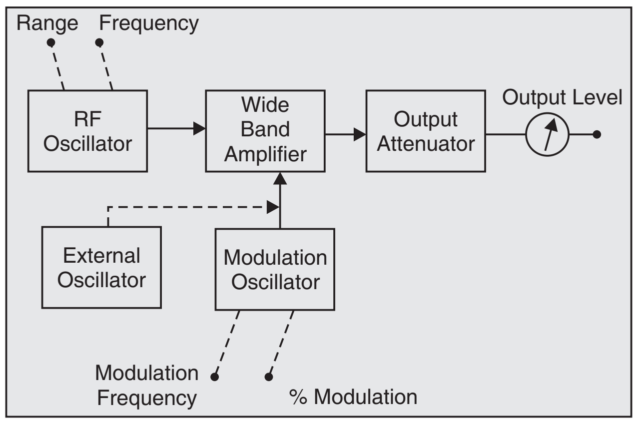


Fig. 9.2.

The carrier frequency is generated by a very stable RF oscillator using an LC tank circuit, having a constant output over any frequency range. The frequency of oscillations is indicated by the frequency range control. AM is provided by an internal sine wave generator or from an external source. Modulation is done in the output amplifier circuit. This amplifier delivers the output, modulation carrier to an attenuator. The output voltage is read by an output meter and the attenuator output setting.

It is used as power source for the measurement of gain, signal to noise ratio (S/N), bandwidth, standing wave ratio and other properties. It is extensively used in the testing of radio receivers and transmitters.

9.5 Audio Generators

The audio generators covers the frequency range 20 Hz to 20 kHz, although few models produce signals up to 100 kHz. Audio generators always produce *pure sine* waves and most also produce square waves. They uses a 600 Ω output impedance and produce output levels from – 40 dB mW to + 4 dB mW.

Two methods of frequency selection are typically used in audio signal generators, *continuous* and *step*. On the continuous type of a dial, we turn a knob to the desired frequency. Many such audio generators have a scale that reads 20 to 200 (or alternatively 2 to 20) and a *range* selector switch determines whether the output frequencies will be 20 to 200 Hz, 200 to 2000 Hz or 2000 to 20,000 Hz. In a step-tuned generator, these controls are replaced by a *rotary* or

Audio signal generator

pushbutton switch bank. As many as four decode switches might be used, although there is a more common number. These will be marked 0 through 100, 0 through 10 and 0.1 through 1.0 in decade steps. A multiplier switch determines whether the actual frequency will be X1, X10, X100 or X1000 the frequency indicated on the selector switches.

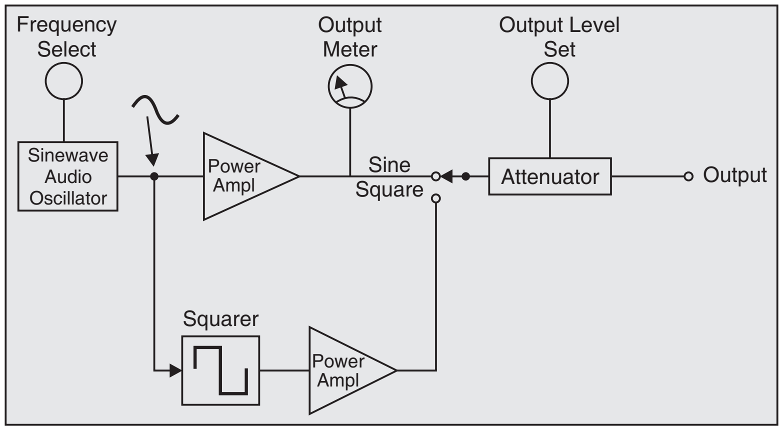


Fig. 9.3.

Figure 9.3 shows a block diagram of an audio signal generator. The audio oscillator section is usually in *RC* phase-shift oscillator (or a Wien Bridge oscillator) circuit. A power amplifier stage provides buffering between the load and the oscillator and it develops the output signal amplitude. The ac voltmeter at the output is strictly optional, but in some models it is used with a *level control* to set precisely the input signal to the attenuator. Not all quality audio signal generators use this feature. So the lack of an ac output meter is not, in itself, indication of quality. In some models, an audio digital frequency counter is used ahead of the attenuator to provide digital display of the output frequency.

Applications

The audio generators are basically used to test the amplitude and frequency response of audio amplifiers.

A typical specification of an audio generator may be expressed as follows:

1. Frequency range: 20 Hz to 100 kHz in 4 range with 10:1 vernier control
2. Accuracy : ± 2 %
3. Output Waveforms: Sine or square TTL
4. Output Impedance: 600 Ω ± 1 %
5. Sine wave amplitude: 5 mV – 5 V rms (open circuit)
6. Square wave amplitude: 15 mV to 15 V peak-to-peak (open circuit)
7. Rise time: < 0.75 μs
8. Distortion: Less than 1% at 1 kHz
9. Power Supply: 230 V, 50 Hz

9.6 Function Generators

A function generator is a signal source that has the capability of producing a wide variety of waveforms and frequencies. The most common output waveforms are sine-waves, triangular-waves, square-waves, and sawtooth-waves. The frequencies of these waveforms are adjusted from a fraction of a hertz to several hundred kHz.

Fig. 9.4.

Function generators are also capable of generating two different waveforms simultaneously. This feature is useful when two generated signals are required for particular application. For example, by providing a square wave for linearity measurements in an audio-system, a simultaneous sawtooth output may be used to drive the horizontal deflection amplifier of an oscilloscope, providing a visual display of measurement result.

Another important feature of function generators is their capability of phase-locking to an external signal source. One function generator may be used to phase lock a second function generator and the two output signals can be displaced in phase by an adjustable amount. A function generator is a piece of electronic test equipment or software used to generate simple waveforms. These waveforms can be either repetitive, or single-shot in which case some kind of triggering source is required (internal or external).

The major difference between a function generator and an audio generator is in the number of output waveforms. The audio signal generator produces only sine waves and square waves. While almost all function generators produce these basic waveforms plus triangular waves. Besides this, some function generators also produce sawtooth, pulse and non-symmetrical square waves. Figure 9.4 shows the controls of a typical function generator.

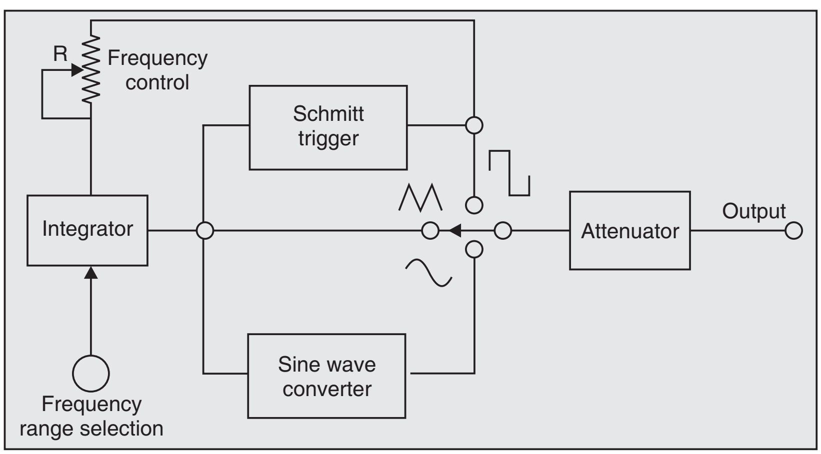


Fig. 9.5.

Figure 9.5 shows a simple block diagram of a function generator. The major parts of a function generator are schmitt trigger, integrator, sine-wave converter and an attenuator. The schmitt trigger converts a slowly varying input signal to a square wave signal. This square wave signal is available at the output as well as it is also connected to the integrator as an input through a potentiometer (*R*). The potentiometer is used to adjust the frequency of the output signal. The frequency range is adjusted by selecting the appropriate capacitor connected in the integrator circuit.

The sine-wave converter is a six-level (or more) diode-resistor loading circuit.

Let us see how a simple diode-resistor circuit shown in Fig. 9.6(*a*) is used to convert a triangular wave into a square wave.

Note that if diodes D_1 and D_2 and resistors R_3 and R_4 were not present in the circuit, of Fig. 9.6(*a*), R_1 and R_2 would simply behave as a voltage divider. In this case the output from the circuit would be an attenuated version of the triangular wave:

$$V_0 = V_i \frac{R_2}{R_1 + R_2}$$

With diodes D_1 and R_3 in the circuit, R_1 and R_2 still behave as a simple voltage divider until the voltage drop across R_2, VR_2 exceeds + V_1. At this point D_1 becomes forward biased, and R_3 is effectively in parallel with R_2. Now,

$$V_0 = V_i \frac{R_2 \parallel R_3}{R_1 + R_2 \parallel R_3}$$

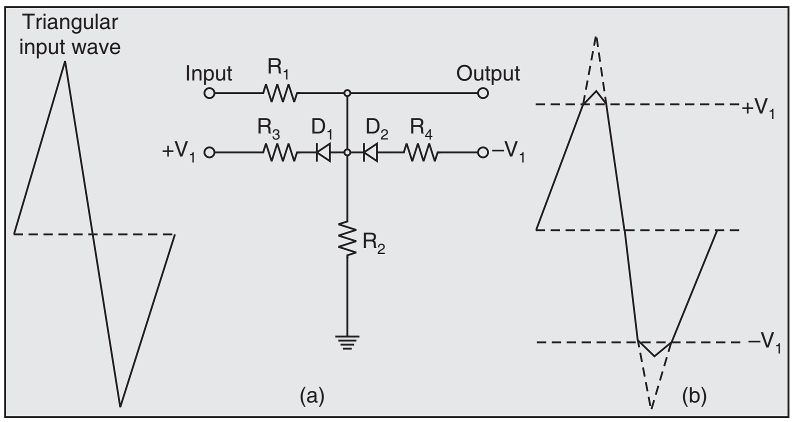


Fig. 9.6.

Output voltage levels above + V_1 are attenuated to a greater extent than levels below + V_1. Consequently, the output voltage rises less steeply than without D_1 and R_3 in the circuit (refer to Fig. 9.6(*b*). When the output falls below + V_1, the diode D_1 is reverse biased. As a result of this, R_3 is no longer in parallel with R_2, and the attenuation is once again $R_2 / (R_1 + R_2)$. Similarly during the negative half cycle of the input, the output voltage,

$$V_0 = V_i \frac{R_2}{R_1 + R_2}$$

until V_0 goes below – V_1. Then D_2 becomes forward biased, putting R_4 in parallel with R_2 and making,

$$V_0 = V_i \frac{R_2 \parallel R_4}{R_1 + R_2 \parallel R_4}$$

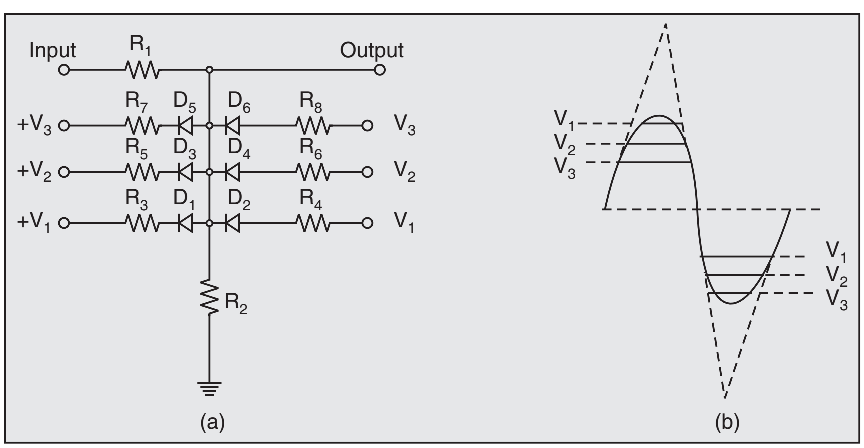


Fig. 9.7.

With $R_3 = R_4$, the negative half-cycle of the output is similar in shape to the positive half-cycle. If we employ six or more diodes, all connected via resistors to different bias voltage levels (refer to Fig. 9.7(*a*), a good sine-wave approximation can be achieved. With six diodes, the three positive bias voltage levels and three negative bias voltage levels, the slope of the output wave changes three times during each quarter cycle. Assuming correctly selected bias voltages and resistor values, the output wave shape is as shown in Fig. 9.7(*b*).

Applications

The function generator is an essential equipment for an electronic laboratory to generate signals to test a variety of analog and digital system during the design phase as well as to trouble shoot such systems.

Figure 9.8 shows the picture of a Tektronix function generators Model No. CFG 253. This model has a frequency range form 0.03 Hz to 3 MHz. In addition to sine, square and triangular waves it can also produce *TTL* signals. Another function generator from Tektronix (Model No. CFG280 has a wide frequency range form 0.01 Hz to 11 MHz. It has a built in frequency counter with a range from 1 Hz to 100 MHz.

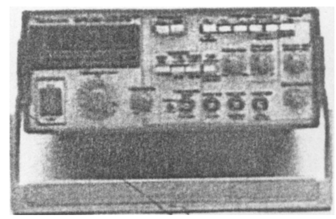


Fig. 9.8. (Courtesy: Tektronix Corporation)

Applications

The function generators can be employed in a variety of applications in the area of product design, training, manufacturing production test, field repair, bench calibration and repair, laboratory and research, and education. Mainly they are used for testing amplifiers, filter and digital circuits.

A typical specification of a function generator may be expressed as follows:

1. Output waveforms: Sine, square, triangular, ramp, pulse, AM and FM modulated, arbitrary.
2. Frequency range: 0.001 Hz to 20 MHz.
3. Frequency stability: 0.05 %.
4. Distortion: –55 dB below 50 kHz, –40 dB above 50 kHz.
5. Output amplitude (open circuit): 10 V_{p-p}
6. Impedance: 50Ω

9.7 Comparison between Signal Generator and Function Generator

Table 9.1 shows some of the important points of comparison between the signal generator and function generator.

Table 9.1 Comparison between Signal Generator and Function Generator

S. No	*Signal Generator*	*Function Generator*
1.	Generates signal with Sinewave only	Generates signals with many waveforms like sine, square, sawtooth, triangular etc.
2.	Frequency stability is limited.	Frequency Stability is high.
3.	Frequency is controlled by frequency range controller.	Frequency is controlled by varying the magnitude of the current which drives the integrator.

9.8 Pulse Generators

A pulse generator can either be an internal circuit or a piece of electronic test equipment used to generate pulses. Simple pulse generators usually allow control of the pulse repetition rate (frequency), pulse width, delay with respect to an internal or external trigger and the high- and low-voltage levels of the pulses. More-sophisticated pulse generators may allow control over the rise time and fall time of the pulses. Pulse generators may use digital techniques, analog techniques, or a combination of both techniques to form the output pulses. For example, the pulse repetition rate and duration may be digitally controlled but the pulse amplitude and rise and fall times may be determined by analog circuitry in the output stage of the pulse generator. With correct adjustment, pulse generators can also produce a 50% duty cycle square wave. Pulse generators are generally single-channel providing one frequency, delay, width and output. To produce multiple pulses, these simple pulse generators would have to be ganged in series or in parallel.

A new class of pulse generator offers both multiple input trigger connections and multiple output connections. Multiple input triggers allow experimenters to synchronize both trigger events and data acquisition events using the same timing controller.

Figure 9.9 shows the block diagram of a pulse generator. As seen, an a stable multivibrator generates square waves. This is used to trigger monostable multivibrator (i.e. one-shot). The pulse repetition rate is set by the square-wave frequency. The one-shot triggers on the leading edge of the square-wave and produces one output pulse for each input cycle. The duration of each output pulse is set by the one-time of the one-shot. It may be very short or may approach the period of the square wave. The attenuator facilities output amplitude control and dc level shifting.

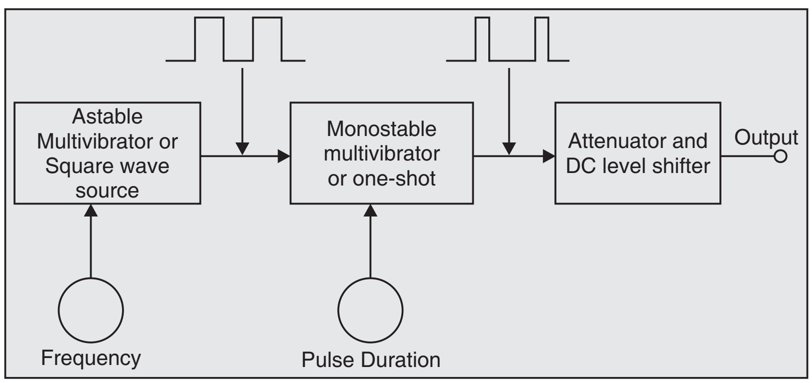


Fig. 9.9.

A typical pulse generator will allow the user to select the repetition rate, duration, amplitude and number of output pulses to be output in a given burst. The most common frequency range is from 1 Hz to 50 MHz. The pulse width is adjustable from 10 ns to over 10 ms and the output is variable from 3 mV to 30 V.

Figure 9.10 shows a pulse generator from Fluke Corporation Model No. PM5786. This instrument has a frequency range from 1 Hz to 125 MHz. The output pulse width can be varied from 8 ns to 100 ms. The instrument can also be used to generate pulse bursts. The output voltage level can be adjusted up to 10 V.

Fig. 9.10. (Courtesy Fluke Corporation)

9.9 General Purpose Pulse Generator

The basic circuit for pulse generation is the asymmetrical multi-vibrator.

The frequency range of the instrument is covered in seven decade step from 1 Hz to 10 MHz, with a linearly calibrated dial for continuous adjustment on all range. The duty cycle can be varied from 25-75 %. There are two independent outputs available:

(*a*) 50 Ω source that supplies pulses with a rise and fall time of 5 ns at 5V peak amplitude.

(*b*) 600 Ω source which supplies pulses with a rise and fall time of 70 ns at 30V peak amplitude.

This instrument can be used as free-running generator, or it can be synchronized with external signals. Trigger out pulses for synchronization are also available.

Basic Generating loop consist of the current source, ramp capacitor, the Schmitt trigger and a current switching circuit as shown in Fig. 9.11.

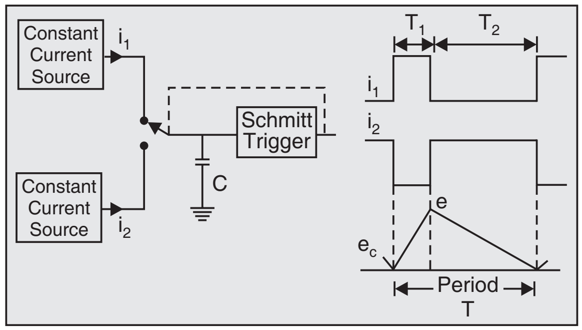


Fig. 9.11. Basic generating Loop

A laboratory type square and pulse generator is shown in Fig. 9.11 the upper current source (i_1) supplies a constant current to the ramp capacitor. The capacitor is charged at a constant current rate and the ramp voltage increase linearly. When the positive slope of the ramp voltage reaches the upper limit set by internal circuit components, the Schmitt trigger changes state. Then the trigger circuit output becomes negative and the reverse the condition of the current control switch, and capacitor start discharging. The discharging rate is linear and controlled by lower current source (i_2).

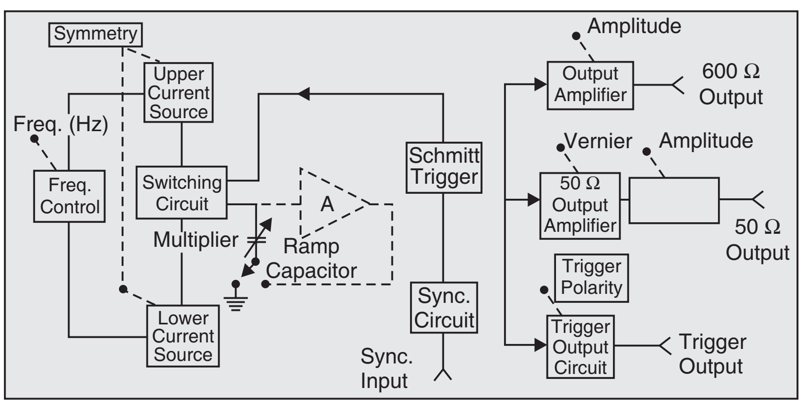


Fig. 9.12. Block Diagram of General Purpose Pulse generator

The Schmitt trigger again switches back to its original state, when the negative ramp reaches to a predetermined lower level. This provides a positive trigger circuit output that reverses the condition of the current switch again, cutting off the lower current source and switching on the upper current source. This gives one cycle of operation. The entire process is repetitive and the Schmitt trigger circuit provides negative pulse at a continuous rate. The ratio of currents, i_1/i_2 determines the duty cycle and the sum of currents ($i_1 + i_2$) determines the frequency. The size of the capacitor is selected by the multiplier switch.

The unit is powered by an internal supply that provides regulated voltages for all stage of the instrument.

Requirements of a Pulse

Some of the requirement of the pulse are given below :

1. The pulse should have minimum distortion, so that any distortion, in the display is solely due to the circuit under test.
2. The basic characteristics of the pulse are rise time, overshoot, ringing, sag and undershoot.
3. The pulse should have sufficient maximum amplitude, if appreciable output power is required by the test circuit, e.g. for magnetic core memory. At the same time, the attenuation range should be adequate to produce small amplitude pulses to prevent over driving of some test circuit.
4. The range of frequency control of the pulse repetition rate (PRR) should meet the needs of the experiment.
5. Some pulse generators can be triggered by an externally applied trigger signal; conversely, pulse generators can be used to produce trigger signals, when this output is passed through a differentiator circuit.
6. DC coupling of the output circuit is needed, when dc bias level is to be maintained.

Applications

The pulse generators are used extensively to test:

1. Memory circuits
2. Shift registers
3. Counters
4. Other digital components, subsystems and systems.

9.10 RF Generators

As radio frequency (RF) signal generator has a sinusoidal output with a frequency somewhere in the range of 100 kHz to 40 GHz region. Figure 9.13 shows the block diagram of an RF. generator. As soon, the instrument consists of an RF oscillator, an amplifier, a calibrated attenuator and an output level meter.

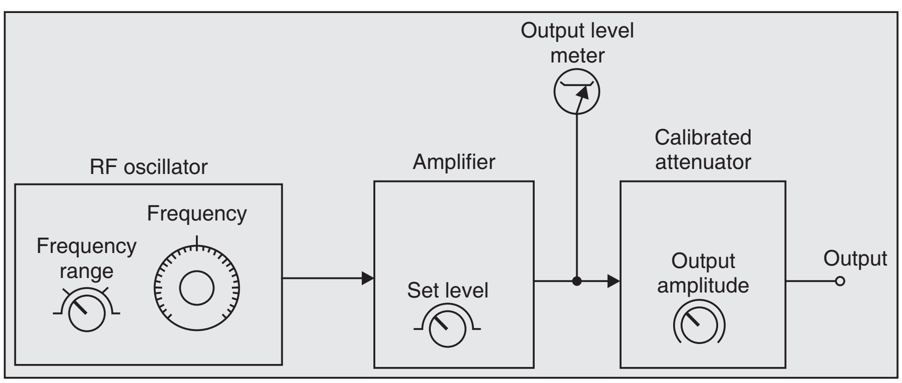


Fig. 9.13.

The RF oscillator has a continuous frequency control and a frequency range switch, to set the output to any desired frequency. The amplifier includes an output amplitude control. This allows the voltage applied to the attenuator to be set to a calibration point on the output level meter. The output level must always be *reset* to this calibration point everytime the frequency is changed. This is necessary to ensure that the output voltage levels are correct, as indicated on the calibrated attenuator.

The oscillator circuit used in an RF generator is usually either a Hartley Oscillator or Colpitts oscillator. Most RF signal generators include facilities for amplitude modulation and frequency modulation of the output. Switches are provided on the front panel to allow the user to select no modulation as well as internal or external AM or FM modulation. It may be noted that each section of the RF generator is *shielded* by enclosing it in a metal box. The whole system is then completely shielded. The purpose of shielding is (1) to prevent RF interference between the components and (2) to prevent the emission of RF energy from any point except the output terminals. As a matter of fact, even the power line is decoupled by means of RF chokes and capacitors to prevent RF emission from it.

Figure 9.14(*a*) shows an analog RF generator Model No. SML01 manufactured by Tektronics Corporation. This instrument is a general purpose signal generator and is available at low cost. It has a wide frequency range from 9 kHz to 3.3 GHz. Another RF generator Model No. SMP04 shown in Fig. 9.14(*b*) from Tektronix Corporation is a high precision signal source. It has a wide frequency range from 0.01 GHz to 40 GHz. This instrument can produce, AM–, FM–, phase– and pulse modulated signals as well.

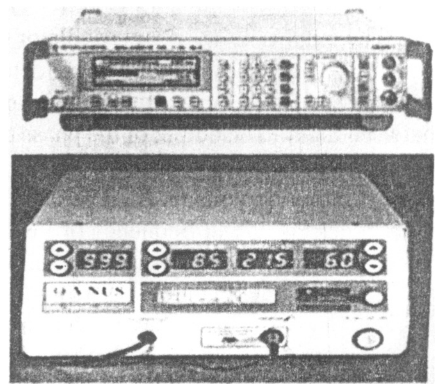


Fig. 9.14. (Courtesy Fluke Corporation)

Applications

The RF signal generators are widely used in the area of radar and communication, research and development laboratories, education and training, electromagnetic interference (*EMI*) testing and material testing. Their main applications are:

1. To perform variety of tests on radio transmitters and receivers.
2. To test the amplitude and frequency response of RF amplifiers during the design phase.

9.11 Random Noise Generator

A random noise generator gives a signal output whose instantaneous amplitude varies at random and has no periodic frequency components. Generators that cover frequency bands from low audio to microwave frequency bands are used in testing of radio and radar for signal reception in the presence of noise, and intermodulation and cross-talk tests in communication systems.

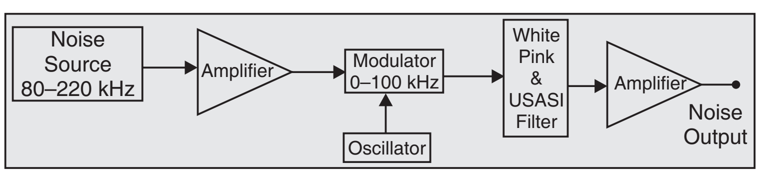


Fig. 9.15. Block diagram of random noise generator

Figure 9.15 shows the block diagram of a random noise generator. The frequency values indicated inside the block diagram are for audio frequency (AF) range. The instrument offers the possibility of using a single measurement to indicate performance over a wide frequency band, instead of many measurements of one frequency at a time. The random noise spectrum covers all frequencies and is referred to as white noise (noise having a constant power spectral density at all frequencies). The power spectrum of a noise signal generator gives its frequency content but does not characterize its wave shape. The spectrum does not specify the signal uniquely because it contains no phase information.

Random noise can be generated by using a semiconductor noise diode, which gives frequencies on a band roughly extending from 80-220 kHz. The output from the noise diode is amplified and heterodyned down to the AF band by means of a balanced symmetrical modulator. The filter arrangement controls the bandwidth and provides an output signal in three spectrum choices-white noise, pink noise and USASI noise.

From Fig. 9.16 it is seen that white noise is flat from 20 Hz to 25 kHz and has an upper cut-off frequency of 50 kHz with a cut-off slope of -12 db/octave. Pink noise has higher amplitude at lower frequency (amplitude varying inversely as the square root of frequency), and is given its name because of the similarity of its spectrum with that of red light. It is used in bandwidth analyses. USASI noise ranging simulates the energy distribution of speech and music frequencies and is employed for testing audio amplifiers and loudspeakers.

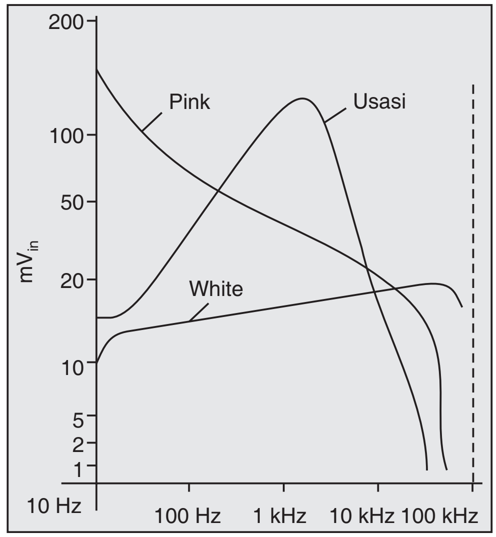


Fig. 9.16.

9.12 Frequency Synthesizer

A frequency synthesizer is an electronic system for generating any range of frequencies from a single fixed time base or oscillator. They are found in many modern devices, including radio receivers, mobile telephones, radiotelephones, walkie-talkies, CB radios, satellite receivers, GPS systems, etc. A frequency synthesizer can combine frequency multiplication, frequency division, and frequency mixing (the frequency mixing process generates sum and difference frequencies) operations to produce the desired output signal.

Three types of synthesizer can be distinguished.

(*a*) Direct Analog Synthesis (also called a mix-filter-divide architecture.

(*b*) Direct Digital Synthesizer (DDS) (Table-Look-Up).

(*c*) The third type is routinely used as communication system IC building-blocks: indirect digital (PLL) synthesizers including integer-N and fractional-N.

It is another type of RF generator that uses *phase-locked loop* (*PLL*) to generate output frequencies over a wide range. The most common range is from 1 MHz to 160 MHz. Figure 9.17 shows a simple block diagram of a frequency synthesizer. As seen, the major components of the frequency synthesizer are: voltage controlled oscillator (*VCO*), divide-by-N counter, phase detector, crystal oscillator, low-pass filter and a square-wave circuit.

The output of the crystal oscillator (a reference frequency, *fr*), is fed into one input of a phase detector. The other input of a phase detector has another square-wave applied to it as shown in the figure 9.17. The frequencies of these two square waves is identical but there is a phase difference (ϕ) between them, the output of the phase detector is a pulse waveform with pulse width controlled by the phase difference. The output of the phase detector is applied to the low-pass filter which converts it into a dc voltage, *E*. The dc voltage, *E* is used as the control voltage for the *VCO* and it determines the output frequency of *VCO*. The output of *VCO* is fed to a circuit that converts it into a square wave for triggering a digital divide-by-N counter. The divide-by-N counter divides the *VCO* frequency by a number set by a bank of switches. These switches may be push buttons with digital readouts or they may be thumb-wheel type which indicate their position numerically. The switches are connected in such a way that the displayed number is the factor N by which the output frequency is divided before being applied to the phase detector. The switches allow the user to obtain frequency which is any integer multiple of the crystal oscillator frequency.

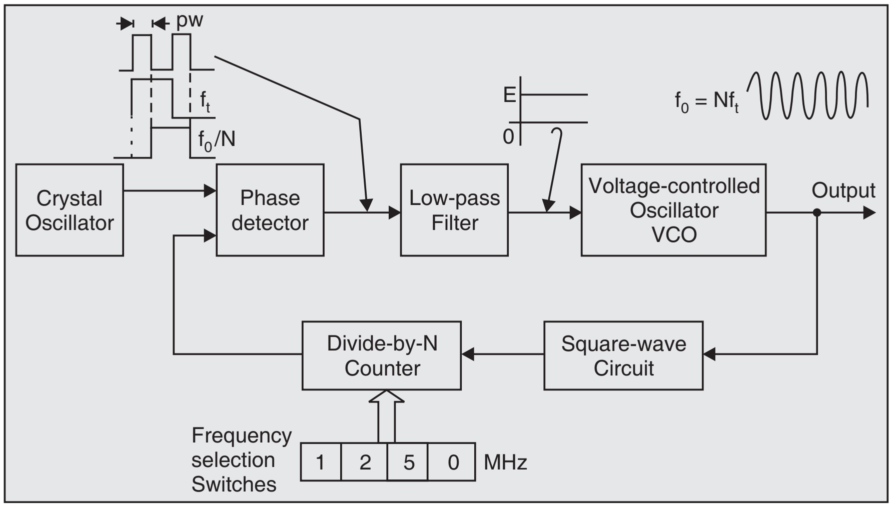


Fig. 9.17.

Applications

The frequency synthesizer is used in almost same areas as the RF signal generators.

9.13 Other Signal Generator

There are some signal generators that do not fit well in various pres-established categories. Some of these signal generators are as discussed below:

1. **RF Markers:** These devices are usually crystal controlled and have a fixed output frequency for use as a reference. These are used to calibrate TV signals.
2. **Digitally Programmable Test Oscillators:** These instruments can have extremely wide frequency range although some versions have much narrow range also. The set frequency can be programmed through the front panel keypad or via a computer interface input such as IEEE-488 general purpose interface bus (commonly known as GPIB).

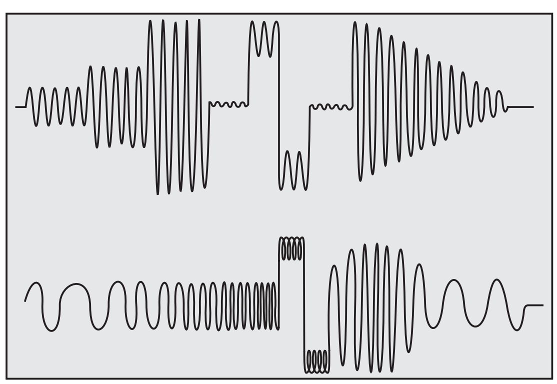


Fig. 9.18.

3. **Arbitrary Waveform Generators:** These instruments allow the user to design and generate virtually any desired waveform. The arbitrary waveform generator is quite useful

to perform a variety of tests on communication equipment. For example, a modulated signal that varies over the entire bandwidth and amplitude range of the equipment shown in Fig. 9.18 could be created for testing purpose. Noise could also be superimposed upon the signal and gaps might be introduced between waveform bursts, to investigate the response of the system. Once such a waveform has been designed, it could be stored in the instrument memory and can be recalled repeatedly for production testing.

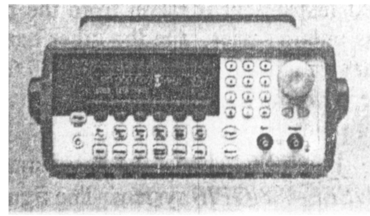


Fig. 9.19. (Courtesy: Agilent Technologies)

Figure 9.19 shows an arbitrary waveform generator from Agilent Technologies Model No. 33250A. This instrument can generate real world signals up to 80 MHz. It has a capability to display the waveforms in colour. It can be used as a function generator/pulse generator as well. The instrument has a GPIB/LAN interfaces.

Applications

The arbitrary waveform generators are used extensively in the following areas:

1. Communications design and test for producing (*a*) arbitrary IF based signals and (*b*) standard waveforms for communication.
2. Mixed signal design and test.
3. Disk drive read/write design and test.
4. Real world simulations.
5. High-speed low filter data and clock pulse generation.

9.14 Wave Analyser

Wave analyser is an instrument to measure relative amplitudes of single frequency components in a complex waveform. It is a frequency selective voltmeter which is tuned to the frequency of one signal while rejecting all other signal components.

Types of wave analyser:

1. Basic Wave analyser
2. Based upon the frequency ranges
   (*a*) Frequency selective wave analyser (frequency ranges from 20 Hz to 20 kHz)
   (*b*) Heterodyne wave analyser (frequency ranges from 10 kHz to 18 MHz)

9.15 Basic Wave Analyser

A wave analyser is an instrument designed for measuring the relative amplitudes of single-frequency components in a complex or distorted waveform. Basically the instrument acts as a frequency-selective voltmeter which is tuned to the frequency of one signal component while rejecting all the other signal components. The amplitude is indicated either by a suitable voltmeter or a CRO. Fig. 9.20 shows the basic wave analyser. It consists of:

(*a*) Primary Detector: This is a simple LC circuit. It's adjusted for resonance at the frequency of the particular harmonic component to be measured.

(*b*) Full-wave rectifier: It is an intermediate stage of the basic wave analyser. It obtains the average value of the input signal.

(*c*) Indicating Device: The indicating device is a simple dc voltmeter that is calibrated to read the peak value of the sinusoidal input voltage.

The LC circuit is tuned to a single frequency of the input signal and rejects all other frequencies. The full wave rectifier provides the average value of the input. A number of tuned filters are connected to the indicating device thorough a selector switch.

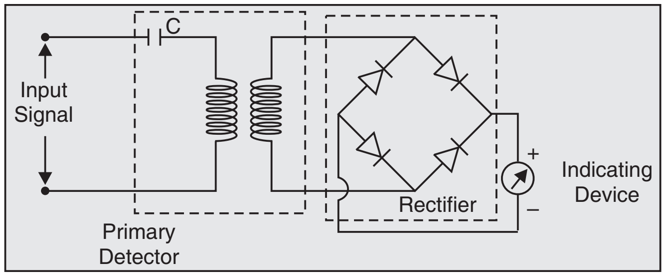


Fig. 9.20. Basic Wave Analyser

9.16 Frequency Selective Wave Analyser

Frequency selective wave analyser is used for measurements in the audio frequency ranges from 20 Hz to 20 kHz. Figure 9.21 shows the block diagram of frequency selective analyser. It consists of a narrow pass-band filter section that can be tuned to a particular frequency. The block diagram consists of attenuator, drive amplifier, High Q active filter, meter circuit and buffer amplifier.

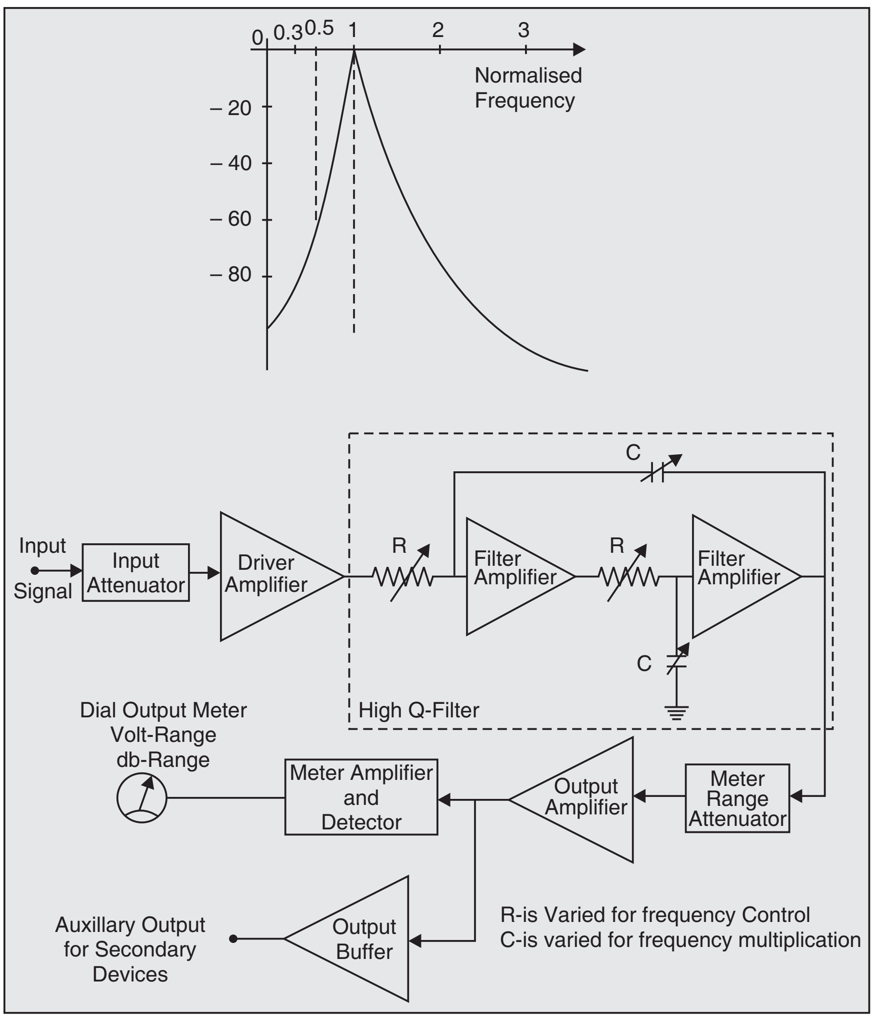


Fig. 9.21. Block diagram of a frequency selective wave analyser.

The purpose of the attenuator is to reduce the amplitude or power of the signal without distorting the waveform. The complex waveform is passed through the adjustable attenuator. It's serves as a range multiplier and permits a large range of signal amplitudes to be analysed without loading the amplifier.

The driver amplifier applies the attenuated input signal to a high Q active filter. The Q active filter consists of a cascaded arrangement of RC resonant sections and filter amplifier. This high Q filter is a low pass filter which allows the selected frequency to pass and rejects all others.

The magnitude of the frequency is indicated by the meter and the filter section identifies the frequency of the component. The capacitors generally used are the closed tolerance polystyrene type and the resistances used are precision potentiometers. The capacitor is for range changing and resistance is used to change the frequency within the filter. This wave analyser is also called a frequency selective voltmeter.

The selected signal output from the final amplifier stage is applied to the meter circuit and to an unturned buffer amplifier. The function of the buffer amplifier is to drive the output devices such as recorders or electronic counters.

The wave analyser must have extremely low input distortion, undetectable by the analyser itself. The bandwidth of the instrument is very narrow, typically about 1% of the selective band given by the following response characteristics shown in Fig. 9.22.

9.17 Heterodyne Wave Analyser

The ordinary wave analyser discussed in the last article is useful for measurement in audio frequency range but not for radio frequency (RF) range and above (MHz) ranges.To measure the frequency in the MHz range, special types of wave analysers operating on the principle of heterodyning (mixing) are needed. Such wave analysers are called the heterodyne wave analysers.

In this analyser the input signal to be analysed is heterodyned (mixed) with the signal from the tunable local oscillator in the mixer stage to produce a higher intermediate frequency (IF). The various signal frequency components can be shifted within the pass-band of the IF amplifier by tuning the local oscillator frequency. The output of the IF amplifier is rectified and applied to the meter circuit.

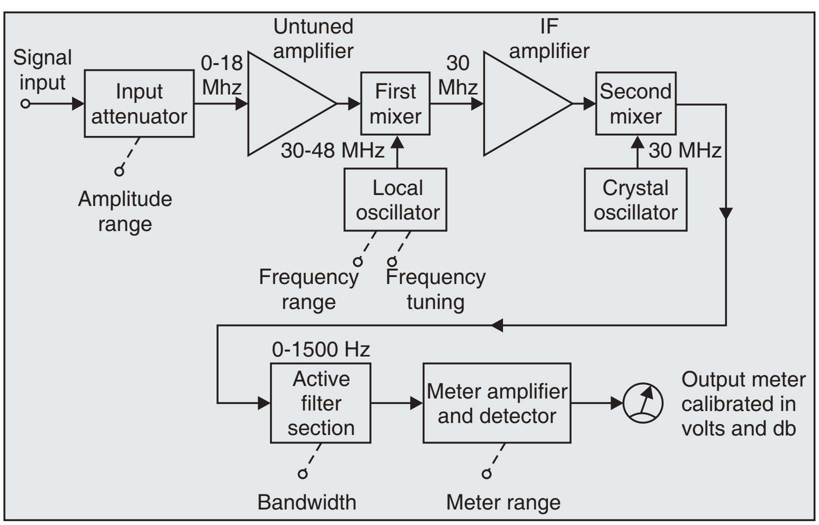


Fig. 9.22. Heterodyne Wave Analyser

A wave analyser employing the heterodyning principle is shown in Fig. The heterodyne wave analyser operates on frequency range from 10 kHz to 18 MHz. Figure 9.22 shows the block diagram of heterodyne wave analysers. The input signal enters the instruments through a probe connector that contains a unity gain isolation amplifier. After appropriate attenuation the input signal is heterodyned in the mixer stage with the signal from a local oscillator. The output of the mixer forms an intermediated frequency that is uniformly amplified by the 30 MHz IF amplifiers. This amplified signal is then mixed again with a 30 MHz crystal oscillator signal, which results in information centered on a zero frequency. An active filter with controlled bandwidth and symmetrical slopes of 72 dB per octave then passes the selected component to the meter amplifier and detector circuit. The output from the meter detector cab be read off a decibel-calibrated scale or may be applied to a recording device.

Good frequency stability in a wave analyser is achieved by using frequency synthesizers, which have high accuracy and resolution, or by automatic frequency control (AFC). In an automatic frequency control system the local oscillator locks to the signal, and so eliminates the drift between them.

Applications

Following are some of the important applications of Heterodyne Wave Analyser, which are important from the subject point of view :

1. Measure relative amplitudes of signal frequency components in a completer waveform.
2. Measure the signal energy with well defined bandwidth.
3. The wave analysers are applied industrially in the field of reduction of sound and vibrations generated by rotating electrical machines and apparatus.
4. Measure the harmonic distortion of an amplifier.
5. Measure the amplitude in the presence of noise and other interfering signals.
6. Use in harmonic analysis.

9.18 Spectrum Analyser

A spectrum analyser or spectral analyser is a device used to measure the magnitude of an input signal within the full frequency range. The main purpose of the spectrum analyser is to measure the power of spectrum of “known” and “unknown” signals. The input signal a spectrum analyser measures is electrical. However, it can measure other signals such as acoustic pressure waves or optical light waves converted to their electrical signal using transducers.

By analyzing the spectral signals of electrical signals, we can determine the dominant frequency component, power distortion, harmonics, bandwidth, and other spectral components of the signal that are not easily detectable in time domain waveforms. These parameters are useful in the characterization of electronic devices such as wireless transmitters.

The spectrum analyser displays the frequency on the horizontal axis and amplitude on the vertical axis. A spectrum analyser might look like an oscilloscope to a casual observer. But in reality it is different except for those laboratory instruments which can operate as oscilloscope or a spectrum analyser.

Figure 9.23(*a*) shows a signal which is time and frequency dependent. The same signal when viewed in the time domain is shown in Fig. 9.23(*b*) and when viewed in frequency domain, is shown in Fig. 9.23(*c*).

The main signal consists of two frequency components f_1 and $2f_1$. In the time domain a single display with a composite frequency $f_1 + 2f_1$ would be seen on the oscilloscope. In the frequency domain the components of the composite signal can be clearly seen.

Thus the study of energy distribution across the frequency spectrum of a given signal is defined as the spectrum analysis.

Spectrum analysers use either a parallel filter bank or a swept frequency technique.

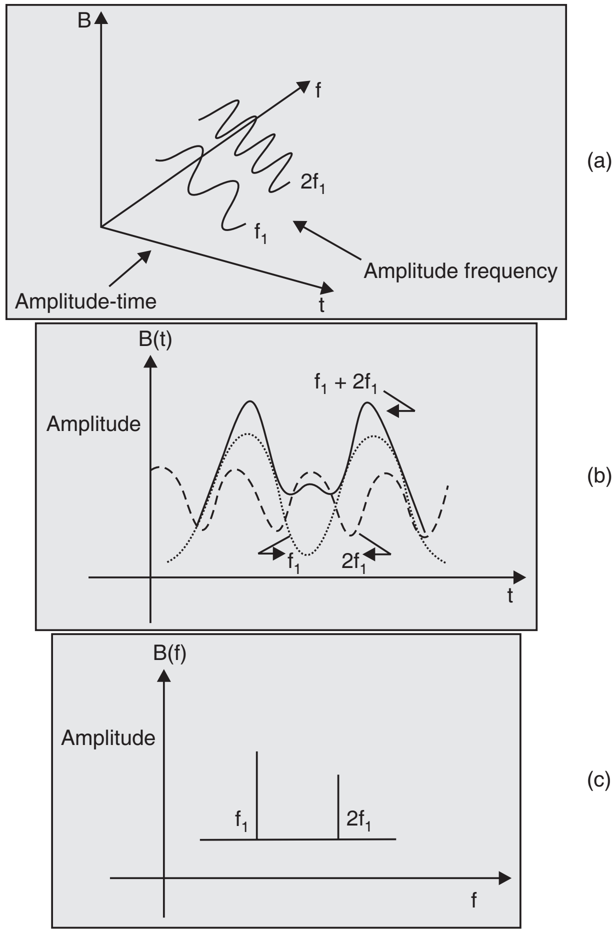


Fig. 9.23. (a), (b), (c)

Parallel Bank Analyser: In this technique the frequency range is covered by a series of filter whose central frequencies and bandwidth are so selected that they overlap each other.

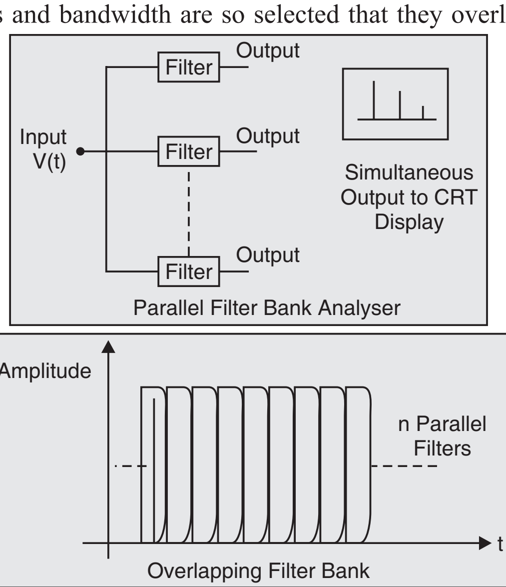


Fig. 9.24. Spectrum Analyser

Swept Technique: This technique is used in RF or microwave signals for wide band narrow resolution analysis

The spectrum analysis is divided into major categories on account of instrumentation limitations and capabilities:

(*a*) Audio Frequency (AF) analysis

(*b*) Radio Frequency(RF) spectrum analysis

The RF spectrum analysis covers a frequency range of 10 MHz to 40 GHZ, and hence is more important because it includes the majority of communication, navigation, radar, and industrial instrumentation frequency bands.

The spectrum analysis of a signal provides the information about:

1. Measurement of frequency and its response
2. Component levels
3. Bandwidth
4. Frequency Stability
5. Harmonic and intermodulation distortion
6. Spectral purity
7. Modulation index and attenuation

9.19 Block Diagram of Spectrum Analyser

The spectrum analyser is an instrument that brings together a superhetrodyne radio receiver with a swept frequency local oscillator and an oscilloscope to present a display of amplitude versus frequency. The block diagram consists of:

1. Input Mixer
2. Sweep Oscillator
3. Filter
4. Detector
5. Display (CRT)

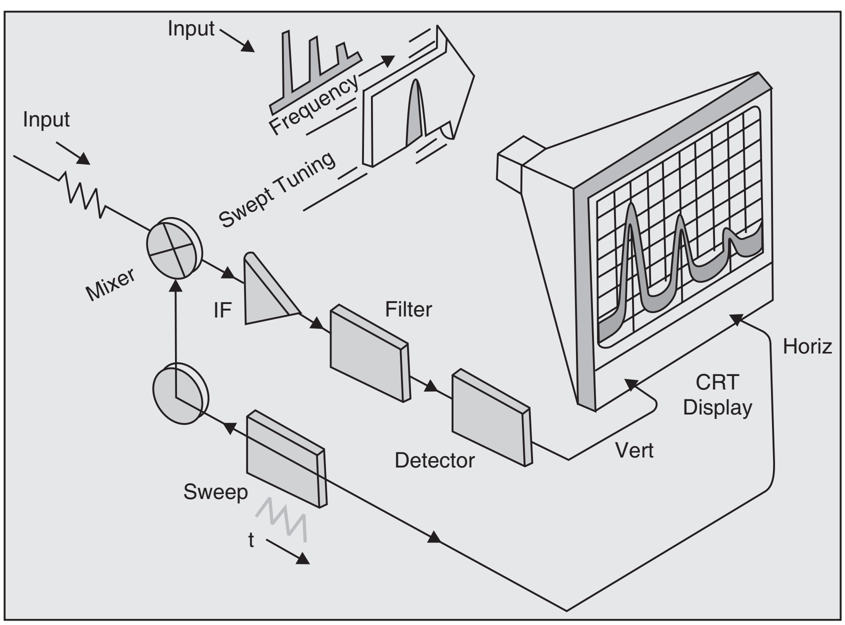


Fig. 9.25.

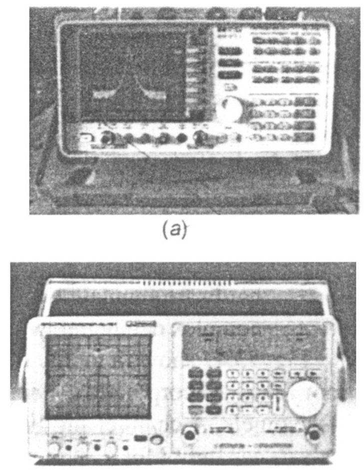
Figure 9.25 shows a simple block diagram of a spectrum analyser. As seen, the spectrum analyser is actually a superhetrodyne receiver in which local oscillator is a sweep generator. A low frequency saw-tooth wave is applied to both the sweep oscillator and the horizontal deflection plates of the CRT, producing a horizontal deflection that is a function of frequency. The lowest frequency is represented by left side of the trace while the highest frequency is represented by the right side of the trace. The sweep is from left to right.

The input signal is mixed with local oscillator to produce the IF (i.e. intermediate-frequency or difference) signal. The bandwidth of the IF amplifier is relatively narrow. So the output signal at the detector will have a strength that is proportional to the frequency that the local oscillator is converting to the IF at that instant. The display will then contain "poles" that represent the amplitudes of the various input frequency components.

There are several spectrum analysers available in the market manufactured by the companies like Rhode and Schwarz (Tektronix), Hewlett Packard (now called Agilent Technologies), and so on. Figure 9.26 shows two commercially available spectrum analyses.

The spectrum analyser shown in Fig. 9.26(*a*) is Model FSE 30 manufactured by Rhode and Schwarz but marked by Tektronix Corporation.

It has a frequency range from 20 Hz to 76.5 GHz, a bandwidth from 1 Hz to 10 MHz. Another spectrum analyser Model No. 3066 shown in Fig. 9.26(*b*) is a real-time instrument. It has a frequency range from DC to 5 MHz, a bandwidth from DC to 3 GHz. The real-time spectrum analyser take a very different approach compared to traditional sweeping spectrum analysers. Rather than acquiring one frequency step at a time, the real time spectrum analyser captures a block of frequencies all at once.



(*a*) (*b*)

Fig. 9.25. (Courtesy: Rhode and Schwarz and Tektronics Corporation)

It is possible to use computers to do spectrum analysis of the signals. There is a variety of software available over the internet from several companies. Some softwares can be downloaded free of cost from the companies web-sites.

Applications

The spectrum analyser is used to:

1. check the spectral purity of signal sources.
2. evaluate local electromagnetic interference (*EMI*) problems.
3. do site surveys prior to installing radio receiving or transmitting equipment.
4. test transmitters.
5. analyse signatures.

9.20 Real Time Spectrum Analyser

The Spectrum analyser which presents the effect of changes in all the input frequencies, on its spectrum display is called real time spectrum analyser.

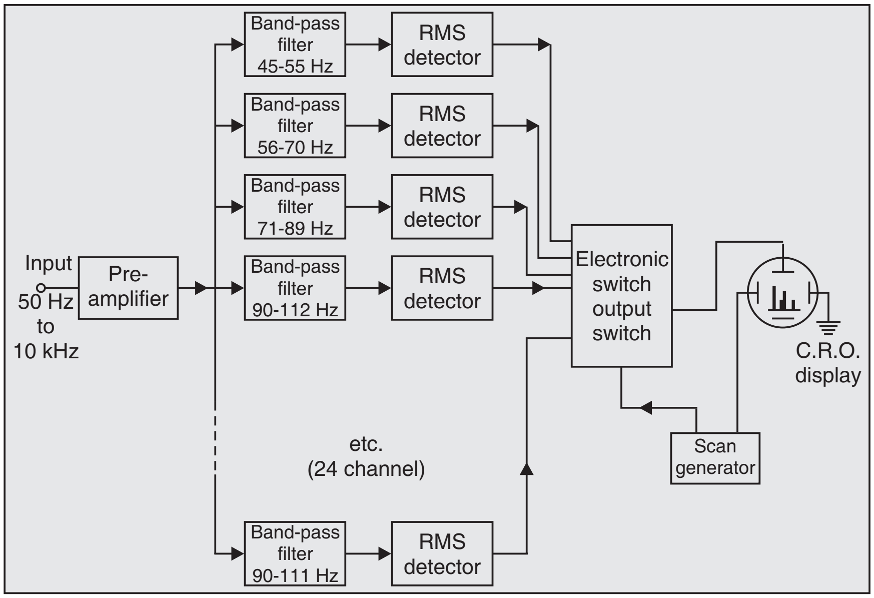


Fig. 9.27.

Figure 9.27 shows the block diagram of spectrum analyser. It covers the frequency range from 50 Hz to 10 kHz. It's a multichannel analyser consisting of a set of bandpass filters and RMS detector. These are connected through an electronic scan switch called output scanner to the CRO. The electronics switch sequentially connects the filter outputs to the CRO. The scan generator provides the horizontal deflection on CRO. The output of scan generator is a sawtooth output which is synchronized with the electronic switch.

These analysers are only used in the audio frequency applications and can use as many as 32 filters.

Disadvantages

Real Time Spectrum Analyser has some disadvantages also, they are given below:

1. System is Complex.
2. Poor resolution.
3. Frequency axis of the display is in flexible.
4. Resolution cannot be adjusted.

Applications

Spectrum analysers are widely used to measure the frequency response, noise and distortion characteristics of all kinds of RF circuitry, by comparing the input and output spectra. Following are some of the important applications :

1. Check the spectral purity of signal sources.
2. In telecommunications, spectrum analysers are used to determine occupied bandwidth and track interference sources.
3. In EMC testing, spectrum analysers may be used to characterize test signals and to measure the response of the equipment under test.
4. Do site surveys prior to installing radio receiving or transmitting equipment.
5. Test transmitters.
6. Analyses signatures.

9.21 Logic Analysers

The oscilloscope is probably the best tool for the development of analog or digital system design. It can be used to examine the waveforms and determine the voltage and rise time of the analog or digital signals. But the oscilloscope has two limitations especially when used in digital system design: (1) high speed random pulses can not be observed easily (2) oscilloscope cannot monitor a few signal lines simultaneously. For example, in a commonly available oscilloscope, the maximum number of inputs are four.

For these reasons, the logic analysers has been developed. It operates on a slightly different principle than that of an oscilloscope. Because there are many signal lines in a digital system (such as a microprocessor based system), the data is changing rapidly on each line, a logic analyser must take a *snap shot* of the activities on the lines and store the logic state of each signal in memory for each cycle of the system clock. The conditions under which the snapshot is taken are determined by triggering circuits, which can respond to various combinations of events.

The logic analyser enables the activity of many digital signal points to be recorded simultaneously and then examined in detail. The information is recorded with respect to a clock signal to determine whether they are HIGH or LOW with respect to a defined threshold voltage. This information is stored in memory and is then available for detailed analysis via the logic analyser's display. The clock signal can be internally or externally generated.

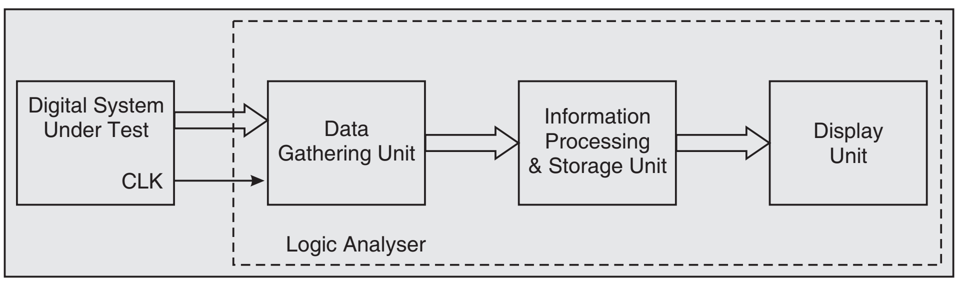


Fig. 9.28.

Figure 9.28 shows a block diagram of a typical logic analyser. It has a data gathering unit, information processing and storage unit and a display unit. The data gathering unit has (1) a pod slots for carrying data from the digital system under test to the logic analyser and (2) a key pad. The key pad is used to enter commands and set up the parameters that the logic analyser will use. The display unit is a cathode ray tube (*CRT*) that displays the command menu for the operator and also displays the output data.

Applications

- hardware/software debugging
- parametric/mixed signal testing
- hardware simulation and stimulus-response testing
- complex debugging with deep memory.

Figure 9.29 shows a family of logic analysers, available from Tektronix corporation. Each logic analyser has at least 34 channels. 4-channel digitizing oscilloscope, off-line analysis capability for viewing data and creating setups on a separate PC.

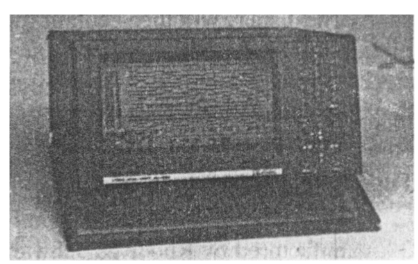


Fig. 9.29. Logic analysers

Applications

Logic analyser is a very powerful tool in the field of microprocessor based system development.

Some of its major applications in this area are:

1. Hardware debug and verification.
2. Processor/bus debug and verification.
3. Embedded software integration, debug and verification.

9.22 Harmonic Distortion

When the sinusoidal input signal applied to electronic devices, such as an amplifier, result should be a sinusoidal output waveform. But the output waveform is not exact replica of the input waveform because of various types of distortions that may occur. Distortion is the result of the inherent non-linear characteristics of different components used in an electronic circuit.

Non-linear behavior of circuit elements introduces harmonics in the output waveform and the resultant distortion is often called as harmonic distortion. The different types of distortion caused by amplifiers are:

1. Frequency Distortion
2. Phase Distortion
3. Amplitude Distortion
4. Intermodulation Distortion
5. Cross-over Distortion

9.23 Total Harmonic Distortion

The distortion caused due to nonlinear behaviour of the critical elements is called harmonic distortion. If a sine wave is harmonically distorted it consists of a fundamental frequency 'f' and the harmonic multiples of fundamental frequency $2f$, $3f$ … etc.

The harmonics consisting of sine waves with frequencies which are multiples of the fundamental of the input signal. Total harmonic distortion (THD) is given by,

$$THD = \frac{[\Sigma(\text{Harmonics})^2]^{1/2}}{\text{Fundamental}}$$

A measure of distortion represented by a particular harmonic is simply the ratio of amplitude to that of the fundamental harmonic distortion (HD) and is represented by,

$$D_2 = \frac{E_2}{E_1}, \quad D_3 = \frac{E_3}{E_1}, \quad D_4 = \frac{E_4}{E_1}, \ ...... \ D_n = \frac{E_n}{E_1},$$

Where D_n is the distortion of the nth harmonic and E_n represents the amplitude of the nth harmonic. E_1 is the amplitude of fundamental.

$$\text{THD} = \frac{[\Sigma(\text{Harmonics})^2]^{1/2}}{\text{Fundamental}}$$

$$= \frac{[E_2^2 + E_3^2 + E_4^2 \ .... \ E_n^2]^{1/2}}{E_1}$$

$$= \sqrt{\left(\frac{E_2}{E_1}\right)^2 + \left(\frac{E_3}{E_1}\right)^2 + \left(\frac{E_4}{E_1}\right)^2 + ... + \left(\frac{E_n}{E_1}\right)^2}$$

$$= \sqrt{D_2^2 + D_3^2 + D_4^2 + ... + D_n^2}$$

Percentage harmonic distortion

$$= \sqrt{D_2^2 + D_3^2 + D_4^2 + ... + D_n^2} \times 100$$

9.24 Transient Intermodulation Distortion

The transient intermodulation distortion occurs in amplifier when the input signal of the amplifier changes rapidly then the amplifier is not able to respond this rapid change.

To test amplifier output for the transient intermodulation distortion the amplifier fed with a square wave signal with high frequency sine wave superimposed on it. When an amplifier is ideal then the output will change accordance with the change in the input as shown in Fig. 9.30. In such cases the amplifier output is free of transient intermodulation distortion.

For practical amplifier, there always exists a transient intermodulation distortion.

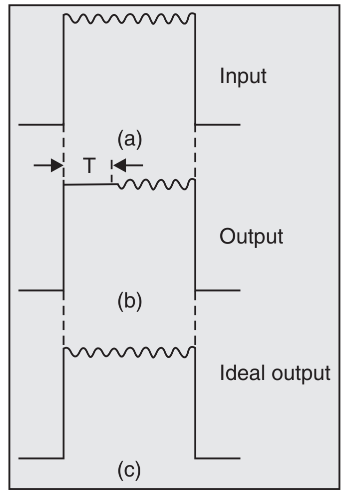


Fig. 9.30. Transient Intermodulation Distortion

9.25 Intermodulation Distortion Meter

When a signal with high frequency, f_1 and a signal with low frequency, f_2 are mixed in a linear circuit the output contains two frequencies only. If the same two signals with frequencies f_1 and f_2 are mixed into the non-linear circuit then the output contains sum and the difference of original frequencies as $(f_1 + f_2)$ and $(f_1 - f_2)$. This is a modulation. The common example of non-linear circuit is an amplifier with distortion.

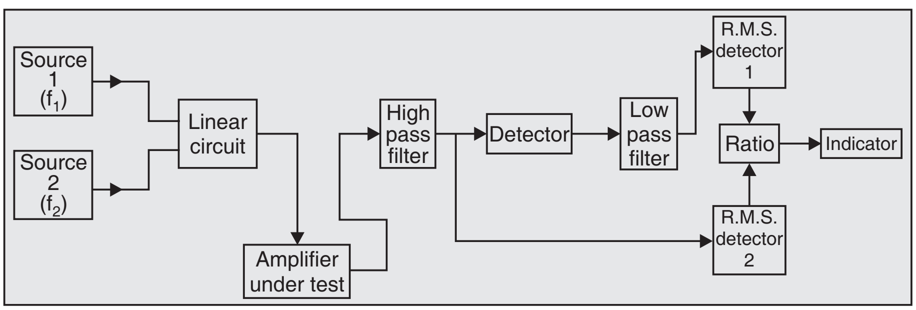


Fig. 9.31. Intermodulation Distortion Meter

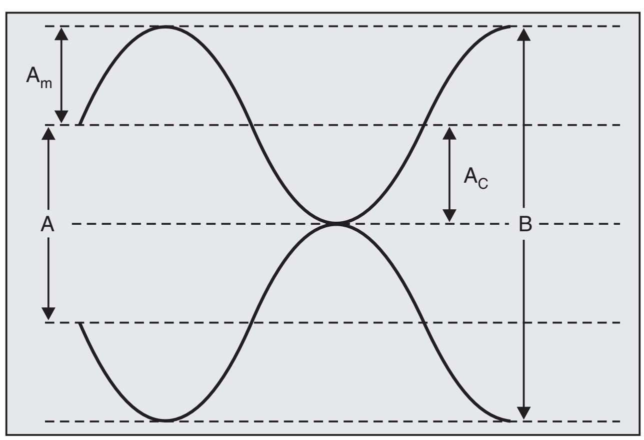


Fig. 9.32. Output waveform of intermodulation distortion meter.

In intermodulation distortion two frequencies are mixed using a linear circuit. The output we get has only two frequency components. The output of a linear circuit is applied to the amplifier under test and then is fed into the high pass filter. The output of the high pass filter is detected by r.m.s detector 2. The same output is further demodulated by using detector and then it is fed to the low pass filter section to remove high frequency components. The output of the low pass filter consisting only low frequency component is detected by r.m.s detector 1. The output of both the detectors is applied to the ratio detector where intermodulation distortion (IMD) is calculated by taking the ratio of the detector outputs. The value of IMD is then displayed directly by using an indicator or display device.

The intermodulation distortion (IMD) can be calculated directly by observing the waveform on the device like oscilloscope. IMD is given by,

$$\text{IMD} = \frac{\text{Amplitude of modulation}}{\text{Amplitude of carrier}} \times 100 = \frac{B - A}{A} \times 100$$

9.26 Difference Frequency Distortion Meter

It is the special case of the intermodulation distortion meter. In this type of the distortion meter only the lower frequencies are considered. The block diagram of difference frequency distortion meter is obtained by removing the high pass filter and detector section from the intermodulation distortion meter as shown in Fig. 9.33. The output of the amplifier is directly connected to the low pass filter which outputs only low frequency components.

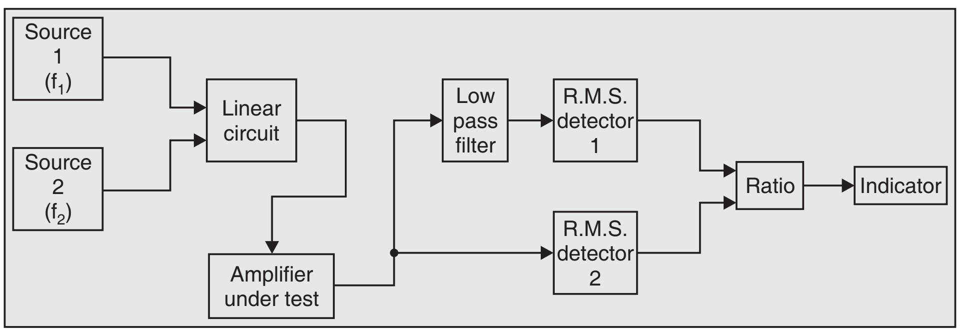


Fig. 9.33. Difference Frequency Distortion Meter

9.27 Harmonic Distortion Analysers

Harmonic distortion measurement is used for testing of amplifiers and networks as to what they distort the input signal.

There are several methods of measuring the harmonic distortion caused either by a single harmonic or by the sum of the entire harmonic. Some of the better-known methods will be described here.

9.28 Heterodyne Harmonic Distortion Analyser

Drawbacks of tuned–circuit harmonic analyser have been overcome in the heterodyne harmonic analyser by employing a highly selective, fixed-frequency filter. Fig. 9.34 shows the block diagram of heterodyne harmonic distortion analyser. In this analyser a highly selective fixed frequency filter is used.

The input signal is mixed with output of variable frequency oscillator in a mixer circuit. The balance mixer consists of a balanced modulator and it eliminates original frequency of the harmonic. After successful mixing, output of mixer supplies the sum and the difference of each harmonic beating against the oscillator frequency. Now for each harmonic component either the sum or difference of frequencies is made equal to the frequency of the filter by varying the frequency of oscillator. The quartz crystal type highly selective filters can be used as each harmonic frequency is converted to a constant frequency. This allows selecting constant frequency signal related to a particular harmonic and passing it to the metering circuit. Output of mixer has *rms* value which is proportional to the *rms* value of that harmonic component. So when output of mixer is supplied to a true *rms* reading voltmeter through amplifier, the voltmeter reads the *rms* value of that harmonic component. This instrument is also called carrier frequency voltmeters and selective level voltmeters.

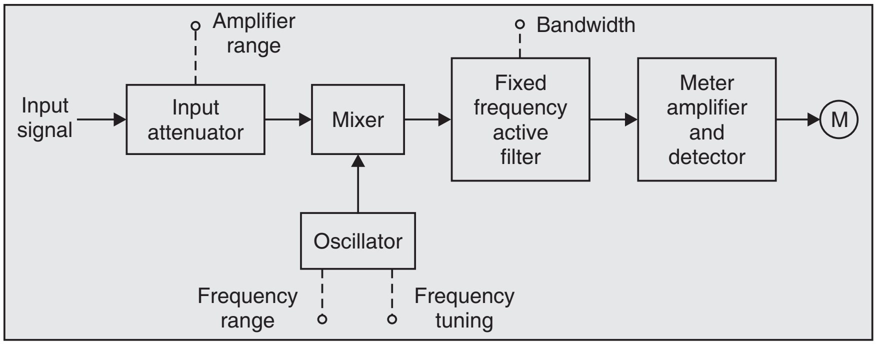


Fig. 9.34. Heterodyne Harmonic Distortion Analyser

Let us assume, for example a 50 Hz distorted sinusoidal signal for analysis. The oscillator has a frequency range of 50-60 kHz and the filter has a frequency of 50 kHz. Now harmonic components occur at frequencies of 50, 100, 150, 200 Hz and so on. Now we take one harmonic at a time and the difference of two frequencies i.e., the frequency of an oscillator and that of harmonic equals filter frequency. Now let us suppose the oscillator frequency is adjusted to 50.05 kHz. Output of mixer contains the sum and differences of each harmonic beating against the oscillator frequency. But only mixer output signal, whose frequency is 50 kHz, which is the result of 50 Hz frequency signal beating with oscillator frequency of 50.05 kHz, passes through the filter. All other mixer output signals are of frequencies above or below 50 kHz. So voltmeter reads the *rms* value of 50 kHz signal. Since *rms* value of 50 kHz signal is proportional to the *rms* value of 50 Hz harmonic component or fundamental of input signal, so the voltmeter can be calibrated to read directly the *rms* value of the 50 Hz fundamental wave.

Now the oscillator frequency is set to 50.1 kHz in order to analyze the second harmonic component. In this case second harmonic component beats against the 50.1 kHz to produce a 50 kHz frequency signal that can be passes through the filter. The voltmeter reading indicates the *rms* value proportional to that of 2nd harmonic component.

Thus by adjustment of oscillator frequency, each harmonic can be separated out from the other harmonics and *rms* value of each harmonic component can be obtained.

Since each harmonic frequency is converted to a constant frequency, use of highly selective filters of the quartz-crystal types is possible. With such technique, only the constant frequency signal, corresponding to the particular harmonic being measured, is passed and delivered to the metering circuit. The mixer usually consists of a balanced modulator as it offers a simple means of eliminating the original frequency of the harmonic. The low harmonic distortion produced by the balanced modulator is another advantage over different types of mixers. Excellent selectivity is obtained by using quartz-crystal filters or inverse feedback filters.

On some heterodyne analyzers the meter reading is calibrated directly in terms of voltage, other analyzers compare the harmonics of the impressed signal with a reference voltage, usually making the reference voltage equal to the *rms* value of the fundamental. Direct reading instruments of the heterodyne type are sometimes known as frequency selective voltmeter. In such instruments the frequency of input signal is read off on a calibrated dial. A low pass filter in the input circuit excludes the sum of the mixer frequencies and passes only the difference frequency. This voltage is compared to the input signal and read off on a calibrated voltmeter in dbm and volts. The level range for most of these meters is from – 90 dbm to +32 dbm.

9.29 Tuned-Circuit Harmonic Analyser

This is one of the oldest method employed for determination of the harmonic content in a waveform. The functional block diagram of a tuned circuit harmonic analyser is shown in Fig. 9.35. The parallel resonance circuit consisting of L_P, R_P and C_P is to provide compensation for the variation in the ac resistance of the series-resonant circuit consisting of inductor L and capacitor C and also for the variation in the amplifier gain over the frequency range of the instrument. The output of the series resonant circuit is transformer-couples to the input of an amplifier. The output of the amplifier is rectified and applied to a meter circuit.

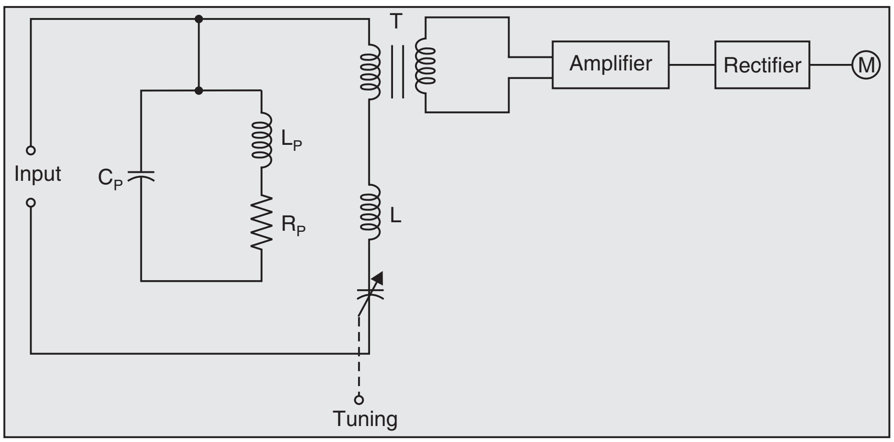


Fig. 9.35.

Series resonant circuit is tuned to a specific harmonic frequency. After reading is obtained on the meter, the series-resonant circuit is tuned to another harmonic frequency and next reading is noted, and so on.

This type of analyser is simple in construction and operation but have two major drawbacks.

Its resolution is very poor so when harmonics of signal to be analyzed are very closed, it is difficult to distinguish them.

At low frequency, very large values of L and C are required which is not possible in practice.

Such an analyser is used whenever measurement of each harmonic component individually is important rather than determination of total harmonic distortion.

9.30 Fundamental-Suppression Harmonic Distortion Analyser

This instrument is used when the total harmonic distortion rather than the harmonic distortion of each component. The input is applied to a network of filters that suppresses or rejects the fundamental frequency but passes the harmonic frequency components. Block diagram of the instrument is shown in Fig. 93.6. The major sections of the instrument are:

1. **Input circuit with impedance converter:** The impedance converter offers a low-noise, high-impedance input circuit, independent of the signal source impedance placed at the input terminals to the instrument.
2. **Rejection amplifier:** The rejection amplifier rejects the fundamental frequency of the input signal and passes the remaining frequency components on to the metering circuit where the harmonic distortion is measured.
3. **Metering circuit:** The meter circuit provides a visual indication of total harmonic distortion in terms of a percentage of total input voltage.

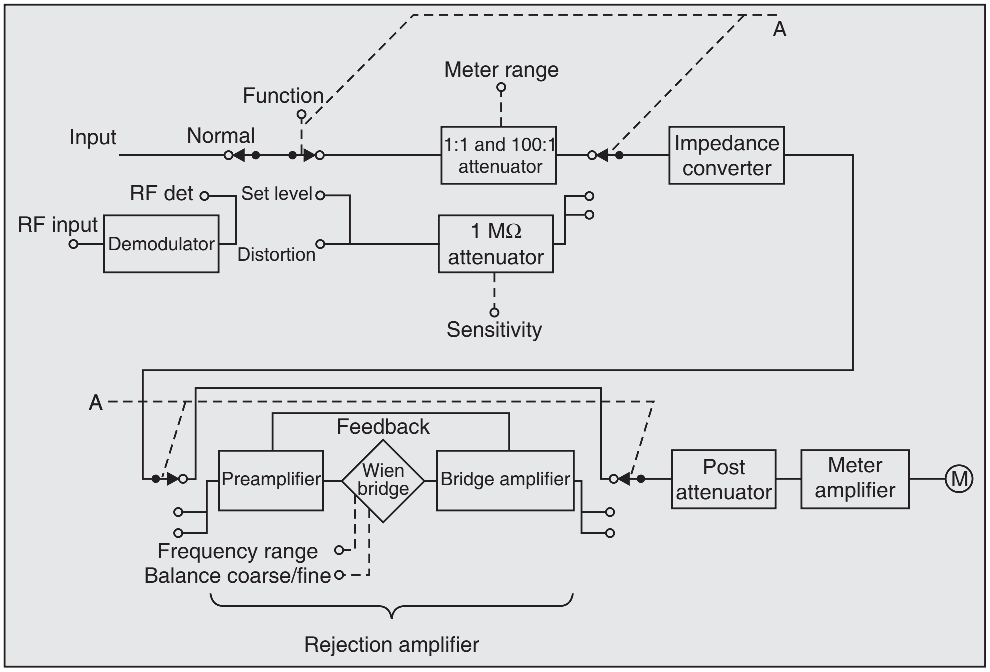


Fig. 9.36.

The instrument can be operated in two modes: (*i*) voltmeter mode and (*ii*) distortion mode. Both these modes are explained below :

Voltmeter Mode:

With the function switch in the voltmeter position, the instrument operates as a conventional ac voltmeter, a very convenient feature. In this mode the input signal is applied to the impedance converter circuit through the 10/1 or 100/1 attenuator, which selects the appropriate meter range. The output of the impedance converter then bypasses the rejection amplifier and the signal is impresses directly to the metering circuit. The voltmeter section can be employed separately for general-purpose voltage and gain measurements

Distortion Mode:

With the function switch in the distortion position, the rejection amplifier is included in the circuit and distortion is measured. In this mode the input signal is applied to 1 MΩ attenuator that provides 50db attenuation in 10db steps, controlled by a front panel switch marked sensitivity. When the desired attenuation is selected, the signal is supplied to the impedance converter, which is a low-distortion, high-input impedance amplifier circuit whose gain is independent of the source impedance placed at the input terminals. The overall negative feedback in this amplifier results in unity gain and low distortion. Signals having high impedance can be measured accurately and the sensitivity selector can be used in high-impedance positions without distorting the input signal.

Pre-amplifier, Wien bridge, and a bridge amplifier constitute the rejection amplifier circuit. The pre-amplifier provides additional amplification to the signal received from the impedance converter at extremely low distortion levels. The Wien bridge circuit is used as a rejection filter for the fundamental frequency of the input signal. When the function switch is in the distortion position, the Wien bridge is connected as an interstate coupling element between the pre-amplifier and the bridge amplifier. The bridge is tuned to the fundamental frequency of the input signal by setting the frequency range selector and is balanced for zero output by the coarse and fine balance controls. When the bridge is tuned and balanced, the voltage and phase of the fundamental, which appears at the junction of series reactance and the shunt reactance, are the same as the voltage and phase, no output signal will appear.

For frequencies other than the fundamental, the Wien bridge offers a varying degrees of phase shift and attenuation, and the resultant is connected through a post-attenuator to the meter circuit and displayed on the front panel meter. The attenuator limits the signal level to the meter amplifier to 1 mV for full-scale deflection on all ranges. The meter amplifier is a multistage circuit designed for low drift and low noise, and with flat response characteristics. The meter is connected in a bridge-type rectifier and reads the average value of the signal impressed on the circuit. The meter scale is calibrated to the *rms* value of a sinusoidal wave. The advantages are as follows

1. The harmonic distortion generated within the instrument is very small and can be neglected
2. Only the fundamental frequency component must be suppressed

SUMMARY

1. The signal generator is used to provide known test condition for the performance evaluation of various electronic systems and for replacing missing signals in system.
2. The audio generators cover the frequency range 20 Hz to 20 kHz, although few models produce signals up to 100 kHz.
3. Audio generators produce *pure sine* waves and square waves.
4. Function Generators are mainly used for testing amplifiers, filter and digital circuits.
5. The frequency range of the **pulse generator** instrument is covered from 1 Hz to 10 MHz
6. The RF signal generators are widely used in the area of radar and communication, research and development laboratories etc.
7. A **frequency synthesizer** is an electronic system for generating any of a range of frequencies from a single fixed time base or oscillator.
8. Wave analyser is an instrument to measure relative amplitudes of single frequency components is a complex waveform.
9. Frequency selective wave analyser is used for measurements in the audio frequency ranges from 20 Hz to 20 kHz.
10. The ordinary wave analyser cannot be used for the measuring of RF range and above (MHz range).
11. Spectrum Analyser provides the energy distribution of a signal as a function of the frequency on its CRT. It is widely used to measure the frequency response, noise and distortion characteristics of all kinds of RF circuitry
12. Distortion is the result of the inherent non-linear characteristics of different components used in an electronic circuit.
13. The harmonics consisting of sine waves with frequencies which are multiples of the fundamental of the input signal. Total harmonic distortion (THD) is given by,

$$\text{THD} = \frac{[\Sigma(\text{Harmonics})^2]^{1/2}}{\text{Fundamental}}$$

GLOSSARY

Function Generator: A function generator is an equipment used to generate simple repetitive waveforms.

Frequency Selective Wave Analyser: It consists of a narrow pass-band filter section that can be tuned to a particular frequency.

Frequency Synthesizer: It is another type of RF generator that uses phase-locked loop (PLL) to generate output frequencies over a wide range.

Heterodyne Wave Analyser: It is special types of wave analysers working on the principle of heterodyning (mixing) are used.

Pulse Generator: A pulse generator is a circuit used to generate pulses.

Radio-frequency (RF) oscillators: An oscillator that produces frequency output from 1 MHz and higher.

Real Time Spectrum Analyser: The real time spectrum analyser presents the effect of changes in all the input frequencies, on its spectrum display.

RF Signal Generator: A radio frequency (RF) signal generator has a sinusoidal output with a frequency range of 100 kHz to 40 GHz region.

Signal Generator: A signal generator is an instrument that provides a controlled output waveform or signal for use in testing, aligning or in measurements on other circuits or equipment.

Spectrum Analyser: The spectrum analyser is an instrument that brings together a superhetrodyne radio receiver with a swept frequency local oscillator and an oscilloscope to present a display of amplitude versus frequency.

Wave analyser: Wave analyser is a frequency selective voltmeter which tuned to the frequency of one signal while rejecting all other signal components.

DESCRIPTIVE QUESTIONS

1. What is a signal generator? Explain briefly.
2. Classified the signal generators?
3. Draw the block diagram of an audio frequency and square wave generator and explain its working.
4. What is function generator? Explain briefly?
5. Compare the signal generator and function generator.
6. Draw the simple diagram of a pulse generator and explain it briefly.
7. Explain briefly the following:
   (*a*) Sweep generator.
   (*b*) Frequency Synthesizer.
8. Write short notes on;
   (*a*) RM makers.
   (*b*) Digitally programmable test oscillators.
9. What is arbitrary waveform generators.
10. What is frequency synthesizer? What are its types? Explain any one frequency synthesizer with the help of block diagram.
11. Explain briefly with a neat block diagram, the working of a frequency selective wave analyser.
12. Discuss the working of wave analyser
13. What is wave analyser? Explain the working of (*i*) frequency selective (*ii*) Heterodyne wave analysers.
14. Describe the construction and working of wave analysers for audio-frequency and MH ranges. *(GBTU/MTU, 2005-06)*
15. Draw the block diagram of the frequency selective wave analyser. How is a complex wave analysed with this analyser?
16. With the help of functional block diagram explain the working of heterodyne wave analyser. *(GBTU/MTU, 2004-05)*
17. What are heterodyne wave analysers? Explain the theory of a RF heterodyne wave analyser for 0-20 MHz RF. *(GBTU/MTU, 2005-06)*
18. Describe spectrum analyser with the help of block diagram.
19. Explain with block diagram the working of spectrum analyser. *(GBTU/MTU, 2004-05)*
20. Distinguish the principle of working of a spectrum analyser and wave analyser. Draw the block diagram of a spectrum analyser. How is the spectrum of a given signal displayed on the spectrum analyser? *(GBTU/MTU, 2003-04)*

21. Draw the block diagram of spectrum analyser with harmonic mixing and explain its principle of working. Explain in detail the various applications of spectrum analyser.

(GBTU/MTU, 2004-05)

22. With the help of a neat block diagram, develop the theory of a spectrum analyser. Indicate the common applications of this instrument.

(GBTU/MTU, 2005-06)

23. What are the applications of spectrum analyser? Draw the block diagram of spectrum analyser and explain its working.

(GBTU/MTU, 2002-03)

24. What is harmonic distortion? Define distortion factor.

25. Define harmonic distortion and give a method for its determination.

26. With the help of block diagram explain the working of harmonic analyser.

(GBTU/MTU, 2003-04)

27. Explain the harmonic distortion analyser

28. What do you understand by the total harmonic distortion?

29. Explain the operation of wave analyser and logic analyser.

(VTU, May 2007, Dec. 2007, Dec. 2009)

30. State the principle of measurement by fundamental suppression analyser. Explain it with neat block diagram.

(VTU, Dec. 2007, Dec. 2008)

31. Name the various application of a wave analyser. *(PTU, Dec 2008)*

32. Draw and explain block diagram of superheterodyne spectrum analyser. *(VTU, May 2008)*

33. Write a brief note on accuracy of network analyser. *(VTU, May 2008)*

34. With a neat diagram, explain elements of network analyser system. Explain each block in detail.

(VTU, May 2009)

35. Explain with neat block diagram the principle of signal analysis using any two signal analyzing instruments.

(VTU, Dec. 2008)

36. What is the basic principle of wave analyser? Explain heterodyne wave analyser with applications.

(Mumbai University,Dec 2008)

37. Describe a harmonic distortion analyser with help of a block diagram. How does a commercial harmonic distortion analyser differ?

(PTU, May 2009)

38. Give the applications of wave analyser. *(PTU, May 2006)*

39. Differenciate between square wave generator and pulse generator. *(PTU, May 2007)*

40. Explain the working of spectrum analyser with the help of a block diagram

(PTU, May 2007)

41. Explain the significance of a signal analyser. Describe the principle of operation of a wave analyser.

(Mumbai University, June 2009)

MULTIPLE CHOICE QUESTIONS

1. In signal generator,

(*a*) Energy is created

(*b*) Energy is generated

(*c*) Energy is converted from a simple d.c source into a.c energy at some specific frequency

(*d*) All of the above

2. A triangular wave shape is obtained,
(*a*) By integrating a square wave (*b*) By differentiating a sine wave
(*c*) By differentiating a square wave (*d*) By integrating a sine wave

3. Harmonic distortion is due to,
(*a*) Change in the behaviour of circuit elements due to change in temperature.
(*b*) Change in the behaviour of circuit elements due to change in environment.
(*c*) Linear behaviour of circuit elements.
(*d*) Non-linear behaviour of circuits elements.

4. The level range of harmonic analyser using crystal filter is form
(*a*) –90db to 32db (*b*) 20db to 10db (*c*) 40db to 90db (*d*) 90db to 180 db

5. A wave analyser is basically a super heterodyne receiver covering the following range of frequency with an IF of 100 kHz.
(*a*) 20 Hz to 50 kHz (*b*) 100 kHz to 1 MHz
(*c*) 5 MHz to 5 GHz (*d*) 100 kHz to 100 GHz

6. Spectrum analyser is the combination of,
(*a*) Narrow band superheterodyne receiver and CRO.
(*b*) Signal generator and CRO
(*c*) Oscillator and wave analyser
(*d*) VTVM and CRO

7. Which of the following units are present in a spectrum analyser?
(*a*) Mixer (*b*) Sawtooth generator
(*c*) Local Oscillator (*d*) All above

8. Spectrum analyser is used across the frequency spectrum of a given signal to study the ,
(*a*) Current distribution (*b*) Voltage distribution
(*c*) Energy distribution (*d*) Power distribution

9. Frequency spectrum of a waveform can be determined using a,
(*a*) Q-meter (*b*) LCR bridge
(*c*) Wave analyser (*d*) Wien bridge oscillator

10. Harmonic distortion analyser,
(*a*) Measure the amplitude of each harmonic component
(*b*) Measure the *rms* value of fundamental frequency component
(*c*) Measure the *rms* value of all the harmonic components except the fundamental frequency component
(*d*) Displays the *rms* value of each harmonic component on the screen of a CRO

(UPSC Engg. Service. 1999)

11. Harmonic distortion analyser is an instrument used to,
(*a*) Measure the amplitude of each harmonic component individually
(*b*) Measure the *rms* value of amplitudes of all harmonic simultaneously
(*c*) Measure the signal levels of each harmonic of an unknown waveform
(*d*) Display the value of amplitude of each harmonic on the CRO.

(UPSC Engg. Service. 2003)

ANSWERS

1. (*c*)	**2.** (*a*)	**3.** (*d*)	**4.** (*a*)	**5.** (*b*)	**6.** (*a*)
7. (*a*)	**8.** (*b*)	**9.** (*c*)	**10.** (*c*)	**11.** (*b*)	

Chapter 10

Instrument Calibration

Outline

Objectives

After completing this chapter, you should be able to:

- Explain the construction and operation of potentiometer.
- Understand the use of potentiometer to find the resistance, current, voltage, power of any element in circuit.
- Know what are the calibration and their need.
- Discuss the calibration of voltmeter, ammeter and ohmmeter.

10.1 Introduction

As a matter of fact, all measuring instruments provide the user with a quantitative measurement. The user always expects a known level of confidence in that measured value. The ultimate objective of a measurement is to have accuracy, reliability and confidence in the exercise of measurement and its quantitative output.

Calibration is comparison between two measurements-one of known magnitude or correctness made or set with one device and another measurement made in as similar way as possible with the second device.

The device with the known or assigned correctness is called standard. The second device is unit under test (UUT), test instrument (TI) or any of the several other names for the device being calibrated.

10.2 Why Instrument Calibration is Required

Although there are several reasons for instrument calibration yet the followings are important from subject point of view.

1. with a new instrument
2. when a specified time period is elapsed
3. when a specified usage (operating hours) has elapsed
4. when an instrument has had a shock or *vibration* which potentially may have put it out of calibration
5. sudden changes in weather
6. whenever observations appear questionable

10.3 Quality

To improve the quality of calibration and have the results accepted by outside organisations, it is desirable for the calibration and subsequent measurements to be "traceable" to the internationally defined measurement units. Establishing traceability is accomplished by a formal comparison to a standard which is directly or indirectly related to national standards (Bureau of Indian Standards, India), international standards or certified reference material.

Quality management systems call for an effective metrology system which includes formal, periodic and documented calibration of all measuring instruments. ISO 9000 and ISO 17023 sets of standards require that these traceable actions are to a high level and set out how they can be quantified.

10.4 Measurement Traceability

The term "measurement traceability" is used to refer to an unknown chain of comparisons relating an instrument's measurements to a known standard. Calibration to a traceable standard can be used to determine an instrument's bias, precision and accuracy.

In many countries, national standards for weights and measures are maintained by a National Measurement Institute which provides the highest level of standards for the calibration/measurement traceability infrastructure is that country. Examples of government agencies are the National Physical Laboratory (Delhi), Bureau of Indian Standards (BIS), Delhi.

In general use, calibration is often regarded as including the process of adjusting the output or indication on a measurement instrument to agree with value of the applied standard, within a specified accuracy. For example, a thermometer could be calibrated so the error of indication or the correction is determined, and adjusted (e.g. via calibration constants) so that it shows the true temperature in Celsius at specific points on the scale. This is the perception of the instrument's end-user. However, very few instruments can be adjusted to exactly match the standards they are compared to. For the vast majority of calibrations, the calibration process is actually the comparison of an unknown to a known and recording the results.

10.5 Potentiometer

A potentiometer is an instrument used for measuring and comparing the emfs of different cells and for calibrating and standardizing voltmeters, ammeters etc. It is a device used for measurement of unknown emf by comparison. The unknown emf is compared with a known emf which is obtained from a standard cell or any reference voltage source.

A **potentiometer** is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used, it acts as a *variable resistor* or *rheostat*. Potentiometers are commonly used to control electrical devices such as volume controls on audio equipment.

Fig. 10.1 shows the potentiometer. A basic potentiometer circuit consists of a slide wire AB of uniform cross section and unit length. Generally slide wire is made up of manganin. The battery B_2 supplies a current through the slide wire which is limited with the help of rheostat. The battery B_1 whose emf is to be measured is connected in series with a galvanometer G and switch K. The unknown emf or potential difference is measured by balancing it whole part or in part against a known difference of potential.

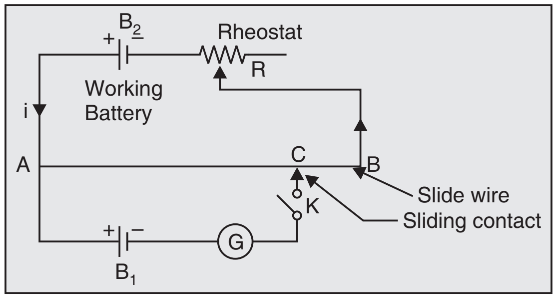


Fig. 10.1. Potentiometer.

When the switch *K* is opened:

Let when the switch *K* is opened then the current through the slide wire is '*i*'. If the sliding contact is at position *C*, then the length of *AC* is '*l*' units. Then the voltage across *AC* is given by irl.

When the switch *K* is closed:

When the switch *K* is closed then the both emf of battery B_1 and B_2 oppose each other. The deflection in the galvanometer *G* depends on the magnitude of voltage drop across the slide wire portion *AC* and emf of B_1.

When the voltage drop across length '*l*' of the slide wire is greater than emf of battery B_1, then the current will flow in the direction *A* to *C* through the galvanometer.

If the emf of the battery B_1 is greater than the voltage drop across the length '*l*' of the slide wire then the current will flow in the direction *C* to *A* through galvanometer.

If the both emfs are equal then the no current will flows through the galvanometer. A scale is provided along with the slide to measure the length of portion *AC*.

Working

To measure the emf of a battery first adjust a current through slide wire with switch *K* open. Then insert battery whose emf is to be measured. By closing switch *K* adjust sliding contact such that the galvanometer shows zero deflection. Measure the length of the portion of the slide wire with the help of scale provided. Then the unknown emf of battery is given by,

$$E = i(rl)$$

Where *r* is the resistance per unit length,'*i*' is the working current adjusted using rheostat *R*.

If emfs of the two batteries B_1 and B_2 are to be compared then insert the first battery B_1 in series with the galvanometer and then adjust the sliding contact such that no current flows through the galvanometer. Lets the length of the sliding wire is 'l_1'. Same as for battery B_2, the length will be 'l_2'. Lets emf of batteries B_1 and B_2 by E_1 and E_2 respectively then we can write

$$E_1 = i(rl_1) \qquad \ldots(i)$$

$$E_2 = i(rl_2) \qquad \ldots(ii)$$

from equation (*i*) and (*ii*) we can write

$$\frac{E_1}{E_2} = i(rl_1) \,/\, i(rl_2)$$

If one of the batteries used is a standard cell, lets battery B_2 of known voltage then the emf of battery B_1 is given by,

$$E_1 = E_2 \frac{l_1}{l_2}$$

Following precaution must be taking while using the potentiometer:

The supply battery B_2 should be of high capacity so that a constant current flows through the slide wire throughout the measurements.

A small resistance should be used in series with the galvanometer to protect it during initial adjustments of contact *C*.

The measurement of the measurement depends on how accurately ratio $\left(\frac{l_1}{l_2}\right)$ is determined.

Example 1. *Using a Weston cadium cell of 1.0183 V and a standard resistance of 0.1 Ω a potentiometer was adjusted so that 1.0183 m was equivalent to the amf of the cell, when a certain direct current was flowing through the standard resistance, the voltage across I correspond to 150 cm. What was the value of current?*

Solution. Given: E_1 = 1.0183 V ; I_1 = 1.0183 m and I_2 = 150 cm = 1.5 m

We know that voltage across the standard resistance of 0.1 Ω corresponding to I_2,

$$\frac{E_2}{E_1} = \frac{I_2}{I_1}$$

$$E_2 = E_1 \frac{I_2}{I_1} = 1.0183 \times \frac{1.5}{1.0183} = 1.5 \text{ V}$$

Current flowing through the standard resistance

$$I_2 = \frac{E_2}{R} = \frac{1.5}{0.1} = 15 \text{ A } \textbf{Ans.}$$

10.6 Application of Potentiometer

Following are some of the important applications of potentiometer, which are important from the subject point of view:

1. Measurement of a small emfs (upto 2 volts)
2. Comparison of emfs of two cells.
3. Measurement of high emfs (say 250 volts)
4. Measurement of resistance
5. Measurements of current
6. Calibration of ammeter
7. Calibration of voltmeter

10.7 Volt-Ratio Box

The volt-ratio box is shown in Fig. 10.2 it is base on the concept of potentiometer divider. It consists of high resistance having number of tapings with properly adjusted resistances between various pairs of tapings.

Consider that the voltage of the order of 150 V is to be measured. Then this voltage is connected between the terminals 150 V and common terminal. The leads to the potentiometer are taken from two taping points say 50. If the voltage on the potentiometer is 1.3 V then the actual voltage to be measured is given by

$$V_{\text{unknown}} = 1.3 \left(\frac{5000}{50}\right) = 130 \text{ V}$$

Using this concept of potential divider we can measure unknown voltage.

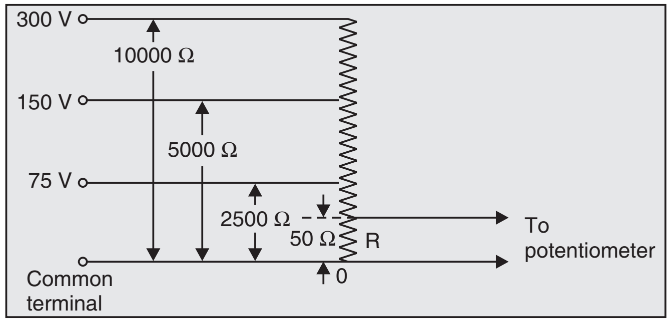


Fig. 10.2. Volt-Ratio Box.

10.8 Measurement of Resistance

Fig. 10.3 shows the setup of potentiometer to measure the resistance of the unknown resistor. The unknown resistance is connected is series to the standard resistance. The current is supply by the stable dc source. The rheostat is used to control the dc supply voltage. The current is adjusted such that the drop across each resistors is of the order of 1 V. Due to the current I voltage are developed across R_S and R. The voltages are measured by using dc potentiometer.

The voltage (V_S) across standard resistance

$$V_S = IR_S \qquad \ldots\text{(i)}$$

Voltage (V_{XR}) across the unknown resistance

$$V_{XR} = IR \qquad \ldots\text{(ii)}$$

From equation (*i*) and (*ii*),

$$\frac{V_{XR}}{V_S} = \frac{R}{R_S}$$

$$R = R_S\left(\frac{V_{XR}}{V_S}\right)$$

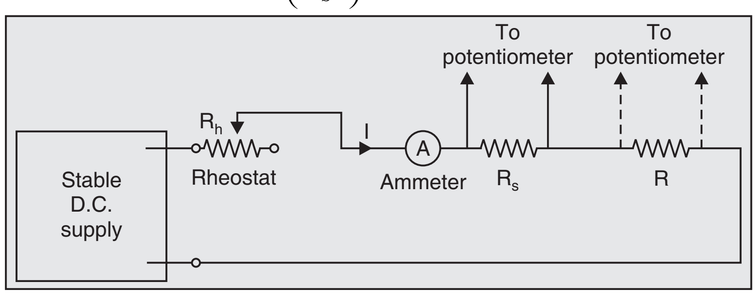


Fig. 10.3. Set up for Resistance Measurement.

The value of R can be accurately known since the value of standard resistance R_S is accurately known. The current flowing through the circuit should remain same during measurement of voltage across R and R_S. This method is used for measurement of low resistance value.

10.9 Measurement of Current

Fig. 10.4 shows the circuit to measure the current with a potentiometer. The unknown current I, whose value is to be determined is passed through a standard resistance (R_S). The standard resistance should be of such value that voltage drop across is caused by flow of current to be measured. The voltage drop across the resistance is calculated by the potentiometer.

The unknown current is given by,

$$\text{Unknown Current } I = \frac{\text{Voltage drop across } R_S}{\text{Value of resistance } R_S}$$

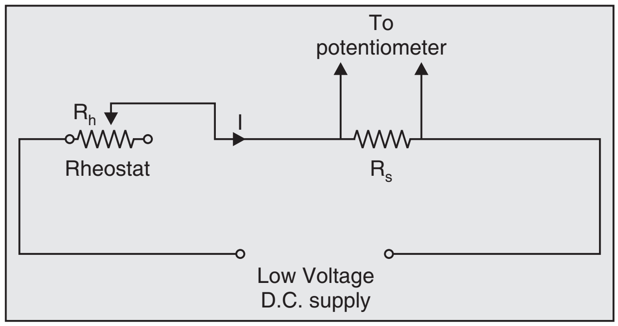


Fig. 10.4. Set up for Current Measurement

10.10 Measurement of Power

Fig. 10.5 shows the setup of potentiometer to measure the power. The potentiometer is connected across the standard resistance R_S and across the output terminals of volt-ratio box. The measurement across the standard resistance and load

The power across load can be calculated as,

$$P = IV$$

Voltage across standard resistance R_S is measured using potentiometer, then current flowing through it is given by,

$$I = \frac{V_S}{R_S} \quad \ldots(i)$$

To measure the voltage (V) across load the volt-ratio box is connected across load. The output of volt-ratio box is then connected to potentiometer.

$$V = kV_R \quad \ldots(ii)$$

Where k is the multiplying factor of volt-ratio box and V_R is the actual reading of potentiometer when it is connected across volt-box. Power is given by the equation (i) and (ii),

$$P = VI = (kV_R) \times \left(\frac{V_S}{R_S}\right)$$

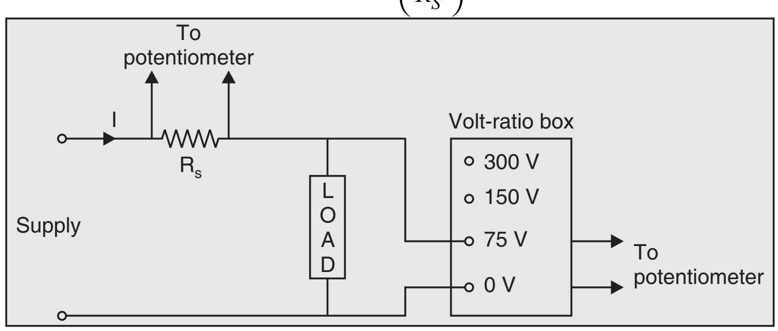


Fig. 10.5. Set up for Power Measurement.

10.11 Types of Calibration

Calibration is a comparison between measurements one of known magnitude or correctness made or set with one device and another measurement made in as similar a way as possible with a second device. The device with the known or assigned correctness is called the standard. The second device is the unit under test (UUT), test instrument (TI), or any of several other names for the device being calibrated. It is the procedure for determining the correct values of measured by compression with the standard ones.

The process of calibration involves the comparison of a given instrument with a standard instrument to determine its accuracy. A dc voltmeter may be calibrated with a standard or by comparison with a potentiometer. There are main two types of calibration methods:

1. Direct Comparison Calibration Method
2. Indirect Comparison Calibration Method

We will know discuss each method one by one in detail.

10.12 Direct Comparison Calibration Method

In a direct comparison, a source applies a known input to the meter under test. The ratio of what meter is indicating and the known source values gives the meter's error. In this case meter is test instrument while source is the standard instrument.

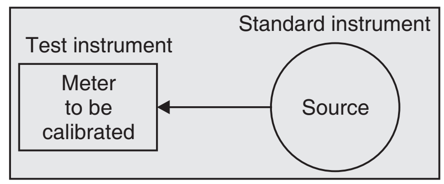


Fig. 10.6. Direct Calibration.

10.13 Indirect Comparison Calibration Method

In the indirect comparison, the test instrument is compared with the response of standard instrument of same type. If the test instrument is meter then the standard instrument is also meter. Fig. 10.7 shows the direct calibration method.

If the test instrument is a meter then the same input is applied to the test meter as well as a standard meter. The indication of test meter is compared with the indication meter for the same input.

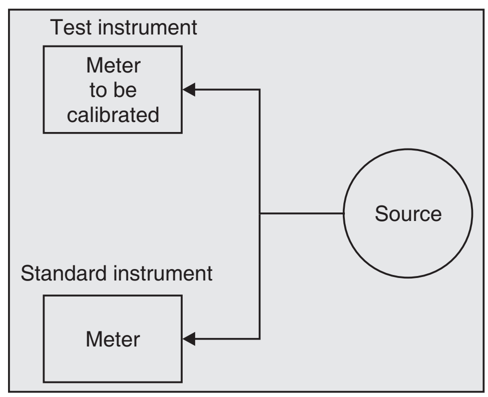


Fig. 10.7. Indirect Calibration.

10.14 Need of Calibration

The instrument calibration plays an important role in any manufacturing industry. Behind the origin of any successful product it is a perfect calibration. Instrument calibration is to ensure a continuous work flow. Some of the main needs of calibration are given below :

1. **Before major critical measurements:** Before any measurements that requires highly accurate data, send the instruments out for calibration and remain unused before the test. Without instrument calibration, you cannot manufacture quality products that will satisfy the clients.
2. **After major critical measurements:** Send the instrument for calibration after the test helps user decide whether the data obtained were reliable or not. Also, when using an instrument for a long time, the instrument's conditions will change.
3. **After an event:** The event here refers to any event that happens to the instrument. For example, when something hits the instrument or any kinds of accidents that might impact the instrument's accuracy. A safety check is also recommended.
4. **Per requirements:** Some experiments require calibration certificates. Check the requirements first before starting the experiment.
5. **Indicated by manufacturer:** Every instrument will need to be calibrated periodically to make sure it can function properly and safely. Manufacturers will indicate how often the instrument will need to be calibrated.

10.15 Calibration of Voltmeter

A simple method of calibrating a dc voltmeter is shown in Fig. 10.8. The suitable dc supply voltage is used otherwise change in supply voltage cause change in calibration voltmeter. The voltage drop across the resistor *R* is accurately measured with a potentiometer. The voltmeter to be calibrated is connected across the same two points as the potentiometer. The voltmeter indicates the same voltage as potentiometer. The rheostat is placed in the circuit to control the amount of current and voltage drop across the resistor *R*.

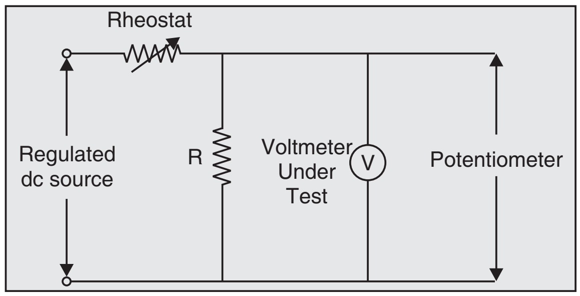


Fig. 10.8. Voltmeter Calibration.

Voltmeter Calibration with two rheostat method is shown in Fig. 10.9. One is for coarse and the other is for fine control of calibrating voltage. With the help of these controls it is possible to adjust the voltage so that the pointer coincides exactly with the major division of the voltmeter.

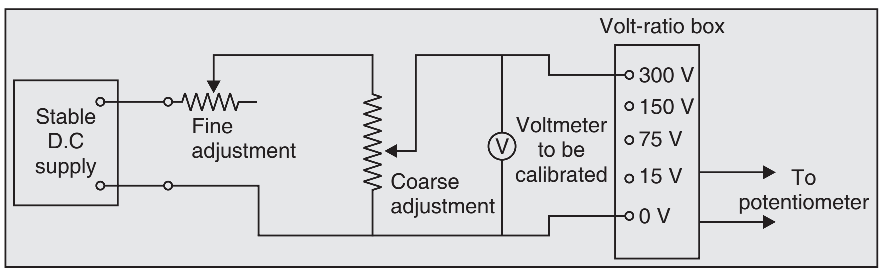


Fig. 10.9.

The volt-ratio box contains different value of standard resistor. With this volt-ratio box the voltage across the voltmeter is stepped down to a different value for different application.

The voltage measurement is maximum range of potentiometer to get the maximum accuracy. The potentiometer measure the true value of voltage. If the reading of the potentiometer does not agree with the voltmeter reading, a positive or negative error is indicated.

10.16 Calibration of Ammeter

A simple method of calibrating a dc ammeter is shown in Fig. 10.10. A good source of constant current is required and is usually provided by storage cells or precision power supply. The potential difference across a standard resistor is measured by voltmeter method. Now we know the value of resistance and voltage across the standard resistor. The current through the standard resistor is calculated by the Ohm's law. The result of this calculation is compared to the actual reading of the ammeter under calibration. The standard resistor is inserted in the circuit. A rheostat is placed in the circuit to control the current.

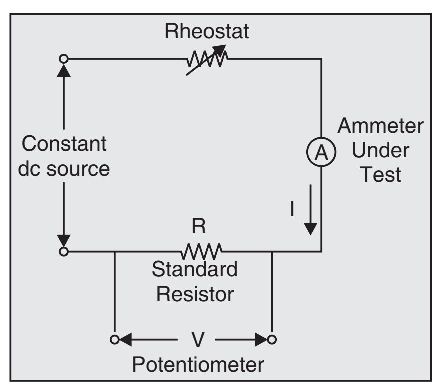


Fig. 10.10. Ammeter Calibration.

Ammeter Calibration with two rheostat method is shown in Fig. 10.11. One is for coarse and the other is for fine control of calibrating current. An ammeter to be calibrated is connected to the series with a standard resistor R_S of suitable value. The current is passes through ammeter as well as standard resistor. With potentiometer a voltage across standard resistance is measured. Current flowing through R_S is given by,

$$I = \frac{V_S}{R_S}$$

Where V_S = voltage across R_S measured using potentiometer

R_S = resistance of standard resistor

The resistance of standard resistor is known accurately and also the voltage across R_S is measured using the standard potentiometer.

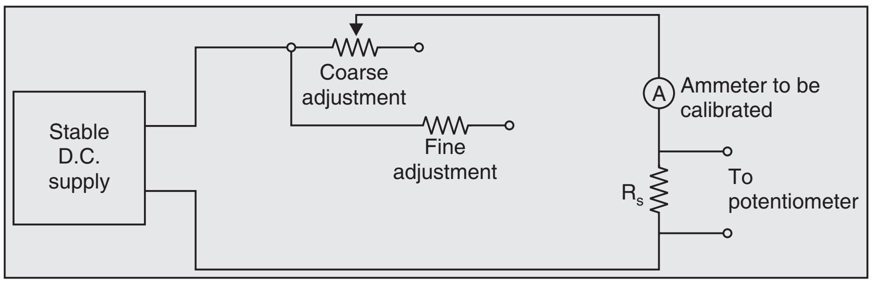


Fig. 10.11.

10.17 Calibration of Shunt Ohmmeter

Fig. 10.12 shows the circuit diagram of shunt ohmmeter, it is already discuses in the previous chapter no. 3. The unknown resistance is shorted then the meter current is zero. Since the current is bypassed by short-circuit. This pointer position is marked as "0" ohms. When the unknown resistor is opened then the full current is flow through the meter movement. The pointer position is marked as "∞" ohms. By selecting the appropriate value of R_1 the pointer can be made to read full scale.

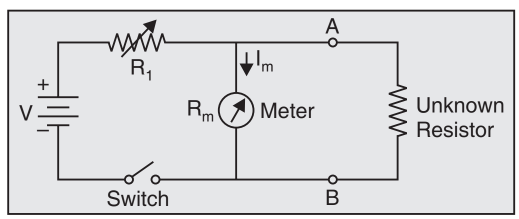


Fig. 10.12. Shunt Ohmmeter

The intermediate marking can be done by connecting known values of standard resistors to unknown resistor. The shunt type ohmmeter has the zero mark at the left hand side of the scale (no current) and the infinite mark at the right hand side of the scale (full scale deflection current) as shown in Fig. 10.13. This ohmmeter is suitable to the measurement of low values of resistance. Hence it is used as a test instrument in the laboratory for special low resistance applications.

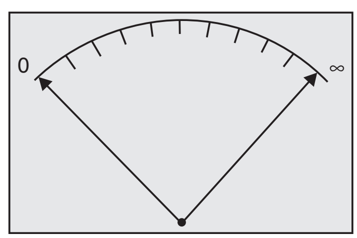


Fig. 10.13. Shunt Ohmmeter Scale

10.18 Calibration of Series Ohmmeter

Fig. 10.14 shows the circuit diagram of shunt ohmmeter, it is already discuses in the previous chapter no. 3. The unknown resistance is shorted,then the maximum current flow through the meter. The shunt resistor R_2 is adjusted until the movement indicates the full scale current. This position is marked as "0". When the unknown resistor is opened then the circuit drops to zero and the movement indicates zero current. This position is marked as "∞".

By connecting different known values of the unknown resistance to terminals *A* and *B*, intermediate marking can be done on the scale. The accuracy of the instrument can be checked by measuring different values of standard resistance, i.e. the tolerance of the calibrated resistance, and nothing the readings.

The shunt type ohmmeter has the infinite mark at the left hand side of the scale (no current) and the zero mark at the right hand side of the scale (full scale deflection current) as shown in Fig. 10.15.

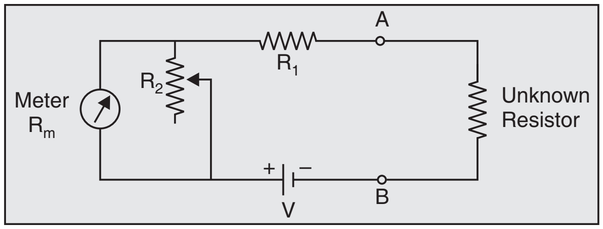


Fig. 10.14. Series Ohmmeter.

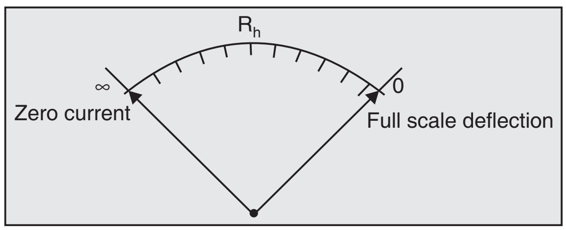


Fig. 10.15. Series Ohmmeter Scale.

A major drawback in the series ohmmeter is the decrease in voltage of the internal battery with time and age. Due to this, the full scale deflection current drops and the meter does not read "0" when *A* and *B* are shorted. The variable shunt resistor R_2 across the movement is adjusted to counteract the drop in battery voltage, thereby bringing the pointer back to "0" ohms on the scale.

It is also possible to adjust the full scale deflection current without the shunt R_2 in the circuit, by varying the value of R_1 to compensate for the voltage drop. Since this affects the calibration of the scale, varying by R_2 is much better solution. The internal resistance of the coil R_m is very low compare to R_1. When R_2 is varied, the current through the movement is increased and the current through R_2 is reduced, thereby bringing the pointer to the full scale deflection position.

The series ohmmeter is a simple and popular design, and is used extensively for general service work.

Therefore, in a series ohmmeter the scale marking on the dial, has "0" on the right side, corresponding to full scale deflection current, and "∞" on the left side corresponding to no current flow.

SUMMARY

1. The volt-ratio box is base on the concept of potentiometer divider.
2. A potentiometer is a device used for measurement of unknown emf by comparison.
3. Volt-Ratio Box consists of high resistance having number of tapings with properly adjusted resistances between various pairs of tapings.

GLOSSARY

Calibration: Calibration is the procedure for determining the correct values of measured by compression with the standard ones.

Potentiometer: The potentiometer compares the unknown emf with a known emf which is obtained from a standard cell or any reference voltage source.

DESCRIPTIVE QUESTIONS

1. What is a potentiometer?
2. Describe the construction and working of a simple potentiometer.
3. Give some significant features/advantage of potentiometers.
4. List the application of potentiometer.
5. What is a volt-ratio box? Explain.
6. Explain calibration process.
7. Describe the different types of calibration.
8. Why we use calibration?
9. Sketch a circuit to show how a standard voltmeter may be used to calibrate a dc voltmeter. Explain the calibrating procedure and discuss the use if calibration. *(VTU, May 2008)*
10. Explain the calibration method in detail. *(VTU, Dec. 2008)*
11. What do you mean by calibration of an instrument? Explain calibration methodology in detail. *(VTU, May 2009)*
12. Describe with the help of suitable diagrams, how potentiometer can be used for
    (*a*) Calibration of voltmeter.
    (*b*) Calibration of an ammeter.
    (*c*) Determine of an unknown resistance.
13. Describe the calibration of ohmmeter both shunt type and series type.
14. What is importance of calibration instrument? Also mention approximate duration of regular calibration of primary and secondary instrument along with reasons. *(GBTU/MTU. 2009-10)*

MULTIPLE CHOICE QUESTIONS

1. Standardization of potentiometers is done in order that, they become,
   (*a*) Accurate. (*b*) Precise.
   (*c*) Accurate and direct reading. (*d*) Accurate and precise.
2. A potentiometer is basically a,
   (*a*) Deflection type instrument. (*b*) Null type instrument.
   (*c*) Deflection as well as null type instrument. (*d*) A digital instrument.
3. Electronic null detectors are,
   (*a*) Less sensitive.
   (*b*) More sensitive.
   (*c*) More expensive.
   (*d*) Of excellent sensitivity, rugged construction and fairly expensive.

ANSWERS

1. (*c*) **2.** (*b*) **3.** (*d*)

Chapter 11

Graphic Recording Instruments

Outline

Syllabus: Recorders: *X-Y* recorders, plotters

Objectives

After completing this chapter, you should be able to:

- Know what is a recorder
- List the various types of recorders and their application.
- Explain the plotter and their uses
- Discuss the different types of plotter

11.1 Introduction

A recorder is an instrument to record the electrical and non-electrical quantities as a function of time. The record shows how a variable varies with respect to another with time. The electrical quantities such as voltage and current are measured directly. The non-electrical quantities are recorded using indirect methods. The non-electrical quantities are first converted to their equivalent voltages or current using various transducers.

A plotter is a very versatile tool. It is sometimes confused with a printer, but a plotter uses line drawings to form an image instead of using dots. A common type of plotter is one that uses a pen or pencil, usually held by a mechanical "arm," to draw lines on paper as images are typed. It may be a component that is added to a computer system or it may have its own internal computer. It can be used to create layouts, diagrams, specifications, and banners.

11.2 Recorder

A recorder is a device whose function is to record the value of a quantity as it is being measured. Recording preserves the experimental data in a manageable and usable form. A recording system is very useful in industries as (*i*) it preserves information which could be obtained at an instant from indicating instruments and (*ii*) it gives information about waveforms and transient behavior or phase relations in different parts of a circuit.

A recorder records both electrical and non-electrical quantities as a function of time or relates two signals to each other. Electrical quantities, such as current voltage etc can be recorded directly while non-electrical quantities, such as pressure, temperature, speed etc are recorded indirectly by first converting them into the form of electrical signal with the help of sensors and transducers. When working with the analog system the analog recording techniques should be used while working with a digital system, digital recording devices should be used. Recording devices are of two types namely: (*i*) analog recorders and (*ii*) digital recorders.

Analog recorders may be classified as:

1. Graphic Recorder
   - (*i*) Strip Chart Recorder
   - (*ii*) Circular Chart Recorder
   - (*iii*) *X*-*Y* Recorders
     - (*a*) Analog *X*-*Y* Recorder
     - (*b*) Digital *X*-*Y* Recorder
2. Oscillographic Recorder
3. Magnetic Tape Recorder

All of these generally contain a built-in measuring apparatus as well as a recording mechanism. This gives recorders the capability of receiving electrical signals from detectors or sensors and converting their magnitudes in to a permanent record.

11.3 Graphic Recorder

The graphic instrument displays and stores the physical quantity being measured. It uses basic elements as chart paper for displaying and storing the quantity and pen for marking the variation in physical quantity. The pen is also called stylus. There are three types of graphic recorders:

1. Strip Chart Recorder
2. Circular Chart Recorder
3. *X*-*Y* Tape recorder

We will discuss all these types of graphic recorder one by one in the following pages.

11.4 Strip Chart Recorder

A chart recorder is an electromechanical device that records an electrical or mechanical input trend onto a piece of paper (the chart). Chart recorders may record several inputs using different color pens and may record onto strip charts or circular charts. Chart recorders may be entirely mechanical with clockwork mechanisms or electro-mechanical with an electrical clockwork mechanism for driving the chart (with mechanical or pressure inputs) or entirely electronic with no mechanical components at all (a virtual chart recorder).

The strip chart recorder often used for the application which require monitoring the quantity. A roll of paper is continuously moved under the pen and a continuous record is maintained. Strip chart recorders are generally multirange voltmeter with a speed range selector to control the paper feed. A strip-chart recorder plots one or more parameters as a function of time. A strip is a ribbon of paper moved through the instrument at uniform speed by an electric motor.

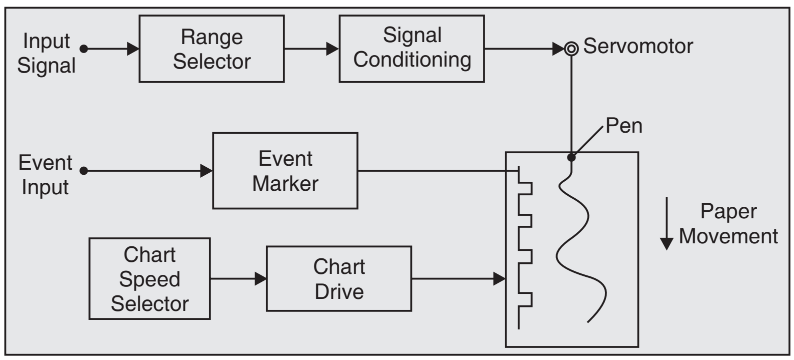


Fig. 11.1. Strip Chart Recorder

Fig. 11.1 shows the basic block diagram of strip chart recorder. The basic element of this recorder is pen for making and chart paper for recording data. The quantity to be measured is given as to the input to the range selector. The range selector switch keeps data within the limit. The stylus moved along the calibrated scale in accordance with input data. To get proper record of input data signal conditioning block is used which gives proper input signal along calibrated scale. The chart paper moves vertically at a uniform speed. The speed selector selects the required speed of the chart paper movement. General diagram of strip char recorder is shown in Fig. 11.2.

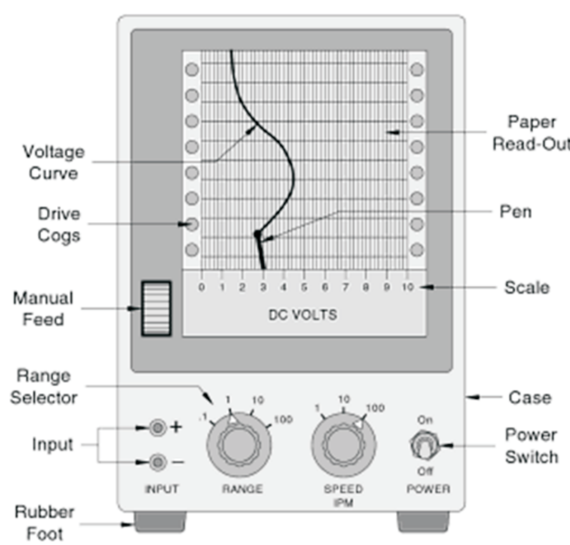


Fig. 11.2.

Mechanism for Marking

There are many mechanisms for marking the marks on the chart paper. These are explained below:

(*a*) **Pen and Ink Stylus:** The ink is filled in the stylus using gravity of capillary action. Any color is used to record data as per color coding. There are several types of pens, including the bucket pen, the *V*-pen, the fiber-tipped pen, and the ballpoint pen. Various types of capillary feeding systems, both pressurized and gravimetric, are mostly used. For ordinary chart speed ranges, *V*-pen, fountain pen, large-reservoir capillary-fed recording tips are common.

(*b*) **Impact Printing:** In this a carbon ribbon is placed between the paper and pointer mechanism. The carbon provides ink for recording data. The marking is done by pressing pointer on the paper.

(*c*) **Chopper Bar Printing:** The marking is done with chopper bar. This chopper bar applies pressure on the special purpose pressure sensitive paper.

(*d*) **Thermal Writing:** In this method, the recording is done by marking on a special paper with heated stylus. The special movable pen is heated by passing an eclectic current through it. During marking the color on the special paper changes as heated stylus moves. In some systems a black paper with white wax coating is used. During recording the heated stylus melts thin white coating wax. Because of this we get high contrast marking on the special paper.

(*e*) **Electrical Writing:** In this method, a paper base with a layer of colored dye and thin surface of aluminum coating is used. The stylus consists of a conducting wire moving over aluminum surface. As the paper is current sensitive, when the current is conducted from stylus, we get traces on the paper with removal of aluminum and keeping color dye at those traces.

(*f*) **Optical Writing:** In this method, a photosensitive paper is used. A beam of ultraviolet is used to record data on the paper. We can have higher resolution with higher frequencies and large paper rolling speeds.

11.5 Advantages of Strip Chart Recorder

The strip chart recorder has a number of advantages. Some of the important ones are given below :

1. Relatively large amount of paper can be inserted at one time.
2. Data conversion is easier with rectangular coordinates system
3. The rate of movement of the chart can be easily changed.
4. More than one separate variable can be recorded on a strip chart.

11.6 Disadvantages of Strip Chart Recorder

Strip Chart recorder has some disadvantages also. These are given below:

1. Mechanism is more complicated than is required to drive a circular chart.
2. Observing behavior several hours or days back is not as easy as picking out one circular chart which covers the desired period of time.

11.7 Application of Strip Chart Recorder

Following are some of the important applications of Heterodyne Wave Analyser, which are important from the subject point of view :

1. **In temperature recorder:** A strip chart recorder may be used to provide a graphic record of temperature as a function of time. There are two primary methods used for recording temperature: (*i*) the thermocouple method and (*ii*) the resistance method.

2. **Sound level recording:** It is required to obtain a record of sound level over a period of time near hospitals, schools or residences, airports etc. It can be done with an ordinary microphone and a strip-chart recorder.
3. **Recording amplifier drift:** Transistor amplifiers are sensitive to temperature changes. The changes in temperature cause the bias voltage of the transistor to change. Due to this the operating or quiescent point of transistor is changed by small amount. This change in the quiescent point is called drift. The drift is recorded by connecting the recorder to the output of the amplifier.

11.8 Galvanometer Type Strip Chart Recorder

This is a type of strip chart recorder. It operates on the deflection principle. The deflection is produced by a galvanometer (D'Arsonval). It produces a torque on account of a current passing through its coil. The current is proportion to the quantity to be measured.

Fig. 11.3 shows the galvanometer type strip chart recorder. The moving coil pointer is in strong magnetic field. The pen-ink system is fitted to the pointer for recording the input signal. The pen-ink system consists of a recording pen at one end while ink reservoir is at other end. Both are connected to each other through bore tube. Ink flow from reservoir to pen by gravity action. The paper is pulled from the roll and the signal is traced on the paper as the paper moves across the pen, when pen is deflected.

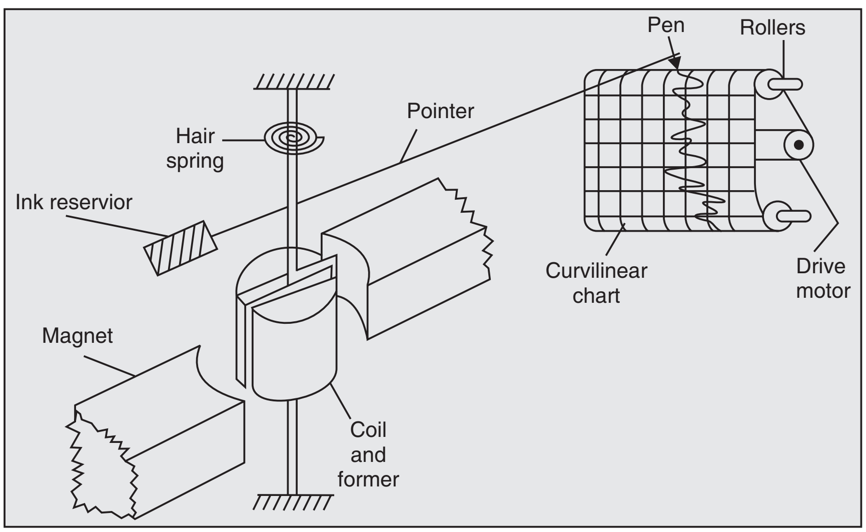


Fig. 11.3. Galvanometer Type Strip Chart Recorder

The pointer deflects according to the current flow through the coil. The magnetic field is varying according to the input current. This change in magnetic field interacts with magnetic field produced by the permanent magnet used. This causes the moving coil to move in angular direction. As this coil is moving as per variation in the signal current, the pen is correspondingly deflected across the paper. Thus, the input signal gets recorded. The grater the amplitude of the input signal, the greater will be deflection.

Advantages

The galvanometer type strip chart recorder has a number of advantages. Some of the important ones are given below:

1. The system is comparatively inexpensive.

2. It records very low frequency a.c. signals.
3. We can change the speed of paper as per requirement.

Disadvantages

Galvanometer type strip chart recorder has some disadvantages as given below:

1. It cannot record fast varying signals such as current, voltage or power.
2. The performance is affected by fraction losses due to moving coil and stylus.

11.9 Potentiometer Type Strip Recorder

The galvanometer type recorder has very low input impedance and sensitivity. The low impedance creates a problem of loading. To overcome this problem we use potentiometer type recorder. These recorders are based on the principle of self-balancing or null conditions. Different types of null type recorders are:

1. Self-balancing Potentiometer Recorders
2. Bridge Recorders
3. LVDT Recorders

11.10 Self-Balancing Potentiometer Type Strip Chart Recorder

Fig. 11.4 shows a block diagram of a self-balancing potentiometer type strip chart recorder. When the input signal given by sensor or transducer is applied to the measuring unit of the recorder, the balanced condition of the instrument gets disturbed. This unbalanced signal produces error signal. Error signal is the difference of input signal and reference potentiometer voltage. The error signal is amplified and subsequently the field coil of DC motor is energized. The error current either flows in clockwise or in anticlockwise direction depending on the value of the voltage. The motor turn in such direction that it reduces the error signal to achieve balanced condition. As the error signal reduces, the motor slows down and stops completely. When error becomes zero, the balance condition is achieved.

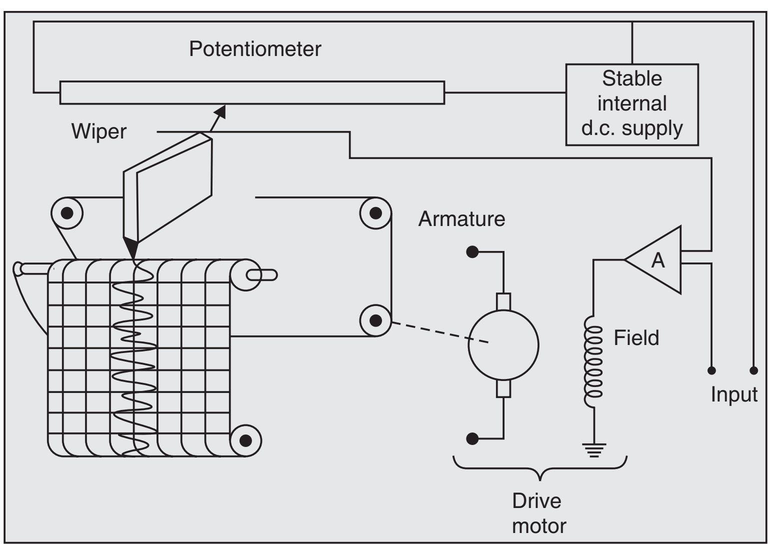


Fig. 11.4. Self-Balancing Potentiometer Recorders

Notice that the pen is mechanically coupled to a wiper, which is turn is mechanically coupled to the armature of the DC motor. Thus the wiper moves according to the error signal, so the pen also moves in the same direction. The pen records the input signal variations moving across the paper.

This recorder has high input impedance, infinity at balance conditions, and high sensitivity of the order of 4 V/mm with an error of less than ± 0.25 % with a bandwidth of 0.8 Hz.

11.11 Application of Self-Balancing Potentiometer Recorders

The main application of potentiometer recorder is for recording and control of process temperatures. It is automatic and eliminates the constant operation of an operator. The recorder draw the curve of the quantity of being measured with the help of recording mechanism.

11.12 Bridge Type Strip Chart Recorder

Temperature is one of the non-electrical quantities which can be measured by this type of recorder. The thermistor converts the temperature into corresponding electrical variations. If a thermistor or resistance thermometer were used as the transducer, the changes in temperature would produce variations in the resistance of the transducer. The thermistor is made part of the bridge as shown in Fig. 11.5.

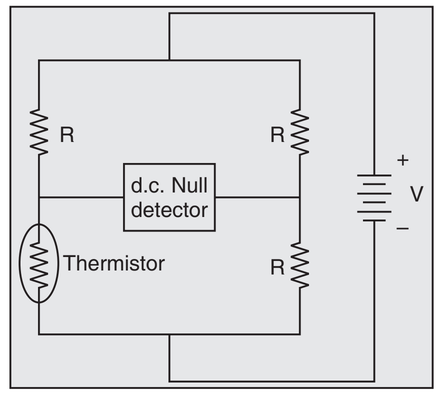


Fig. 11.5. Bridge Recorder

The resistance change in the thermistor cause corresponding changes in the bridge output. This change is applied to detector. The bridge is balanced by varying the resistance of another arm of the bridge, while recording in terms of current, voltage or temperature.

These recorders are used when the signals to be monitored are due to variation in some electrical parameter of a passive transducer such as variation in resistance. The resistance variation occurs in strain gauges, thermistors and photoconductive cells.

11.13 Linear Servo Motor Type Strip Chart Recorder (LVDT)

Fig. 11.6 shows the LVDT type recorder. This recorder is used to record force, pressure etc. It uses linear variable differential transformer (LVDT) T_1 and T_2. The displacement to be recorded is applied to the soft iron of differential transformer T_1. LVDT T_2 is connected with the recording circuit. The primary winding is connected in series to the same AC source while the secondary windings are connected in series opposition. At the balance condition the output voltage of the transformers are equal and opposite and the net output is zero.

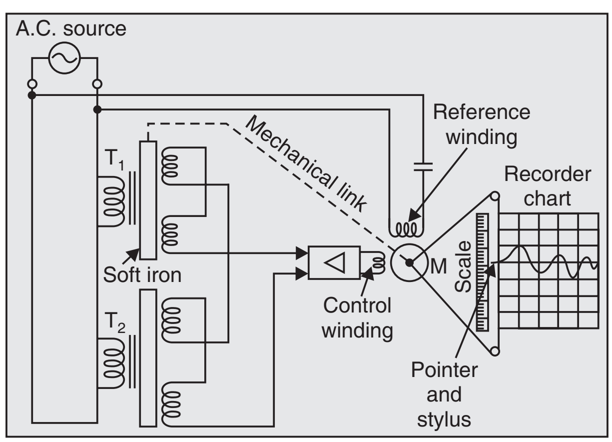


Fig. 11.6.

The displacement is applied to the core of the transformer T_1. Then the output voltages of the two transformers will be different and different output voltage is obtained. The differential output voltage reset the balance and the AC error signal depends upon the direction of the applied displacements.

The amplified AC signal is sent to the control winding of the servomotor (M). It rotates the iron core of transformer T_2 to rebalance the circuit. As the motor rotates, it moves the stylus across the chart of record and the pointer across the scale. When the balance is restored the error signal vanishes and the motor stops. The position of the stylus reflects the new position of the movable core and the trace produced by the stylus on the paper shows the change from the previous position. This pointer indicates the new position on the scale which is calibrated directly in terms of displacement.

11.14 Comparison Between Potentiometric Type Strip Chart Recorder and Galvanometric Type Strip Chart Recorder

The comparison between potentiometric recorder and galvanometric recorder are shown in Table 11.1:

Table 11.1 Comparison between Potentiometer and Galvanometer Recorder

S. No.		*Potentiometric Recorder*	*Galvanometric Recorder*
1.	Principle	Self-balancing or null conditions. It compares the input signal with the reference and produce error signal	It produces deflection when the current passes through the coil.
2.	Response	Faster	Slower
3.	Bandwidth	Higher, order of few hundreds of Hz	Smaller, order of 0-10 Hz
4.	Input impedance	Very high	Very low
5.	Sensitivity	High	Low
6.	Applications	Record the output of transducer in the form of voltage, current, change in resistance or inductance or capacitance, pressure temperature etc.	Commonly used as optical recorder which uses ultraviolet source.

11.15 Circular Chart Recorder

Circular recorders are the polar-coordinate equivalent of the Cartesian coordinate recorders. The chart is a disk and parameter is recorded as a radius on the disk. These recorders provide the same function as a strip chart, expect that they are generally used for long-term monitoring. Speeds on the units are usually in hours, days, and/or weeks. A typical use is to drive the disk at one revolution per day, changing it daily to record a slowly changing parameter such as temperature.

The circular chart uses concentric circles ruled on it to form its scales. These are the printer arcs extending from the centre of the chart to the paper edge. As the pen of the recorder is moved it swings along these arcs, these arcs known as time arcs. The speed of the rotation of chart is usually one revolution per 24 hours or per seven days. The radial position of the pen at any time indicates the instantaneous value of the quantity under measurement.

Fig. 11.7 shows the circular chart recorder instrument.

Advantages

The circular chart recorder has a number of advantages, yet some of them are given below :

1. Charts are flat, easy to handle.
2. The entire record of one process period (12 hr, 24 hr, 7 days etc) is available at a glance.
3. Simultaneous full-chart range recording up to four separate variables is possible.

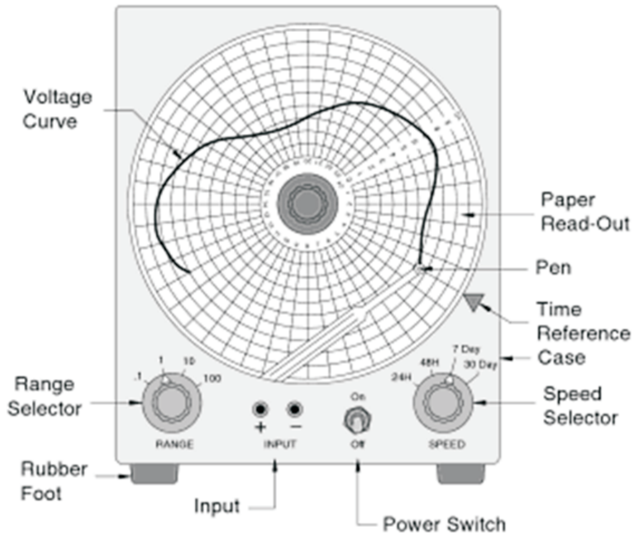


Fig. 11.7. Circular Chart Recorder.

11.16 Comparison between Circular Chart and Strip Chart Recorders

Table 11.2 shows some of the important points of comparison between the circular and strip chart recorders

Table 11.2 Comparison Between Circular and Strip Chart Recorders

S. No.		*Circular Chart Recorders*	*Strip Chart Recorders*
1.	Handling	Easy	Very Easy
2.	Chart shape and size	Circular, varying in size from 100 mm to 250 mm diameter	Curvilinear type, available in the form of long strips rolled on to a drum
3.	Information	Shows all the information at a glance.	Unrolled the chart to see past records
4.	Cost	Low initial cost.	High cost
5.	Chart Speed	Chart speed is limited and as such recording cycles takes longer time for multiple points.	The availability of wide range of chart speeds enables the recording of greater number of points and at a much higher speed than is practical with circular chart instruments
6.	Facility to record	It is possible to simultaneously record on the full chart range up to four separate variables	It is possible to record up to 4 to 6 points simultaneously and thus afford saving a lot of panel space.

11.17 X-Y Recorder

X-*Y* recorder is an instrument which gives a graphic record of the relationship between two variables.

This system has a pen which can be positioned along the two axes with the writing paper remaining stationary. There are two amplifier units. One amplifier actuates the pen in the *Y*- direction as the input signal is applied while second amplifier actuates the pen in *X*- direction. The movements of the pen *X* and *Y* directions are automatically controlled by motor.

There are two types of *X-Y* recorders

1. Analog *X-Y* Recorder
2. Digital *X-Y* recorder

11.18 Analog X-Y Recorder

The *X-Y* recorder plots one voltage as a function of other voltage. Many times *X-Y* recorder is used to record non-electrical physical quantity such as displacement, pressure, strain etc as a function of another non-electrical physical quantity.

The trace of the marking pen will be due to the combined effects of two signals applied simultaneously. In this recorder an emf is plotted as a function of another emf. There are many variations of *X-Y* recorder.

Fig. 11.8 shows the block diagram of *X-Y* recorder. A signal enters in each of the two channels. The signals are attenuated to the inherent full scale range of the recorder. The signal then passes to a balance circuit where it is compared with an internal reference voltage. The balance circuit compares attenuated signal to the fixed reference voltage. The output of error detector is a difference between the variation in input signal and reference voltage. The balancing circuit and error detector gives error signal. This error signal is DC signal. The chopper circuit converts error signal to AC signal. The signal is then applied to the servo amplifier. The servo amplifier drives servomotor which drives writing assembly on a fixed graph paper. There are two circuits for two different inputs to be recorded. The same action takes place in both axes simultaneously.

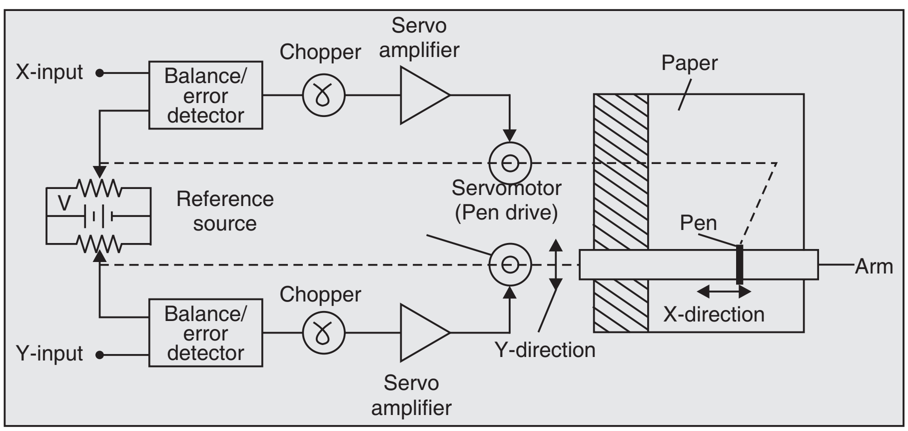


Fig. 11.8. Analog *X-Y* Recorder

11.19 Advantages of X-Y Recorder

The *X-Y* recorder has a number of advantages, yet some of them are given below:

1. This recorder records the relationship between two physical quantities instantaneously.
2. The relationship between either electrical or nonelectrical quantities can be recorded.
3. Zero offset adjustments are available.

11.20 Applications of X-Y Recorder

The *X-Y* recorder mainly used in laboratories to plot the various characteristic curve. Few use of *X-Y* recorder is given below:

1. Plotting of stress-strain curves, hysterics curves.
2. Speed-torque characteristics of motors.
3. Pressure-flow studies for lungs.
4. Pressure–volume diagrams for I.C engine.
5. Regulating curves of power supply.

6. Electrical characteristics of materials such as resistance versus temperature and plotting the output from electronic calculators and computers.
7. Plotting of characteristics of vacuum tubes, Zener diodes, rectifiers and transistors etc.
8. Lift drags wind tunnel tests.

11.21 Digital X-Y Recorder

These days the analog *X-Y* recorders are replaced by digital *X-Y* recorders. The digital recorders provide better performance over analog *X-Y* recorders. It increases the measurement capabilities of the recorder due to advanced techniques. In the digital *X-Y* recorder steeper motor is used in the place of servomotor. It records number of inputs simultaneously with different colors. The communication with such devices is achieved using standard interferences such as RS 232 or IEEE 488 etc. By using proper software and hardware utilities, the recorders can draw grids and charts.

Advantages

The Digital *X-Y* recorder has a number of advantages, yet some of them are given below :

1. The data can be plotted using multi-pen system.
2. It is possible to have simultaneous storage of number of input signals.
3. The hardware and software provide better capabilities.
4. Simultaneous storage of number of input signals is possible.

11.22 Comparison Between Strip Chart Recorder and Analog X-Y Recorder

Table 11.3 shows some of the important points of comparison between strip chart recorder and analog *X-Y* recorder.

Table 11.3: Comparison Between Strip Chart and Analog ***X-Y*** Recorder

S. No.	*Strip Chart Recorder*	X-Y *Recorder*
1.	Also known as *X-t* plotter.	Also known as *X-Y* plotter.
2.	Input variable is plotted as a function of time.	One input variable is plotted as a function of the other.
3.	Paper is kept rotating.	Paper is held stationary.
4.	Zero offset adjustments are not available.	Zero adjustments are available.

11.23 Oscillographic Recorder

The Oscillographic recorders are instruments which record information on paper or film with ink, power, electrostatic charge, liquid, electric arc or light. These recorders are basically electro-mechanical Oscillographic recorders. Fig. 11.9 shows the oscillographic recorder.

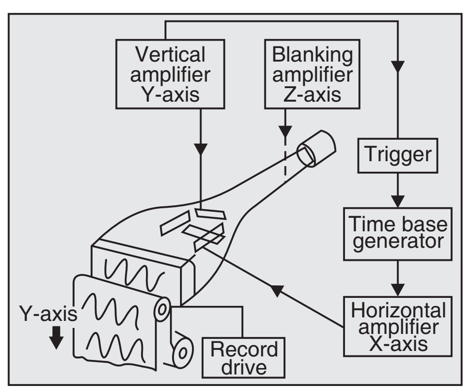


Fig. 11.9.

11.24 Ultraviolet (UV) Recorder

The UV recorders provide recording of phenomena with frequencies ranging from zero to several kHz. The writing part of the recorder consists of an ultraviolet light source, the light beam falling on the recording paper which us sensitive to ultraviolet rays. The trace becomes visible in approximately 30s after exposure. The recordings takes with this can be kept for long periods in places with low ultraviolet light content but if they are to be kept for later references, it is advisable to have them chemically treated and fixed. Otherwise, they will lose their contrast due to the effect of ultraviolet component in day light.

Fig. 11.10 shows a UV recorder. As seen from the diagram, it consists of a number of galvanometer (moving coil) elements mounted in a single magnet block as shown. A paper sensitive to ultraviolet light is used for producing a trace. When a current is passed through the moving coil, it deflects under the influence of the magnetic field of permanent magnet. The ultraviolet light falling on the mirrors is deflected and projected on to the UV light sensitive paper through a lens and mirror system. The paper is driven past the moving high spot and thus a trace of variation of current with respect to time is produced.

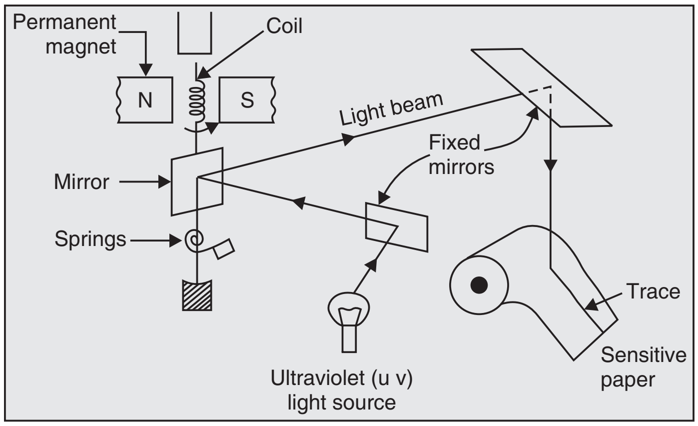


Fig. 11.10.

These recorders are also used for recording the magnitude of low frequency signals which cannot be measured with analog type instruments. One of the main features of any ultraviolet recorder is its ability to make hard copy recordings at high writing speeds. UV recorders are best suited where several phenomena are to be recorded simultaneously. The galvanometers are mounted side by side and overlapping to traces is possible.

Two types of light sources can be used in UV recorders, viz., a 50 or 100 W mercury vapour lamp or a 100 W quartz halogen lamp. The mercury vapour lamp is more expensive than the quartz halogen lamp, but permits higher writing speeds. When a quartz halogen lamp is used, it can be simply turned ON with the mains switch of the apparatus. Provision can be made for continuous control for light intensity. But in the case of mercury vapour lamp, a separate switch has to be operated for accelerating the light arc of the lamp so that right intensity for making recordings can be obtained quickly. Frequent switching on and off for shorter periods of non-operation.

Although the dynamic performance of a UV recorder is determined principally by chart drive characteristics, its overall frequency response depends on galvanometer performance and its maximum writing speed. The latter depends on the quality of the light source and on the efficiency of the optical system. Recorders with frequency response up to 2 kHz (3 db) are commercially available.

Advantages

The main advantage of UV recorders is the wide frequency response, attainable easily as far as 15 kHz.

Disadvantages

The main disadvantage is the quality of the image and cost of photo-sensitive paper as compared to the other pen or ink-jet recorders.

11.25 Magnetic Tape Recorder

The recorders discussed earlier are having very poor higher frequency response. They are mostly used for low frequency operation. The magnetic tape recorders are used for high frequency signal recording. The basic components of magnetic tape recorder are given below:

1. Recording Head. The construction of the recording head is shown in Fig. 11.11. Its construction is similar to that of transformer having toroidal core with a coil. The fine air gap of length 5-15 μm is shunted by the passing magnetic tape. When the current used for recording is passed through the coil wound around magmatic core, it produces magnetic flux. The magnetic tape having iron oxide particles passes the head, the magnetic flux produced gets linked with the iron oxide particles and these particles get magnetized. The state of magnetization of the oxide as it leaves the gap is retained, thus the actual recording takes place at the trailing edge of the gap.

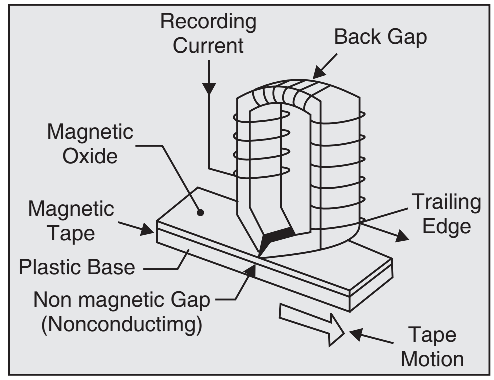


Fig. 11.11. Recording Head

Any signal recorded on the tape appears as a magnetic pattern dispersed in space along the tape, similar to the original coil current variation with time.

2. Magnetic Tape. It is made of a thin sheet of tough, dimensionally stable plastic, one side of which is coated with a magnetic material. Typically the plastic base is polyvinyl chloride (PVC) or polyethylene terephthalate, for example mylar.

The magnetic coating consists of a dispersion of very small particles of iron oxide (Fe_2O_3) on a plastic blinder.

3. Reproducing Head. Its function is to detect the stored magnetic pattern and to convert it back to original electrical signal.

Tape Transport Mechanism

Fig. 11.12 shows the tape transport mechanism. It moves the magnetic tape along the recording head or reproducing head with a constant speed. The magnetic tape is wound on reel. There are two reels, one is called as supply reel and other is called as take-up reel. Both reels rotate in same direction. The transportation of the tape is done by using supply reel and take-up reel. The rollers are used to drive and guide the tape. The tape transport mechanism performs the following tasks:

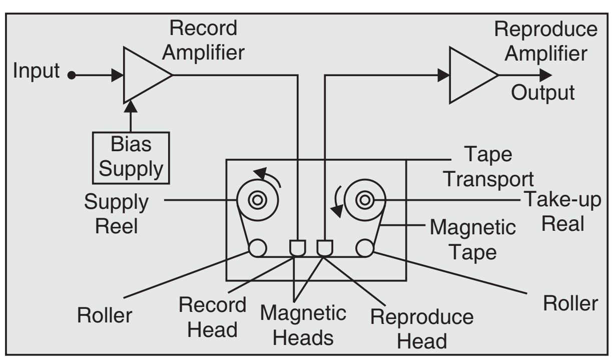


Fig. 11.12. Tape Transport Mechanism

(***a***) To handle the tape without straining and wearing it.

(***b***) To guide the tape across magnetic heads with great precision.

(*c*) To maintain uniform and sufficient gap between the tape and heads

(*d*) To maintain proper tension of magnetic tape.

4. Conditioning Devices. These devices consist of amplifiers and filters to modify signal to a format that can be properly recorded on a tape. Amplifier amplifies the signal to be recorded while filters remove unwanted ripple quantities.

Operating Principle

When a magnetic tape passes through a recorders head, the signal to be recorded appears as some magnetic pattern on the tape. This magnetic pattern is in accordance with the variations of original recording current. The recorded signal can be reproduced back by passing the same tape through a reproducing head where the voltage in induced corresponding to the magnetic pattern on the tape. The induced voltage depends on the direction of magnetization and its magnitude on the tape. The emf thus produced is proportional to the rate of change of magnitude of magnetization

$$e \,\alpha\, N \frac{d\phi}{dt}$$

where N is the number of turns of the winding put on reproducing head.

Let's assume that the original signal is $A.\sin \omega$. The current in the recording head winding and the flux produced will be proportional to this voltage.

$$\phi = k_1 . A . \sin \omega t$$

where is k_1 constant.

The voltage induced in the reproducing head winding,

$$e_{\text{rep}} = N . \frac{d\phi}{dt} = N . \frac{d}{dt} = (k_1 . A . \sin \omega t)$$

$$e_{\text{rep}} = k_1 . N . A . \omega . \cos \omega t = k_2 . A . \omega . \cos \omega t$$

where $k_2 = k_1\, N$ is constant.

The reproduced signal is equal to derivative of input signal and it is proportional to flux recorded and frequency of recorded signal.

Advantages

Some of the main advantages of magnetic tape recorder are:

1. Wide frequency range from DC to several MHz.
2. Low distortion
3. Multi-channel recording possible.
4. Exceedingly high density of data points giving simplified storage and handling.

Applications

Following are some of the important applications of magnetic tape recorders, which are important from the subject point of view:

1. Communication surveillance and spying.
2. Data recording and analysis on missiles, aircraft and satellites.
3. Medical research
4. Industrial research and production monitoring and control.
5. After processing of the recorder information the possibility of erase the reuse of the tape.

11.26 Method of Recording on Magnetic Tape

The methods used for magnetic tape recording used for instrumentation purpose are as follows:

1. Direct Recording Method

2. Frequency Modulation Recording
3. Pulse Duration Modulation Recording

11.27 Direct Recording Method

It is the simplest method of recording and usually requires one tape track for each channel. The signal to be recorded is amplified, mixed with a high frequency bias and fed directly to the recording head as a varying electric current as shown in Fig. 11.13.

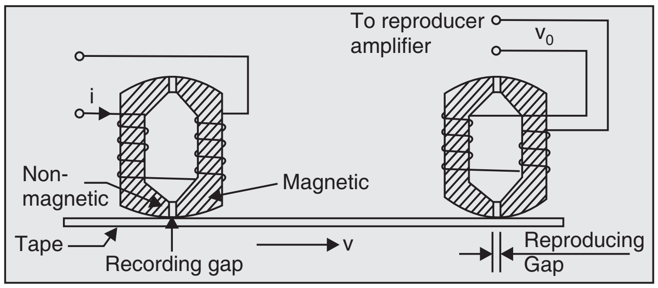


Fig. 11.13.

The input voltage is converted into proportional current and passed through the winding on the recording head. A magnetic flux given by the expression $\phi = K_\phi \, i$ is created at the recording gap and as the tape passes under the gap the oxide particles retain a state of permanent magnetization proportions to the flux existing at the instant the particle leaves the gap. Thus, with a sinusoidal input signal,

$$i = i_o \sin 2 \pi f t$$

A tape speed of v m/s, the intensity of magnetization along the tape varies sinusoidally with the distance x as,

$$\text{Magnetization, } m = K_m K_\phi \, i_o \sin \left(2 \pi f \frac{x}{v} \right)$$

Thus resulting magnetic field created in the recording gap enables magnetic recording of the input information on a tape that passes under the gap. A dc or high frequency ac is added to the recording signal to improve linearity.

For reproduction, the tape is passed over a reproducing head thereby resulting in an output voltage proportional to the magnetic flux in the tape, across the coil of the reproducing head. Since the output voltage depends upon the rate of change of flux, is a dc at the input had produced a constant tape magnetization, the reproducing head would have given zero output.

Thus the direct recording process can be used with varying input signals only, with about 50 Hz being the usual lower limit of frequency. Furthermore, since the reproducing head has a different characteristic, the reproducing amplifier must have an integrating characteristic so that the system output is proportional to the input. An upper limit of frequency also exists, as at sufficiently high frequencies, for a given reproducing gap and tape speed, one wavelength of magnetization will becomes equal to or less than the width of the gap. Then the average magnetization in the gap will be zero and so there will be zero output voltage, with a gap width of 0.002 mm, and a tape speed of 3 m/s, the frequency response can extend from 50 Hz up to about 1 MHz. The main drawback of the direct method of recording is its poor-signal-to-noise ratio, which is typically 25 db/ The direct recording process not given high accuracy because of its poor signal-to-noise ratio.

The direct recording, no doubt, can be adopted for instrumentation purpose but it is mainly employed for recording the speech and music as in recordings, the ear average the amplitude variation errors.

Advantages

The direct recording method has a number of advantages. Some of the important ones are given below :

1. This requires simple electronic circuits.
2. It can be used for recording voice and multiplexing a number of channels of information into one channel of tape recording.
3. It used to record signal where information is contained in the relation between frequency and amplitude, such as spectrum analysis of noise.

Limitations

Some of the limitations of this method are given below:

1. This recorder is only used when maximum bandwidth is required.
2. Difficult to record dc signal.

11.28 Frequency Modulation Recording Method

The major disadvantage of direct recording is that it is difficult to record dc signals. This problem is solved with frequency modulation (FM) recording in which accurate dc response is obtained.

Principle of Operation

In FM the carrier frequency is modulated by the input signal. This recorder uses the variation of frequency to carry the required information instead of amplitude. The modulated signal is then recorded using the recording head. The reproducing head reproduces the signal in normal way. The reproduced signal is passed through FM demodulator, low pass filter to get original signal.

Working

Fig. 11.14 shows the FM recording system. The carrier frequency is called as center frequency f_c. This frequency is modulated by the level of the input signal. The centre frequency is selected with respect to the tape speed and frequency deviation selected for the tape recorders.

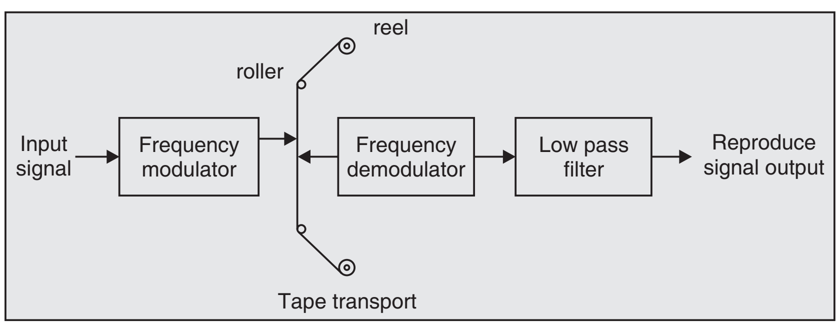


Fig. 11.14. Tape Transport Mechanism

When there is no input signal (zero input), the modulation contains only the centre frequency oscillation. The positive input voltage deviates the carrier frequency by specified percentage in one direction. The negative voltage deviates the carrier frequency by specified percentage in other direction.

For dc inputs the modulated output is a signal of constant frequency and for ac inputs the modulated output is a signal of variable frequency. The frequency variation is directly proportional to the amplitude of input signal.

On playback, the output of the reproducing head is demodulated and fed through a low pass filter which removes the carrier and other unwanted frequencies reproduced due to the modulation process. The frequency demodulation converts the difference between centre frequency and the frequency on the tape, to a voltage proportional to the difference in the frequencies. This system can thus record frequencies from dc to several thousand hertz.

Advantages

This method has a number of advantages as given below:

1. Useful in recording of dc components.
2. Frequency range from 0 Hz to several kHz.
3. Extensively used for multiplexing in the instrument and process system.
4. Extensively used for recording non electrical quantities such as force, pressure etc.

Disadvantages

This method has some disadvantages also, they are given below:

1. Tape speed fluctuations affect the FM recording.
2. It has limited frequency response.
3. It is comparatively expensive.
4. Circuit is complicated.

Uses

This type of recording system is primarily used when the dc component of the input signal is to be preserved or when the amplitude variations of the direct recording process are not tolerable. This system is widely used for recording the voltages from the pressure, force and acceleration transducers and for multiplexing in instrument system.

11.29 Pulse Duration Modulation Recording (PDM) Method

It is also called pulse width modulation. The amplitude and starting time of each pulse of a signal is kept constant while width of pulse is made proportional to amplitude of signal at that instant.

The input signal is converted to a pulse at the sampling instant. The width of each pulse is dependent on the amplitude of the signal at that instant. The sampled signal is recorded at various instants instead of recording instantaneous values continuously. On playback original signal can be obtained by passing recorded signal to appropriate filter.

For example if a sine wave is to be recorded, it is sampled and recorded at uniformly spaced discrete intervals in place of continuously recording the instantaneous values. On playback the original sine wave can be reconstructed by passing the discrete readings through an appropriate filter. Its main advantages are high signal-to-noise ratio, high accuracy and capability of recording information from are large number of channels simultaneously.

This recording system is employed in instrumentation systems for special applications such as for simultaneous recording of large number of slowly changing variables.

Advantages

The pulse duration modulation recording method has a number of advantages. Some of the important ones are given below:

1. High accuracy.
2. High signal-to-noise ratio.
3. The system is capable to record information from a large number of channels simultaneously.

Disadvantages

This pulse duration modulation recording method has some disadvantages also. These are given below:

1. Limited frequency response.
2. Low reliability.
3. Complex circuitry.

11.30 Requirements of Recording Data

We need the recorded data for some of the following reasons:

1. The recording of any quantity is done in order to preserve the details of that quantity time to time.
2. In many applications, there are some critical parameters of the process or equipment. For better performance of process or equipment these parameters are recorded for taking action time to time.
3. The performance of the unit equipment or the process can be overviewed by just looking at the record chart.
4. The efficiency of process can be easily determined by using recorded chart.
5. The recorded chart indicated the performance of the equipment as per the specifications provided by the manufacturer.

11.31 Plotter

A plotter is a computer printing device for printing vector graphics. In the past, plotters were widely used in applications such as computer-aided design, though they have generally been replaced with wide-format conventional printers, and it is now commonplace to refer to such wide-format printers as plotters. A plotter is a pen based output device that is attached to a computer for print large-format graphs or maps such as construction maps or engineering drawings. The images are created by a series of many straight lines. It is used to draw high resolution graphs.

A plotter is a special output device used to produce hardcopies of graphs and designs on the paper. Plotters are divided into two types:

1. Drum Plotter
2. Flatbed Plotter

11.32 Drum Plotter

A drum plotter is also known as Roller Plotter. It consists of a drum or roller on which a paper is placed and the drum rotates back and forth to produce the graph on the paper. The drum rotation is under the control of plotting instructions sent by the computer. In this plotter the pen is moved vertically, i.e. along the *Y*-axis and the paper wrapped on the drum is moved horizontally, i.e. along the *X*-axis. The movement of paper is backward or forward direction to produce a graph or an image. In case, a horizontal line is to be draw, the horizontal movement of a pen is combined with the vertical movement of a page via the drum. It can draw the curves by creating a sequence of very short straight lines.

Fig. 11.15 shows the drum type plotter. The plotter consists of one or more pens that are mounted on a carriage and this carriage is horizontally placed across. It also consists of mechanical device known as Robotic Drawing Arm that holds a set of colored ink pens or pencils. The Robotic Drawing Arm moves side to side as the paper are rolled back and forth through the roller. In this way, a perfect graph or map is created on the paper. This work is done under the control of computer. Drum Plotters are used to produce continuous output, such as plotting earthquake activity.

Fig. 11.15. Drum Plotter

11.33 Flatbed Plotter

A flatbed plotter is also known as Table Plotter. It plots on paper that is spread and fixed over a rectangular flatbed table. In this plotter the position of the paper is kept constant and the pens moved around in various directions to draw graphs and images. The flatbed plotter uses two robotic drawing arms, each of which holds a set of colored ink pens or pencils. The drawing arms move over the stationary paper and draw the graph on the paper.

Typically, the plot size is equal to the area of a bed. The plot size may be 20- by-50 feet. It is used in the design of cars, ships, aircrafts, buildings, highways etc. Flatbed plotter is very slow in drawing or printing graphs. The large and complicated drawing can take several hours to print. The main reason of the slow printing is due to the movement mechanical devices.

Today, mechanical plotters have been replaced by thermal, electrostatic and ink jet plotters. These systems are faster and cheaper. They also produce large size drawings. Fig. 11.16 shows the flatbed type plotter.

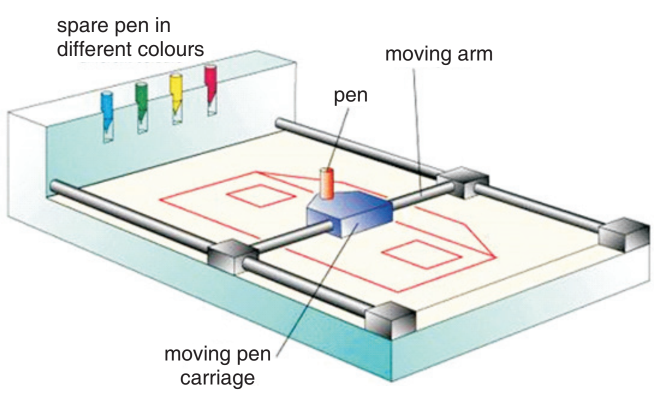


Fig. 11.16. Flatbed Plotter

11.34 Comparison Between Printer and Plotter

Plotters are similar to printers, but plotter draw lines using a pen. The plotters an produce continuous lines whereas the printer can only simulate lines by printing a closely spaced series of dots. Multicolor plotters use different colored pens to draw different colors. Color plots are made by using four pens cyan, magenta, yellow and black.

11.35 Use of Plotter

Some of the main uses of plotter are given below:

1. Use in computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) applications.
2. Use in printing the plans for houses or car parts
3. Use in program like auto CAD to give graphic outputs.

SUMMARY

1. The recorder is the instrument which records the electrical and non-electrical quantities as a function of other variable.
2. The galvanometer type recorder has very low input impedance and sensitivity.
3. The main application of potentiometer recorder is for recording and control of process temperatures.
4. Bridge Recorder are used when the signals to be monitored are due to variation in some electrical parameter of a passive transducer such as variation in resistance which occurs in strain gauges, thermistors and photoconductive cells.
5. Linear Servo Motor Recorder (LVDT) is used to record force, pressure etc.
6. Circular recorders are the polar-coordinate equivalent of the Cartesian coordinate recorders. It used a concentric circles ruled on it to form its scales.
7. *X-Y* recorder is an instrument which gives a graphic record of the relationship between two variables. It plots one voltage as a function of other voltage.
8. The oscillopraphic recorders are instruments which record information on paper or film with ink, power, electrostatic charge, liquid, electric arc or light. These recorders are basically electro-mechanical oscillographic recorders.
9. In UV recorder,a paper sensitive to ultraviolet light is used for producing a trace.
10. The magnetic tape recorders are used for high frequency signal recording.
11. In frequency modulation recording the accurate dc response is obtained.
12. A plotter is a pen based output device that is attached to a computer for print large-format graphs or maps such as construction maps or engineering drawings.
13. A drum plotter is also known as Roller Plotter.
14. A flatbed plotter is also known as Table Plotter.

GLOSSARY

Bridge Recorder: The thermistor is used as a part of bridge.

Circular Chart Recorder: The chart is a disk and parameter is recorded as a radius on the disk.

Drum Plotter: Drum plotter consists of a drum or roller on which a paper is placed and the drum rotates back and forth to produce the graph on the paper.

Flatbed Plotter: In this plotter, the position of the paper is kept constant and the pens moved around in various directions to draw graphs and images.

Frequency Modulation recording: This recorder uses the variation of frequency to carry the required information instead of amplitude.

Galvanometer type recorder: It operates on the galvanometer (D'Arsonval) principle. It produces deflection when the current passes through the coil.

Potentiometric Recorder: Based on Self balancing or null conditions. It compares the input signal with the reference and produce error signal

Pulse Duration Modulation recording (PDM): In this recorder, the amplitude and starting time of each pulse of a signal is kept constant while width of pulse is made proportional to amplitude of signal at that instant.

Strip Chart Recorder: A chart recorder is an electromechanical device that records an electrical or mechanical input trend onto a piece of paper (the chart).

UV recorder: When a current is passed through the moving coil, it deflects under the influence of the magnetic field of permanent magnet. The ultraviolet light falling on the mirrors is deflected and projected on to the u.v light sensitive paper

X-Y Recorder: This system has a pen which can be positioned along the two axes with the writing paper remaining stationary.

DESCRIPTIVE QUESTIONS

1. What is recorder? Give the classification the recorders.
2. Describe the graphic recorder.
3. Explain the basic construction of strip chart recorder.
4. Describe the working of strip chart recorder. Why it is called X-t recorder?
5. Explain the marking mechanism of strip chart recorder.
6. Explain the working of galvanometer type strip chart recorder. Why it is necessary to use large moving coil and strong magnetic field in these recorders?
7. Describe the suitable diagram of null balance recorders.
8. Explain the galvanometer recorder.
9. Explain the circular chart recorder. Describe the advantage of this recorder also.
10. Compare the strip chart and circular chart recorder.
11. What is the X-Y recorder? How it is differ from strip chart recorder. Describe it advantages and application.
12. Explain analog type X-Y recorder with block diagram.
(Nagpur University, Summer 2011)
13. Write short note on digital type X-Y recorder.
14. Explain the principle of working of a magnetic tape recorder. What is the basic components and their functions?
15. Describe the recording method in magnetic tape recorder.
16. Describe the frequency modulation (FM) magnetic tape recording. Give advantages, disadvantage and use.
17. What is pulse modulation recording? Give advantages and disadvantage.
18. Write short note on UV recorder.
19. Explain the plotter. How is different from printers?
20. Explain different types of plotter and their uses.
(GBTU/MTU 2009-10)
21. Explain drum type plotter.
22. Explain flatbed type plotter.
23. Describe the working principle of a digital tape recorder.
(PTU, May 2009)
24. What are necessities of recorders?
(PTU, May 2009)
25. Write down the difference between direct recording and indirect recording.
(PTU, Dec 2006)

26. Explain the function of basic type of strip chart recorder. Explain the different types of marking mechanism used in it.

(PTU, May 2007)

27. Write short notes on the following
(*i*) Strip chart recorder
(*ii*) Plotter
(*iii*) *X-Y* recorder

(GBTU/MTU, 2010-11)
(Nagpur University, Summer 2009)

MULTIPLE CHOICE QUESTIONS

1. A recorder,
(*a*) Is an indicating instrument which display a time varying signal
(*b*) Is a device whose function is to record the value of quantity as it is being measured
(*c*) Records electrical and non-electrical quantities as a function of time or relates two signals to each other.
(*d*) Both (*b*) and (*c*)

2. Strip chart recorders have the advantage,
(*a*) Long period run.
(*b*) More actually usable width.
(*c*) Uniform resolution
(*d*) All of the above.

3. The Recorder used for plotting *B-H* curves for magnetic materials,
(*a*) LVDT type recorder
(*b*) Circular chart recorder
(*c*) *X-Y* recorder
(*d*) Potentiometer type recorder

4. Galvanometer type recorder use,
(*a*) Vibration galvanometer
(*b*) Ballistic galvanometer
(*c*) D'Arsonval galvanometer
(*d*) Tangent galvanometer

5. The advantages of FM magnetic tapes recording are,
(*a*) It can record from dc to several kHz.
(*b*) It is free from dropout effects.
(*c*) It is independent of amplitude variations and accurately reproduces the waveform of input signal.
(*d*) All of the above.

6. *X-Y* recorders,
(*a*) Record one quantity with respect to another quantity.
(*b*) Record one quantity on *X* axis with respect to time on *Y* axis.
(*c*) Record one quantity on *Y* axis with respect to time on *X* axis.
(*d*) Any of the above.

7. *X-Y* recorders record a quantity,
(*a*) With respect to another quantity.
(*b*) On *X*-axis with respect to time on *Y*-axis.
(*c*) On *Y*-axis with respect to time on *X*-axis.
(*d*) Any of these.

ANSWERS

1. (*d*) **2.** (*d*) **3.** (*c*) **4.** (*c*) **5.** (*d*) **6.** (*a*)
7. (*a*)

Chapter 12

Display Devices

Outline

Objectives

After completing this chapter, you should be able to:

- Explain the construction and operation of LED, LCD and Nixie.
- Understand how segment display work to display the alphanumeric character.
- Explain the dot matrix display.
- Describe the other various displays.
- Discuss the specification of digital meter display.

12.1 Introduction

A **display device** is an output device for display the information in visual form by means of various types of display systems. In digital instruments the output device of the instrument indicates the value of measured quantity using the digital display device. This digital display device may receive the digital information in any form but it converts the information in decimal form. The digital display device indicates the value in decimal digits directly. LEDs are most commonly used in the digital displays for displaying alpha numeric character. The LEDs have advantages such as low voltage, long life, high reliability, low cost, fast switching characteristics etc.

12.2 Classification of Display

The most commonly used display devices are CRT (Cathode Ray Tube), LED (Light Emitting Diode) and LCD (Liquid Crystal Display) etc. The display devices may be classified in different ways. Classifications are:

1. On the basis of applications
   (*a*) Analog Displays: CRT.
   (*b*) Digital Displays: Nixie tubes, alphanumeric display, LED.
2. On the basis of physical dimensions and size
   (*a*) Symbol Displays: Alphanumeric, Nixie tube, LED.
   (*b*) Console Displays: LED, CRT
3. On the basic of display format:
   (*a*) Direct View Type(Flat Panel): Segmental display, dot matrix
   (*b*) Stacked Non-planer type: Nixie tube
4. On the basis of resolution
   (*a*) Simple single element indicator
   (*b*) Multielement displays
5. On the basic of planar or non-planer
   (*a*) Planer: LEDs and LCDs
   (*b*) Non-planer: Nixie

In digital electronic field, the commonly used displays are given as follows :

1. Light Emitting Diode
2. Liquid Crystal Display
3. Nixie Tube or Cold Cathode Displays
4. Incandescent Displays
5. Fluorescent Displays
6. Liquid Vapour Based Display
7. Segmented Gas Discharge Displays

We shall now, discuss all the above mentioned display in detail in the following pages.

12.3 Light Emitting Diode (LED)

A PN junction diode, which emits light when forward biased, is known as a light emitting diode (abbreviated as LED). The emitted light may be visible or invisible. The amount of light output is directly proportional to the forward current. Thus, higher the forward current, higher is the light output. The schematic symbol of a light emitting diode is shown in Fig. 12.1 (*a*). The arrows, pointing away from the diode symbol represent the light, which is being transmitted away from the junction.

Fig. 12.1 (*b*) shows the basic structure of a light emitting diode. Here, an N-type layer is grown on a P-type substrate (not indicated in Figure) by a diffusion process. Then a thin P-type layer is grown on the N-type layer. The metal connections to both the layers make anode and cathode terminals as indicated. The light energy is released at the junction, when the recombination of electrons with holes take place. After passing through the P-region, the light is emitted through the window provided at the top of the surface.

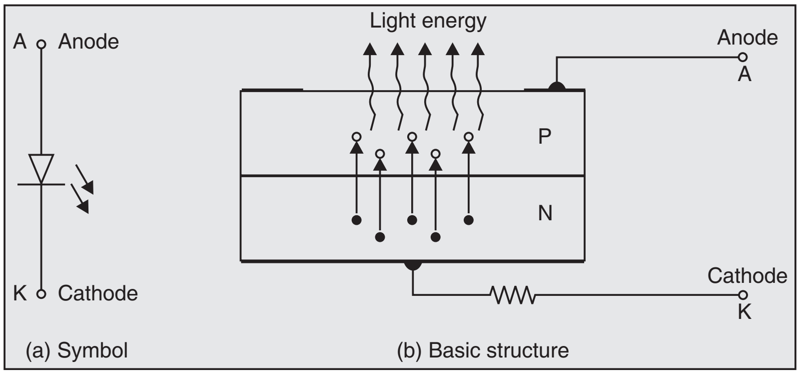


Fig. 12.1. Light emitting diode

It will be interesting to know that when the LED is forward biased, the electrons and holes move towards the junction and the recombination takes place. After recombination, the electrons, lying in the conduction bands of N-region, fall into the holes lying in the valence band of a P-region. The difference of energy between the conduction band and valence band is radiated in the form of light energy. In ordinary diodes, this energy is radiated in the form of heat.

The semiconducting materials used for manufacturing light emitting diodes are gallium arsenide, gallium arsenide phosphide. The silicon and germanium is not used for manufacturing light emitting diodes because these are heat producing materials. Moreover, these materials are very poor in emitting light radiations.

The LED's radiate light in different colours such as red, green, yellow, blue, orange etc. Some of the LED's emit infrared (i.e., invisible) light also. The colour, of the emitted light, depends upon the type of the semiconductor used. Thus gallium arsenide emits infrared radiations, gallium arsenide phosphide produces either red or yellow light, gallium phosphide emits red or green light and gallium nitrite produces blue light.

Since LED's have clear (or semiclear) cases, there is normally no label on the cased to identify the leads. The two leads of a LED are identified using one of the several schemes as discussed below.

The leads may have different lengths as shown in Fig. 12.2 (*a*), when the schemes is used, the longer of the two leads is usually the anode.

One of the leads may be flattened as shown in Fig. 12.2 (*b*). The flattened lead is usually the anode

One side of the case is flattened as shown in Fig. 12.2 (*c*).The lead closest to the flattened side is usually the anode.

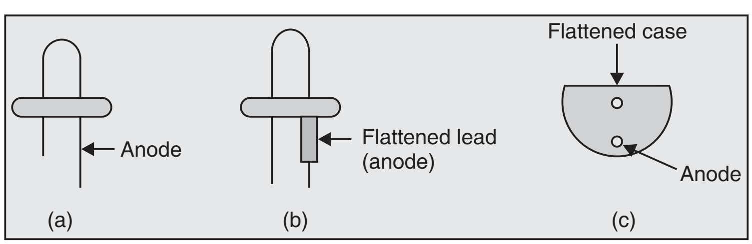


Fig. 12.2.

12.4 Advantages of LED

Thought the LED has a number of advantages, yet some of them are given below :

1. **Efficiency:** LEDs emit more light per watt than incandescent bulbs Their efficiency is not affected by shape and size, unlike Fluorescent light bulbs or tubes.
2. **Color:** LEDs can emit light of an intended color without using any color filters as traditional lighting methods need. This is more efficient and can lower initial costs.
3. **Size:** LEDs can be very small (smaller than 2 mm) and are easily populated onto printed circuit boards.
4. **On/Off time:** LEDs light up very quickly. A typical red indicator LED will achieve full brightness in under a microsecond. LEDs used in communications devices can have even faster response times.
5. **Lifetime:** LEDs can have a relatively long useful life. One report estimates 35,000 to 50,000 hours of useful life, though time to complete failure may be longer. Fluorescent tubes typically are rated at about 10,000 to 15,000 hours, depending partly on the conditions of use, and incandescent light bulbs at 1,000–2,000 hours.
6. **Shock resistance:** LEDs, being solid state components, are difficult to damage with external shock, unlike fluorescent and incandescent bulbs which are fragile.
7. **Focus:** The solid package of the LED can be designed to focus its light.
8. **Low toxicity:** LEDs do not contain mercury, unlike fluorescent lamps.

12.5 Disadvantages of LED

LED has some disadvantages also, they are given below :

1. **High initial price:** LEDs are currently more expensive
2. **Temperature dependence:** LED performance largely depends on the ambient temperature of the operating environment.
3. **Voltage sensitivity:** LEDs must be supplied with the voltage above the threshold and a current below the rating. This can involve series resistors or current-regulated power supplies.

12.6 LED Applications

The LED's operate at low voltages i.e., from 1.5 V to 2.5 V. They have a long life of about 10000 hours and can be switched 'ON' and 'OFF' at a very fast speed ($\simeq$ 1 n sec). These features make LED's very important electronic device. Following are the important applications of the LED's:

1. In 7-segment, 16-segment and dot matrix displays. Such displays are used to indicate alphanumeric characters and symbols in various systems such as digital clocks, microwave-ovens, stereo tuners, calculators electronic d.c. power supplies etc.
2. For indicating power ON/OFF conditions, power level indicators in stereo amplifiers.
3. In optical switching applications.
4. For solid state video displays, which are rapidly replacing cathode ray tubes (CRT's).
5. In the field of optical communication, where LED's are used to transfer (or couple) energy from one circuit to another. They are also used to send light energy to fiber optical cable, which transmits energy by means of total internal reflection. The fiber optical cable is of light weight, flexible, often transparent and as small a 0.043 mm in diameter.
6. For image sensing circuits in picture phone.
7. In burglar alarm systems. In such applications, LED's radiating infrared light are preferred.

12.7 Multicolour LEDs

The LEDs, which emit one colour of light when forward biased and another when reverse biased, are called multicoloured LEDs. One commonly used symbol for a multicolour LED is as shown in Fig. 12.3.

Multicolour LEDs actually contain two PN junction that are connected in reverse-parallel, i.e., they are in parallel, with the anode of one being connected to the cathode of the other. Multicolour LEDs are typically red when biased in one direction and green when biased in the other direction. Incidentally if a multicolour LED is switched fast, the LED will produced a third colour. For example, a red/green LED will produce a yellow light when rapidly switched back and forth between biasing polarities.

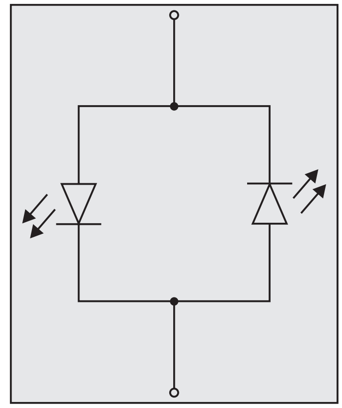


Fig. 12.3. Schematic symbol for multicolour-LED

12.8 Use of LEDs in Facsimile Machines

Fig. 12.4 shows a simplified schematic diagram of a facsimile (or fax) machine. As seen, the light from the LED array is focussed on the document paper. The light reflected at the paper is focussed on a charge-coupled device (CCD) by a combination. The electrical information is then sent through the data-processing unit to its destination via telephone line.

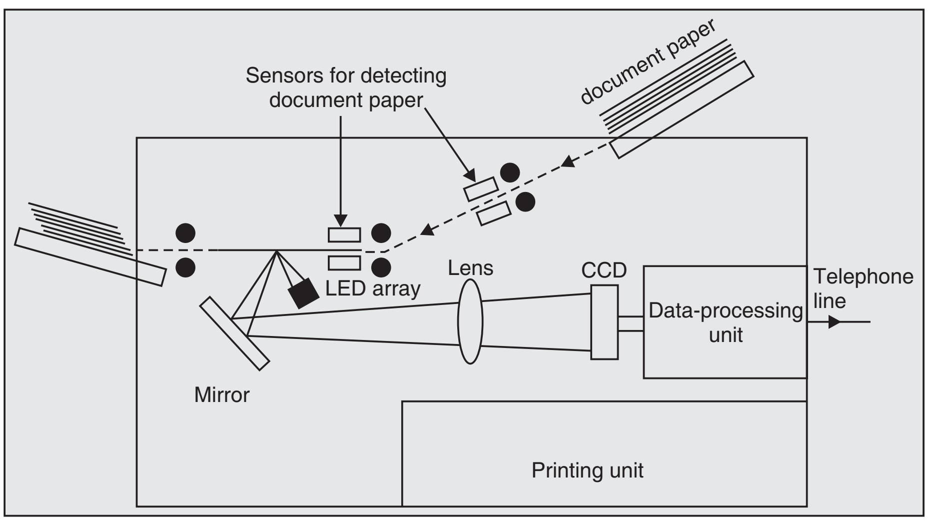


Fig. 12.4.

12.9 Liquid Crystals Displays

A liquid crystal is a material (usually, an organic compound) which flows like a liquid at room temperature but whose molecular structure has some properties normally associated with solids (examples of such compounds are : cholestery l nonanoate and p-azoxyanisole). As is well-known, the molecules in ordinary liquids have random orientation but in a liquid crystal they are oriented in a definite crystal pattern. Normally, a thin layer of liquid crystal is transparent to incident light but when an electric field is applied across it, its molecular arrangement is disturbed causing changes in falls on an activated layer of a liquid crystal, it is either absorbed or else is scattered by the disoriented molecules.

As shown in Fig. 12.5 (*a*), a liquid crystal 'cell' consists of a thin layer about 10 mm) of a liquid crystal sandwiched between two glass sheets with transparent electrodes deposited on their inside faces. With both glass sheets transparent, the cell is known as *transmittive* type cell. When one glass is transparent and the other has a reflective coating, the cell is called *reflective* type. The LCD does not produce any illumination of its own. It, in fact, depends entirely on illumination falling on it from an external source for its visual effect.

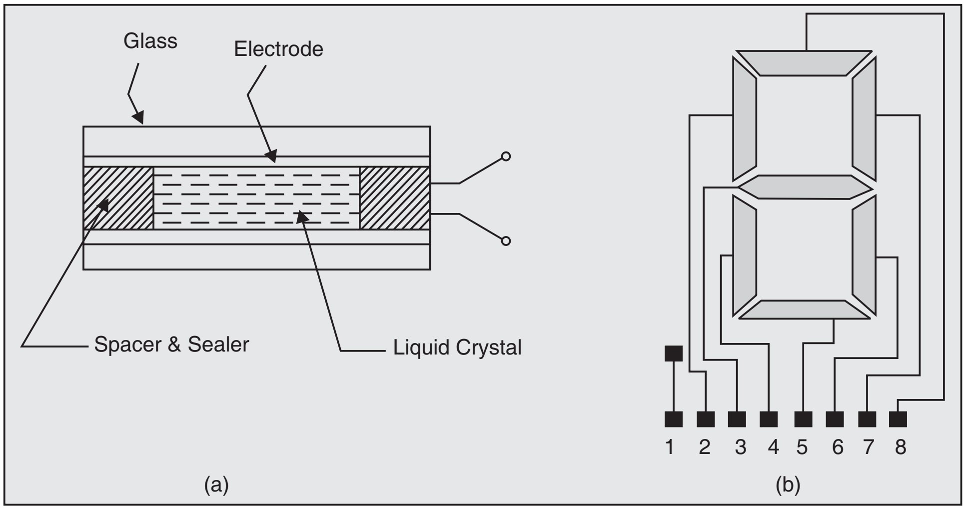


Fig. 12.5.

The two types of display available are known as (*i*) **field-effect display** and (*ii*) **dynamic scattering display**. When field-effect display is energized, the energized areas of the LCD absorb the incident light and, hence give localized black display. When dynamic scattering display is energized, the molecules of energized area of the display become turbulent and scatter light in all directions. Consequently, the activated areas take on frosted glass appearance resulting in a silver display. Of course, the un-energized areas remain translucent.

As shown in Fig. 12.5 (*b*), a digit on an LCD has a segment appearance. For example, if number 5 is required, the terminals 8, 2, 3, 6 and 5 would be energized so that only these regions would be activated while the other areas would remain clear.

12.10 Advantage of LCDs

An LCD has the distinct advantage of extremely low power requirement (about 10-15 micro watt per 7-segment display as compared to a few mili watts for a LED). It is due to the fact that it does not itself generate any illumination but depends on external illumination for its visual effect (colour depending on the incident light). They have a life-time of about, 50,000 hours. Visibility of LCD is superior to that of led even in poor ambient light. Low power consumption characteristic of LCD makes it useful for watches and small portable instruments.

12.11 Disadvantages of LCDs

LCD has some disadvantages also, they are given below :

(***a***) This is very slow device compared to LED. The turn ON and OFF times are quite large. The turn ON time it typically of the order a few milliseconds while the turn OFF is 10 milliseconds.

(***b***) Due to chemical degeneration, life of LCD is limited.

(***c***) They occupy a large area.

(***d***) Operating range of temperature form 0 to 60°C only.

12.12 Applications of LCDs

The liquid crystal display is a matured technology these days. So it is being used in practically all areas where sunlight does not directly on the display following are some of the important applications of LCDs:

1. Field-effect LCDs are normally used in watches and portable instruments such as digital thermometers, blood pressure, blood sugar, pressure monitoring instruments etc. where source of energy is a prime consideration.
2. Recent desk top LCD monitors.
3. Notebook computer display.
4. Cellular phone display,
5. To display data on personal digital assistant (PDAs) such as Palm V_x and pocket PCs etc.

The liquid crystal display (LCDs) commonly used on notebook computers and handheld PADs are also appearing on desktop. These flat panel displays promise great clarity at increasingly high resolutions and are available in screen sizes upto 15 inches. The LCD monitor offers benefits and drawbacks. The first benefit is size. Because of the need to house the tube itself, cathode-ray tube (CRT) monitors are big and heavy. LCD monitors are expensive than CRTs at present. Another problem is the viewing angle. The optimal viewing angle of an LCD is from straight in front and as you move further to the side the screen becomes harder to read, much more so than with a CRT. Moreover screen resolutions generally reach only as high as 1,024 × 768, which is insufficient for some applications.

12.13 Segmental Display

A segment display is a form of electronic display device for displaying alphanumeric character decimal numerals that is an alternative to the more complex dot-matrix displays. Seven-segment displays are widely used in digital clocks, electronic meters, and other electronic devices for displaying numerical information. In seven segments display, as its name indicates, is composed of seven elements. There are also fourteen-segment displays and sixteen-segment displays (for full alphanumeric); however, these have mostly been replaced by dot-matrix displays. Segmental displays are

1. Seven Segment Display
2. Nine Segment Display
3. Fourteen Segment Display
4. Sixteen Segment Display
5. Eighteen Segment Display

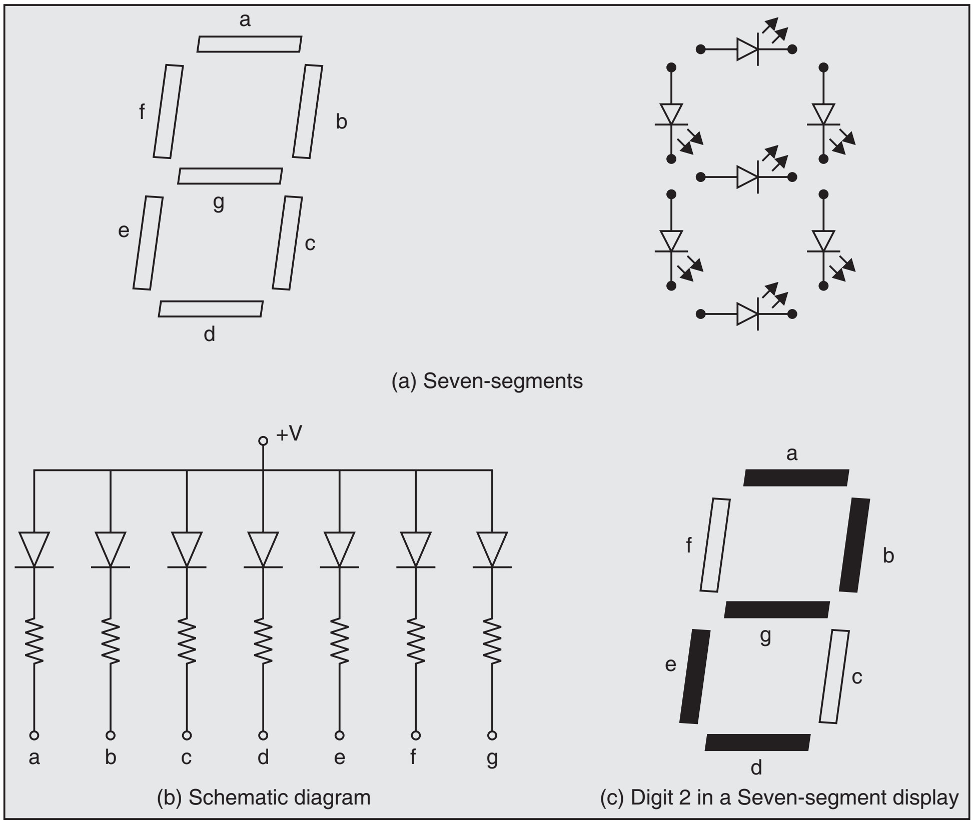
We shall now, discuss each segment display one by one in the following pages.

12.14 Seven-Segment Display

A seven-segment display, or seven-segment indicator, is a form of electronic display device for displaying decimal numerals that is an alternative to the more complex dot-matrix displays. Seven-segment displays are widely used in digital clocks, electronic meters, and other electronic devices for displaying numerical information. A seven segment display, as its name indicates, is composed of seven elements.

The seven segments are arranged as a rectangle of two vertical segments on each side with one horizontal segment on the top, middle, and bottom. Additionally, the seventh segment bisects the rectangle horizontally.

Fig. 12.6 (*a*) shows a seven segment display. It is used to display alphanumeric characters. It consist of 7 rectangular light emitting diodes designated by the letters *a*, *b*, *c*, *d*, *e*, *f* and *g*. Each LED is called a segment, because it forms a part of the character being displayed.



(a) Seven-segments

(b) Schematic diagram

(c) Digit 2 in a Seven-segment display

Fig. 12.6. Seven-segment display.

Fig. 12.6 (*b*) shows a schematic diagram of a seven-segment display. In this circuit, the anodes of all the diodes are connected together to the positive terminal of the dc voltage source. The cathodes are connected to the external resistors. The external resistor is necessary to limit the current through the LED. By grounding the external resistors, we can form any decimal digit from 0 to 9. For example, by grounding *a*, *b*, *g*, *e* and *d*, we can form the digit '2' as shown in Fig. 12.7 (*c*). Similarly, by grounding *f*, *g* and *c*, we can form the digit '4' and so on. The digit 0 can be formed by grounding all the terminals except g. A seven segment display can also display the capital letters, *A*, *C*, *E* and *F*. Besides this, it can also display the lower-case letters *b* and *d*.

Fig. 12.7 shows the seven segment display of clock time 12:26.

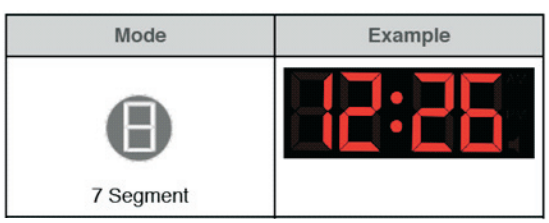


Fig. 12.7.

This table 12.1 gives the hexadecimal encodings for displaying the digits 0 to 9:

Table 12.1

Digit	a	b	c	d	E	F	G
0	**on**	**on**	**on**	**on**	**on**	**on**	off
1	off	**on**	**on**	off	off	off	off
2	**on**	**on**	off	**on**	**on**	off	**on**
3	**on**	**on**	**on**	**on**	off	off	**on**
4	off	**on**	**on**	off	off	**on**	**on**
5	**on**	off	**on**	**on**	off	**on**	**on**
6	**on**	off	**on**	**on**	**on**	**on**	**on**
7	**on**	**on**	**on**	off	off	off	off
8	**on**	**on**	**on**	**on**	**on**	**on**	**on**
9	**on**	**on**	**on**	**on**	off	**on**	**on**

There are two important types of 7-segment LED digital display.

1. The Common Cathode Display (CCD)

In the common cathode display, all the cathode connections of the LED's are joined together to logic "0" and the individual segments are illuminated by application of a "HIGH", logic "1" signal to the individual Anode terminals. Circuit diagram is shown in Fig. 12.8.

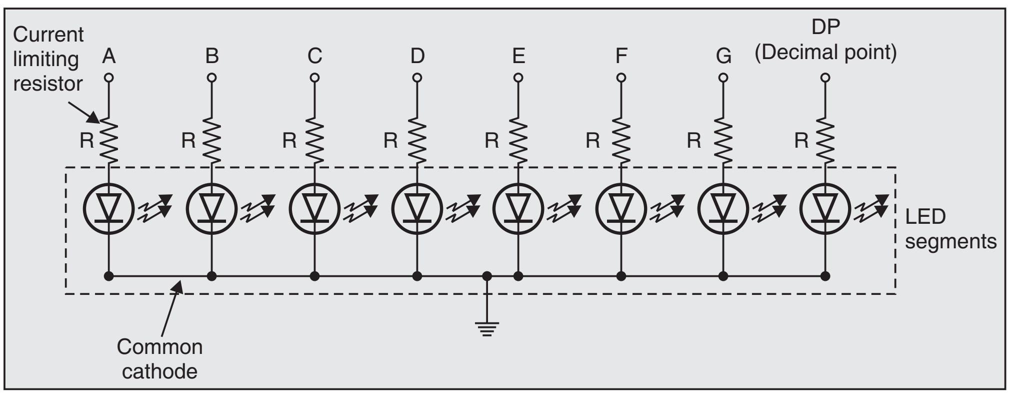


Fig. 12.8.

2. The Common Anode Display (CAD)

In the common anode display, all the anode connections of the LED's are joined together to logic "1" and the individual segments are illuminated by connecting the individual Cathode terminals to a "LOW", logic "0" signal. Circuit diagram is shown in Fig. 12.9.

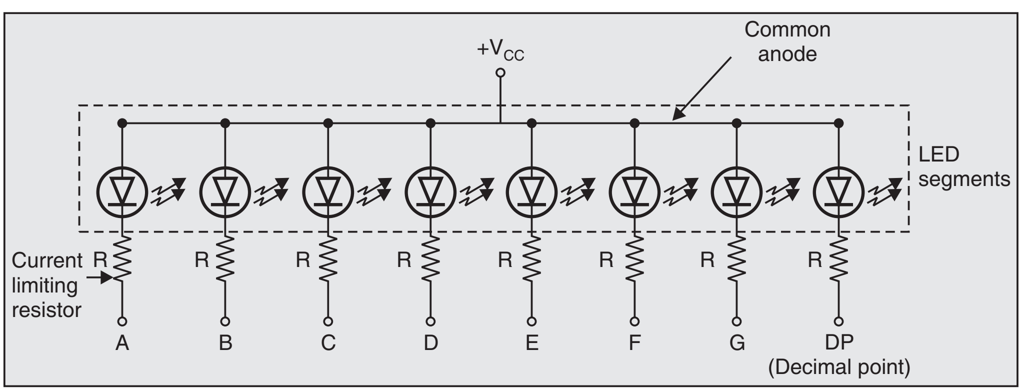


Fig. 12.9.

12.15 Nine-Segment Display

A **nine-segment display** is a type of display based on nine-segments that can be turned on or off according to the graphic pattern to be produced. It is an extension of the more common seven-segment display, having an additional two diagonal or vertical segments between the top, middle, and bottom horizontal segments. This provides a minimal method of displaying alphanumeric characters.

Nine-segment displays were used to provide basic alphanumeric as shown in Fig. 12.10. It used to avoid confusions with representing numbers in electronic products such as calculators, electronic watches etc.

12.16 Fourteen-Segment Display

A **fourteen-segment display** is a type of display based on fourteen- segments that can be turned on or off to produce letters and numerals. A seven-segment display suffices for numerals and certain letters. It is an extension of the more common seven-segment display, having an additional four diagonal and two vertical segments with the middle horizontal segment broken in half as shown in Fig. 12.11.

12.17 Sixteen-Segment Display

The sixteen-segment alphanumeric display system is shown in Fig. 12.12. The **sixteen-segment display** breaks all three horizontal segments in half. It is used to generate additional characters such as those required in a typewriter-style keyboard.

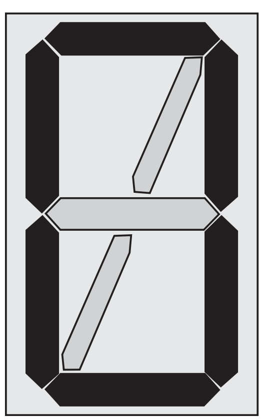


Fig. 12.10. Nine-Segment Display

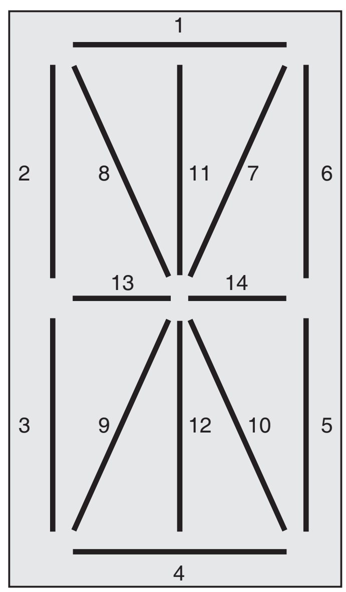


Fig. 12.11.

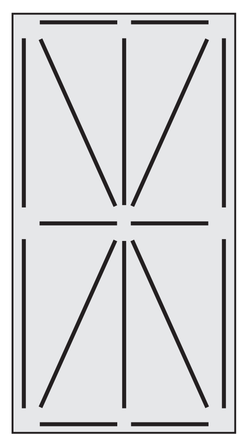


Fig. 12.12.

12.18 Eighteen-Segment Display

Alphanumeric display using eighteen segment display is shown in Fig. 12.13. It use eighteen LEDs in various ways to display the alpha numeric display. In this segment display separate LEDs are used for the decimal point (DP) and colon operator (CO). The various alphanumeric characters are displayed by lighting up the LEDs located in specific positions.

These displays are also used in applications such as machines, clocks, railways departure indicators, reservation charts etc.

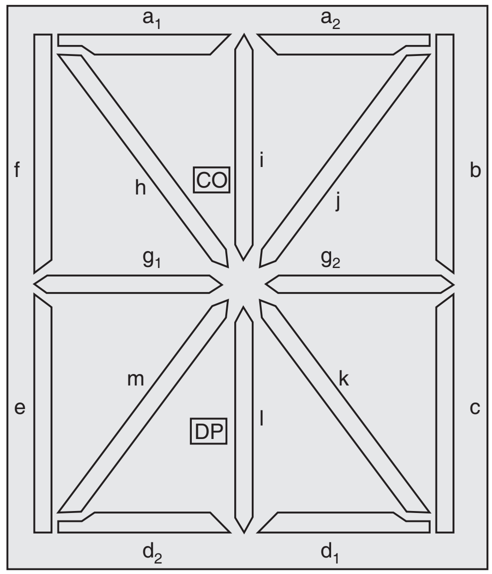


Fig. 12.13.

12.19 Dot Matrix Display

A **dot matrix display** is a display device used to display information on machines, clocks, railway departure indicators and many and other devices requiring a simple display device of limited resolution. The display consists of a matrix of lights or mechanical indicators arranged in a rectangular configuration. The rectangular arrangements are called arrays of LEDs. By switching ON or OFF the selected LEDs, text or Graphics can be displayed. A matrix driver or controller converts the instructions from a processor into signals which turns ON or OFF LEDs in the matrix, so as to obtain the required display.

A dot matrix controller converts instructions from a processor into signals which turns on or off lights in the matrix so that the required display is produced.

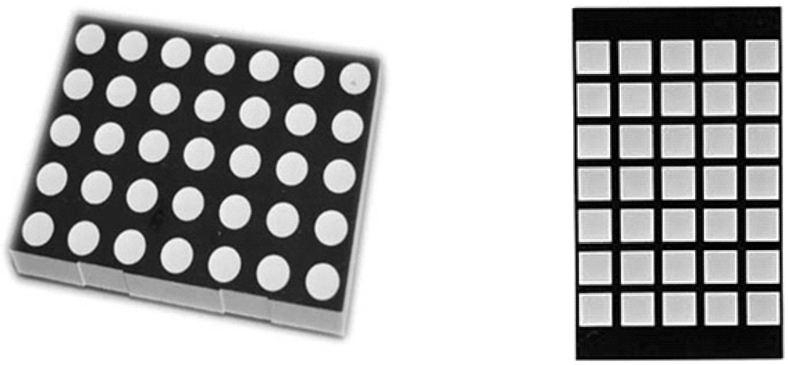
The common sizes of dot matrix displays are 128 × 16 (Two lined), 128 × 32 (Four Lined) and 192 × 64 (Eight Lined). While a common size for a character is 5 × 7 pixels. This is seen on most of the graphic calculators.

The dot matrix displays are used in Varity of applications such as rolling advertisement boards, railway timing, reservation charts, temperature indication outside observatory digital clocks, calculators, digital diaries, microwave oven etc. The display of alphabetic character is shown in Fig. 12.14.

Fig. 12.14.

12.20 5 × 7 Dot Matrix Display

In a 5 × 7 dot matrix display, 5 columns and 7 rows of LEDs. The dot matrix may be in round or square shape shown in Fig. 12.15.



Round Shape Dot Matrix Display   Square Shape Dot Matrix Display

Fig. 12.15.

Circuit connection of 5 × 7 dot matrix display using LEDs is shown in Fig. 12.16.

Depending upon the required character, the corresponding LEDs switched ON, in this display. Fig. 12.17 shows the display of characters "Y".

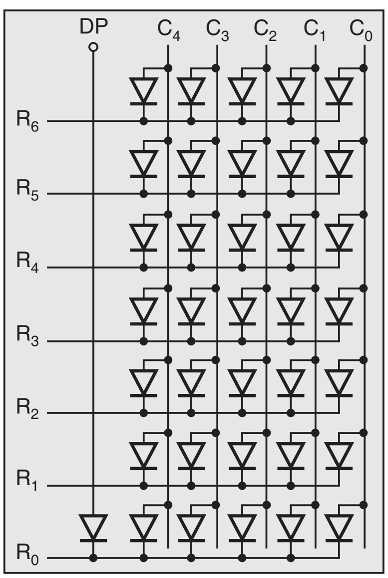


Fig. 12.16.

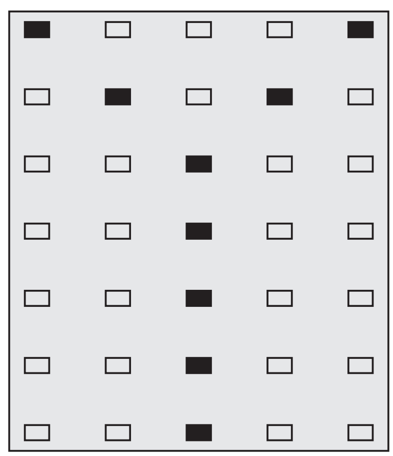


Fig. 12.17.

12.21 3 × 5 Dot Matrix Display

A 3 × 5 dot matrix is shown in Fig. 12.18. It mainly used for displaying the numeric characters.

12.22 Different Types of Dot Matrix and Their Display

Different types of dot-matrix with their display are shown in Fig. 12.19.

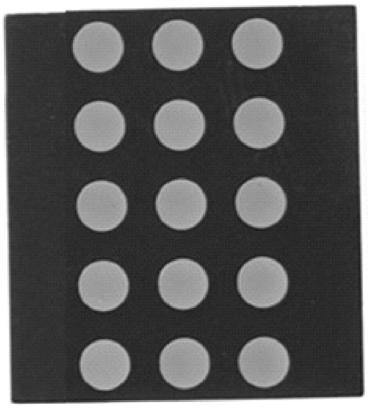


Fig. 12.18.

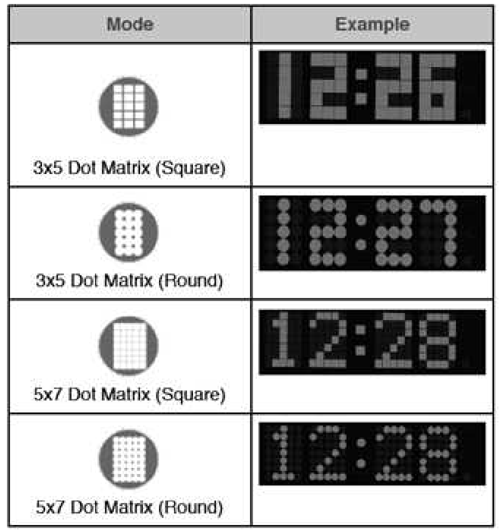


Fig. 12.19.

12.23 Nixie Tube or Cold Cathode Displays

These are also called as neon or gas-discharge displays. A **nixie tube** is an electronic device for displaying numerals or other information. The glass tube contains a wire-mesh anode and multiple cathodes. In most tubes, the cathodes are shaped like numerals.

The basic construction of a digital indicator tube is shown in Fig. 12.20. It is a cold cathode glow discharge tube, which is popularly known as Nixie which is the trade mark of M/s Burrough's corporation U.S.A. The display works on the principle that when a gas breaks down, a glow discharge is produced. A gauze electrode with a positive voltage supply functions as an anode and there are 10 separate wire cathodes, each in the shape of *s* numeral form 0 to 9. Applying power to one cathode surrounds it with an orange glow discharge. The tube is filled with a gas at low pressure, usually mostly neon and often a little mercury and/or argon, in a Penning mixture. At the base of the tube is a set of contacts, one each for the anode and the many cathodes.

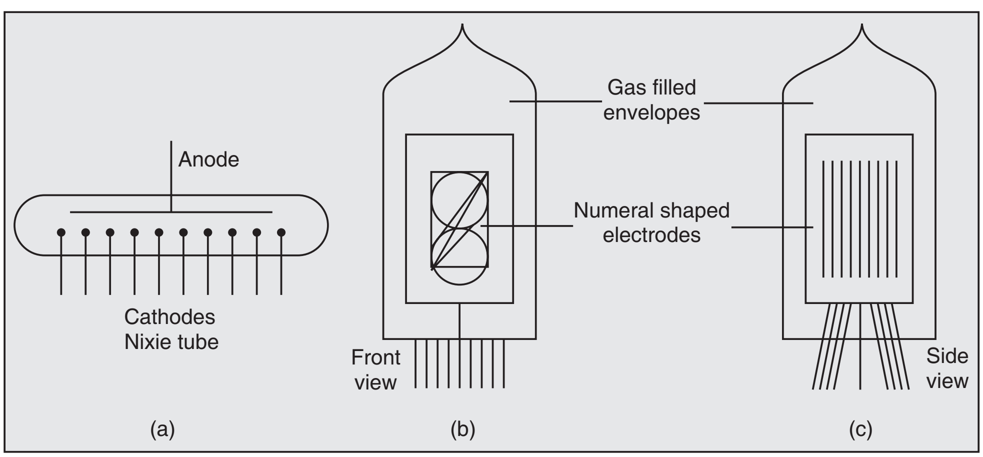


Fig. 12.20.

To create the gas plasma around the cathode, there needs to be a potential difference of greater than 150-220 volts between the cathode and anode. This is called the striking voltage. The current is required in the order of 1-5 mV. When one current begins to flow, the potential difference required to maintain the plasma falls between twenty and thirty volts. The Nixie tube is called a cold-cathode tube because it doesn't require a heated cathode, unlike regular valves which get very hot and use a lot of power. It has the same distinctive flickering orange glow as a neon tube.

The Nixie tube is shown in Fig. 12.21. The internal construction of the Nixie tube is shown is Fig. 12.22. The set of numbers is beautiful. Notice that there are two identical 8's, and that the "one" is made of two lines. This helped to keep it as bright as the other numbers in spite of being so much smaller.

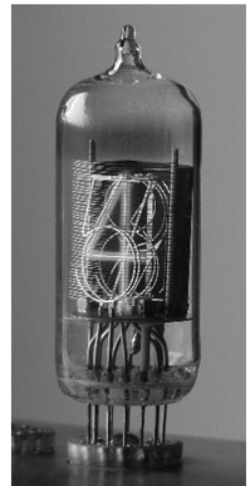
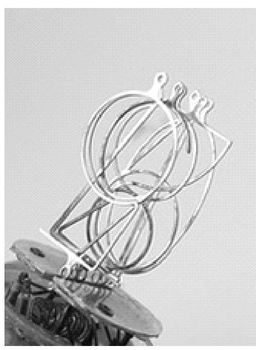


Fig. 12.21.

Nixie Driver Circuit

Fig. 12.23 shows the nixie driver circuit. Each cathode represents one number to glow a particular number. We have to apply signal to only corresponding cathode circuitry. The driving circuit for nixie tube is simpler than for seven-segment displays. However, for nixie tube high voltages around 150-220 V are required to produce glow discharge.



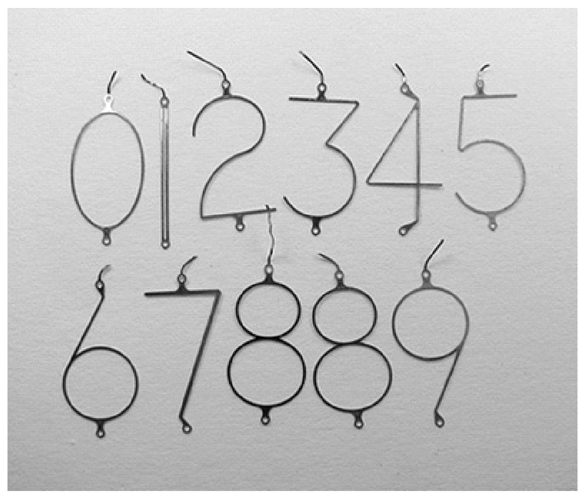


Fig. 12.22.

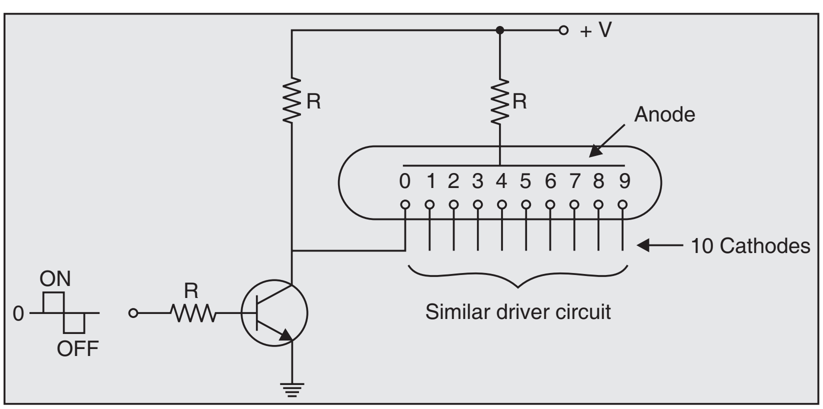


Fig. 12.23.

12.24 Use of Nixie Tube Display

The main use of Nixie tubes was to display numbers in meters and counters. They were also used in the elevators, calculators, signs, and many other devices. Their fragility, high power usage, and high voltage compared to light emitting diodes are the main reasons for the demise of the Nixie tube.

12.25 Advantages of Nixie Tube Display

Thought the nixie tube display has a number of advantages, yet some of them are given below :

1. The characters are well-shaped.
2. The characters are bright and can be large.
3. Driver circuit is simple.

12.26 Disadvantages of Nixie Tube Display

Nixie tube display has some disadvantages also, they are given below :

1. The characters do not lie in the same plane.
2. The number of characters in one tube is limited about 12.
3. It is bulky
4. Requires high existing voltages
5. They are not properly visible in bright ambient light. But visibility is better than LED displays.

12.27 Comparison between LED, LCD and Nixie Tube

Table 12.1 shows the important point of comparison between LED, LCD and Nixie tube displays in various aspects are:

Table 12.1 Comparison between LED, LCD and Nixie tube display

	LED Display	*LCD Display*	*Nixie Tube*
Advantages	• Bright display • Available in different colors like green, red, yellow etc. • Small size • Compatible with ICs	• Good contrast • Low power • Low cost • Compatible with ICs	• Bright display • More color range then LEDs • Low cost • Compatible with ICs
Disadvantages	• High cost per element • Limited reliability • Very low switching speed	• Low reliability • Low switching speed • Limited temperature range	• Required of high drive power
Application	• As indicators • Small displays • Use as dot matrix	• As indicators • Small displays • Use in calculators, digital watches etc	• As indicators • Small group viewing • For small medium and large displays.

12.28 Incandescent Displays

Incandescence has been a basic process of production light for several decades. Incandescent displays can be made in a wide range of sizes and colours. The main drawback of incandescent displays is the poor reliability due to failure of segments. However new methods and materials have improved the reliability of such displays. Many newer incandescent displays have seven segment filaments contained within a single vacuum envelope and are compatible with standard TTL voltages. Such displays are characterized by bright output, simple technology and compatibility with ICs, but at very low operating speeds. Multiplexing is not very advantages for such displays. It is because each display segment usually needs a diode to avoid leakage paths.

12.29 Fluorescent Displays

These devices are properly called “VFDs” or Vacuum Fluorescent Displays. A vacuum fluorescent display (VFD) is a display device used commonly on consumer-electronics equipment such as video cassette recorders, car radios, and microwave ovens. Invented in Japan in 1967, the displays became common on calculators and other consumer electronics devices. Unlike liquid crystal displays, a VFD emits a very bright light with high contrast and can support display elements of various colours. VFDs can display seven-segment numerals, multi-segment alpha-numeric characters or can be made in a dot-matrix to display different alphanumeric characters and symbols.

Fluorescent displays are ideal for multiplexing due to their low current (about 1 mA) and voltage (about 30 V) requirements. Their typical colour is blue green with the character heights upto 15 mm. These displays are mainly employed in calculators.

12.30 Liquid Vapour Based Displays

Liquid vapour based display system is the latest addition of the digital display technology. The arrangement is consisting of a transparent and volatile liquid filed in between two parallel glass plates. The front and the rear glass are sealed with the help of suitable spacers. Internal surface of the front glass is made rough whereas the outer surface of the rear glass is painted black to provide dark background. The reflective index of glad as well as that of the liquid is contact are same. A thin transparent electrode dipped inside the liquid is heated by supply voltage as shown in Fig. 12.24.

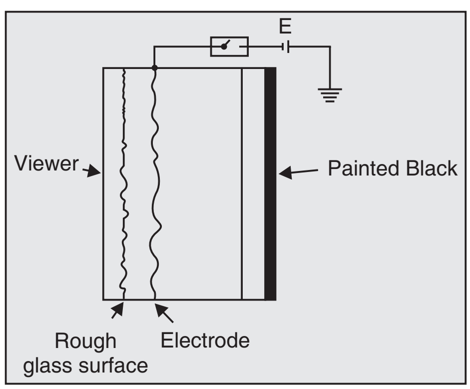


Fig. 12.24.

When there is no voltage applied to the electrode the rear glass with dark background is seen black through the front glass and the liquid combined. When the voltage is applied to the electrode, heating of electrode takes place resulting in starting of evaporation of the liquid that is in contact with the electrode. The evaporation presents thin vapour film as well as its bubble around the rough surface of the glass. Since the refractive index of the vapour is different, a discontinuity is seen near the interface of the glass plate and the liquid resulting in scattering of light. This action is utilized for making display device. The display system made on this principle is superior of LCD based display device.

12.31 Segmented Gas Discharge Displays

Segmented gas discharge displays work on the principle of gas discharge glow, similar to the case of Nixie tubes. They are mostly available in seven-segment or fourteen-segment form, to display numeric and alphanumeric character.

Since these devices require high voltages, special ICs are developed to drive them. The construction of a seven-segment display is shown in Fig. 12.25. Each segment of the seven-segment display formed on a base has a separate cathode. The anode is common to each member of the seven-segment group which is deposited on the covering face plate. The space between the anodes and cathodes contains the gas. For each group of segments, a 'keep alive' cathode is also provided. For improving the switching speeds of the display a small constant current is passes through this keep alive cathode, which acts as a source of ions. Pins are connected to the electrode at the rear of the base plate, with the help of which external connections can be made.

This display follows a simple construction. Fig. 12.25 shows the structure of a typical seven-segment display making use of gas discharge plasma.

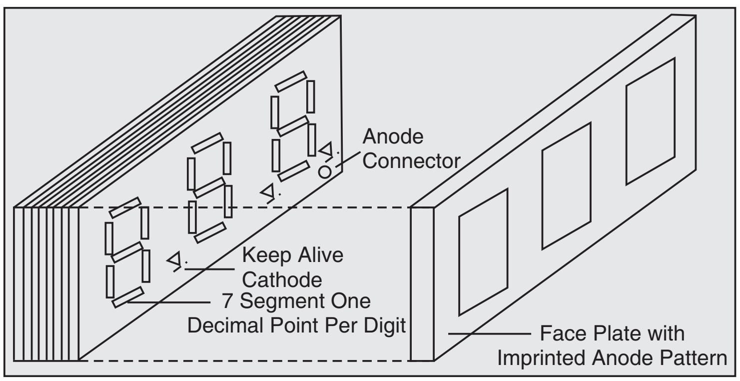


Fig. 12.25. Seven-segment display using gaseous discharge

Fig. 12.26 shows the device with a glass substrate. Back electrodes of the thick film type serve as cathode segments and front electrodes of the thin film type serve as transparent anodes. Neon gas is filled in the discharge space between the cathode and anode segment. The gas is struck between the cathode and anode of a chosen segment so that the cathode glow provides the illumination. All numeric characters can be displayed by activating the appropriate segment. The power requirements of such device are more or less in the same range as those for Nixie tubes.

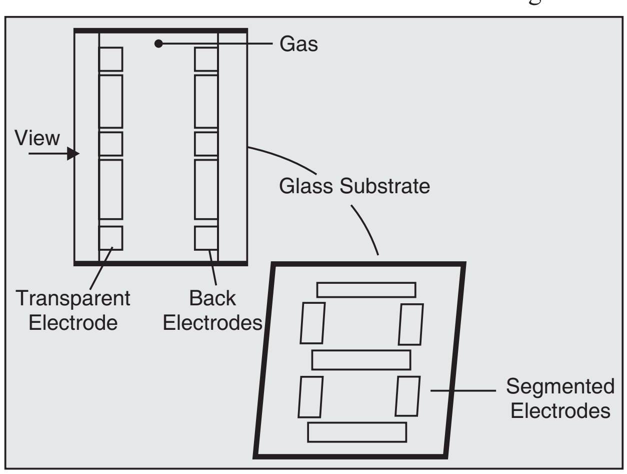


Fig. 12.26. Seven-segment gas filled character

The major disadvantage of this gas discharge tube is that high voltage is required for operating it. Therefore, high voltage transistor, in the range of 150-200 V is required as switches for the cathodes. A major advantage is that the power consumed is extremely small, because a bright display can be obtained even for currents as low as 200 μA.

12.32 Electrophoretic Image Display (EPID)

Electrophoresis is the movement of charged pigment particles suspended in a liquid under the influence of an electric field. Fig. 12.27 shows the electrophoretic displays.

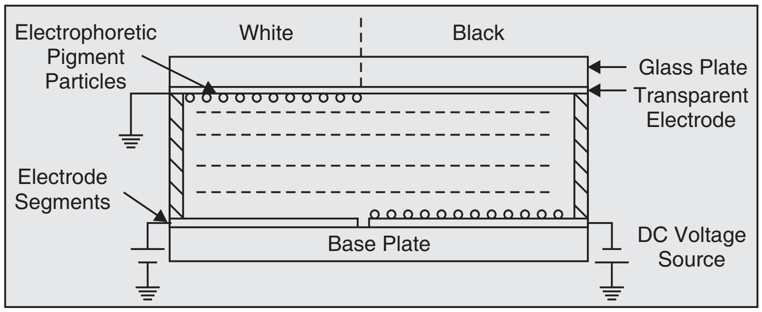


Fig. 12.27.

EPID displays the characterized by large character sixe, low power dissipation and internal memory. The relatively slow speed of these displays is a major limitation particularly for use as a dynamic display. The life span of an EPID is a few thousand hours only.

In EPID a dc electric field is applied across the electrodes. This field moves the particles, the movement depending mainly on the polarity of the charge on the particles. The reflective colour of the suspension layer changes on account of this migration. EDIP panels generally follow a segment character format typically seven segment for numeric characters.

It is usual to have the transparent electrode as a common electrode. The back electrodes are generally segmented. Two such segments are shown in Fig. 12.27. During the normal operation of the display, the transparent electrode is maintained at ground potential and the segmented electrodes at the back are giver different potentials.

It the pigment particles are white and positively charged in the black suspending liquid, the application of a positive voltage to the chosen segment moves the pigment particles away from it and towards the transparent electrode. This is shown on the left side of Fig. Pigment particles appear white in reflective colour as viewed through the transparent electrodes.

In the other hand, when a segment has a negative voltage with reference to the transparent electrode, the white pigment particles go towards it then get immersed in the black suspension. In this case, the viewer sees the reflection from the black liquid itself.

Colour combinations of both the pigment particles and the suspending liquid can be used to achieve a desired colour display. The colour between the displayed pattern and its background can be reversed by changing the polarities of segment voltages. The EPID panel has a memory, because the pigment particles deposited on an electrode surface remain there after the applied voltage is removed.

12.33 Digital Meter Displays

Digital meter displays are used in digital instrument to display the reading. For displaying the reading on the digital meter LED (Light emitting Diode), LCD (Liquid Crystal Display) or Nixie tube is used. Mostly LED and LCD displays are used.

In LED readout, when biased in the forward directions, a PN junction diode emits light as a result of recombination of excess electron hole pairs. The LCD display is most popular for a battery powered meters because they require much less operating current than the LED types.

Both the LED and LCD displays are in segment format. Each word or digit in the display has separate segments or sections. Each segment is independently controlled. Digits are formed by lighting the appropriate segments. In addition to the seven segments, there is also a decimal point as shown in Fig. 12.28. Digital decoders and drivers are used to interface digital output from A/D converter to the display.

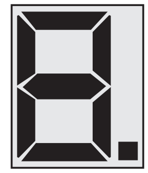


Fig. 12.28.

12.34 Specifications of Digital Meters Display

A **specification** is an explicit set of requirements to be satisfied by a product. The specifications of digital meter are:

12.35 Display Digits and Counts

The resolution of digital meters depends on the number of digits used in the display. The three digit display for 0-1 V range can indicates the values from 0-999 mV with the smallest increment of 1 mV.

One more digit which can be display only 0 or 1 is added. The digit is called half digit and display is called $3\frac{1}{2}$ digit display. This is shown in Fig. 12.29.

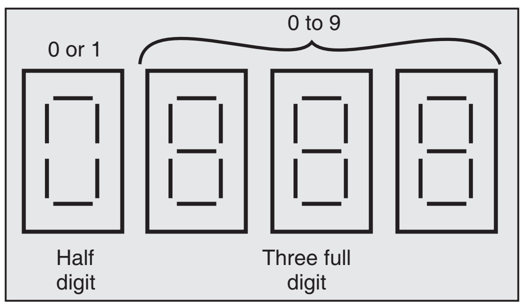


Fig. 12.29.

In digital meter display $3\frac{1}{2}$ digit. This means that there are three complete digits, each capable of displaying the numbers zero to nine, and one additional preceding digit which may display only a zero or a one. Therefore it will display full-scale reading of 1999. It read digital values from 0 to 1999. Thus it count is 2000.

In case of $4\frac{1}{2}$ digit display, there are 4 full digits and 1 half digit. The number obtained is from 0 to 19999.

The latest digital meter shows the full scale range from 399 to 39999 or more. These are dubbed as $4\frac{3}{4}$ and $4\frac{3}{4}$ digits respectively. The digit and count is shown in Table 12.2.

Table 12.2

Digits	**Count**
$3\frac{1}{2}$	2000
$4\frac{1}{2}$	20000
$3\frac{3}{4}$	4000
$4\frac{3}{4}$	40000

$6\frac{1}{2}$ *Digit Display*

To increase the resolution and accuracy of measurement, now a days $6\frac{1}{2}$ digit displays are available. It has six full digits which can display any digit from 0 to 9. Is has one more digit which can display only 0 or 1. This is called half digit. The display is shown in Fig. 12.30.

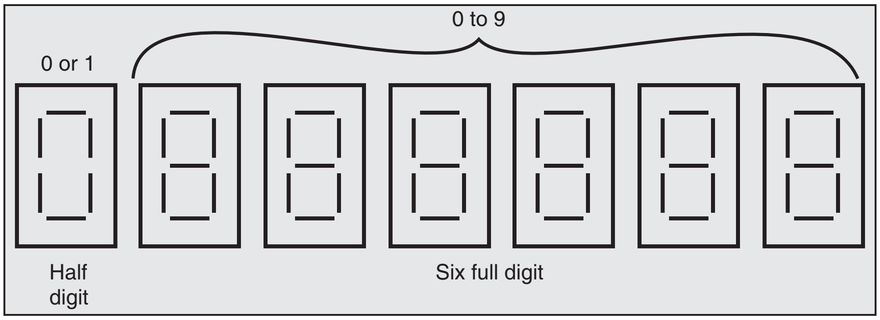


Fig. 12.30. $6\frac{1}{2}$ Digit Display

12.36 Resolution of Digital Meter

It is define as the number of digit positions or simply the number of digits used in a meter. Hence a four digit display on the digital meter for 0-1 V range will be able to indicate from 0000 to 9999 mV,

The measure of the smallest increment in the value that is clearly distinguished is called resolution. The resolution is denoted by R,

$$R = \frac{1}{10^n}$$

Where n = Number of full digits,

Thus for 4 digit display, $n = 4$ so the resolution is given by,

$$R = \frac{1}{10^n} = \frac{1}{10000} = 1/10000 = 0.0001 = 0.01\ \%$$

A display with 4-digit cannot distinguish between the values that differ from each other by less than 0.0001 of full scale.

12.37 Sensitivity of Digital Meter

This is the smallest change of the measured signal that can be detected. Thus it is the full scale value of the lowest voltage range multiplied by the resolution of the meter. Sensitivity is given by,

$$S = (f_S)_{\min} \times R$$

Where $(f_S)_{\min}$ is the lowest full-scale of digital meter, and R is the resolution in decimal.

12.38 Accuracy of Digital Meter

Accuracy is the largest allowable error that will occur under specific operating conditions. It indicates of how close the digital meter displayed measurements is to the actual value of the signal being measured. In general, the accuracy is expressed a percent of the reading or percentage of a true value. For example the accuracy can be expressed as ± 1 % of the true value. So if the true value displayed is 50 V, then for accuracy of ± 1 % , the actual reading may be either 49 V or 51 V.

For example, a $4\frac{1}{2}$ digit digital display having an accuracy specification of ± 0.05 % of reading ± 0.01 %

Range may indicate anywhere from 2.018 to 2.022 V in the 10 V range for a standard input of 2.020 V.

12.39 Uncertainty of Digital Meter

In the manufacturer's specification sheet under accuracy is more properly deemed uncertainty with accuracy being reserved to indicate the probability of the reading being accurate. A specification of 1% uncertainty would have an accuracy of 99%.

12.40 Repeatability or Precision of Digital Meter

Repeatability is often more important than absolute accuracy when making a series of measurements. We want the digital display to read same value each time whenever a measurement of same quantity is made again and again. A better repeatability can be realized by making large number of measurements of a precision source under conditions.

The precision can be expressed mathematically as,

$$P = 1 - \left| \frac{X_n - \overline{X_n}}{\overline{X_n}} \right|$$

Where X_n = value of nth measurement

$\overline{X_n}$ = Average of set of n measured values

12.41 Speed and Settling Time of Digital Meter

Every meter has a settling time associated with its input circuit. The reading rates or measurement speeds of instruments are independent of the settling times. For high resolution meters, it may be necessary to allow time for input settling so as achieve full- rated accuracy.

Example 12.1. *What is the resolution of a $3\frac{1}{2}$ digits display? Find the resolution of the meter in case its range is 1 V and for 10 V range.*

Solution. Given: Digital display = $3\frac{1}{2}$, $n = 3$

Number of full digit in case of $3\frac{1}{2}$ digits display = 3.

We know that the resolution,

$$R = \frac{1}{10^n}$$

$$= \frac{1}{10^3} = 0.001 \text{ Ans.}$$

The meter cannot distinguish between values that differ from each other by less than 0.001 to full scale.

When the full scale range is 1 V then,

Resolution on 1 V range = 1 × 0.001

= 0.001 V **Ans.**

When the full scale range is 10 V then,

Resolution on 10 V range = 10 × 0.001

= 0.01 V **Ans.**

Example 12.2. *A $4\frac{1}{2}$ digital voltmeter is used for voltage measurements. (a) Find its resolution. (b) How would 12.98 V be displayed on 10 V range? (c) How would 0.6973 be displayed on 1 V range? (d) How would 0.6973 be displayed on 10 V range?*

Solution. Given: Digital display = $4\frac{1}{2}$, $n = 4$

(*a*) ***Resolution***

We know that the resolution,

$$R = \frac{1}{10^n} = \frac{1}{10^4} = 0.0001 \textbf{ Ans.}$$

(*b*) ***When the full scale range is 10 V then display of 12.89,***

We know that,

Resolution on 10 V range = 10 × 0.0001 = 0.001 V

For 10 V range the reading can be displayed to 3^{th} decimal place. Hence 12.89 V will be displayed as 12.890 on 10 V range.

(*c*) ***When the full scale range is 1 V then display of 0.6973,***

We know that,

Resolution on 1 V range = 1 × 0.0001 = 0.0001 V

For 1 V range the reading can be displayed to 4^{th} decimal place. Hence 0.6973 V will be displayed as 0.6973 on 1 V range.

(*d*) ***When the full scale range is 10 V then display of 0.6973,***

We know that,

Resolution on 1 V range = 10 × 0.001 = 0.001 V

For 1 V range the reading can be displayed to 3^{th} decimal place. Hence 0.6973 V will be displayed as 0.697 on 10 V range. The digit 3 in the 4^{th} place will be lost.

Example 12.3. *A* $4\frac{1}{2}$ *digital voltmeter is used to measure voltage. Find*

(*a*) *Resolution*

(*b*) *How would 16.58 be displayed on a 10 V range?*

(*c*) *How would 0.7254 be displayed on 1 V and 10 V range?*

(GBTU/MTU, 2006-07)

Solution. Given: Digital display = $4\frac{1}{2}$, $n = 4$

Number of full digit in case of $4\frac{1}{2}$ digits display = 4.

(*a*) ***We know that the resolution,***

$$R = \frac{1}{10^n}$$

$$= \frac{1}{10^4} = 0.0001 \textbf{ Ans.}$$

(*b*) ***When the full scale range is 10 V then display of 16.58,***

Resolution on 10 V range = 10 × 0.0001 = 0.001 V

For 10 V range the reading can be displayed to 3^{th} decimal place. Hence 16.58 V will be displayed as 16.580 V on 10 V range.

(*c*) ***When the full scale range is 1 V 10 V then display of 0.7254,***

Resolution on 1 V range = 1 × 0.0001 = 0.0001 V

For 1 V range the reading can be displayed to 4^{th} decimal place. Hence 0.7254 V will be displayed as 0.7254 V on 1 V range.

Resolution on 10 V range = 10 × 0.0001 = 0.001 V

For 10 V range the reading can be displayed to 3^{th} decimal place. Hence 0.7254 V will be displayed as 0.725 V on 10 V range.

12.42. Plasma Display

A plasma display is a computer video display in which each pixel on the screen is illuminated by a tiny bit of plasma or charged gas, somewhat like a tiny neon light. Plasma displays are thinner than cathode ray tube (CRT) displays and brighter than liquid crystal (LCD). Plasma displays are sometimes marketed as "thin-panel" displays and can be used to display either analog video signals or display modes digital computer input.

The plasma is a state of matter similar to gas in which a certain portion of the particles are ionized. Heating a gas may ionize its molecules or atoms (reduce or increase the number of electrons in them), thus turning it into a plasma, which contains charged particles, positive ions and negative electrons or ions. Ionization can be induced by other means, such as strong electromagnetic field applied with a laser or microwave generator etc.

Also called "gas discharge display," a flat-screen technology that uses tiny cells lined with phosphor that are full of inert ionized gas (typically a mix of xenon and neon). Three cells make up one pixel as shown in Fig. 12.31. One cell has red phosphor, one green, one blue. The cells are sandwiched between x- and y-axis panels, and a cell is selected by charging the appropriate x and y electrodes. The charge causes the gas in the cell to emit ultraviolet light, which causes the phosphor to emit color. The amount of charge determines the intensity, and the combination of the different intensities of red, green and blue produce all the colors required.

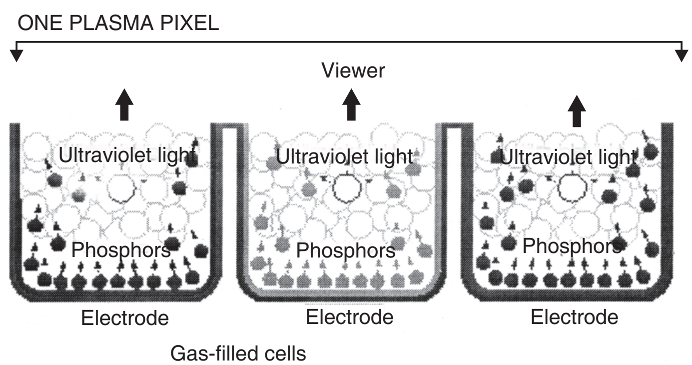


Fig. 12.31.

The plasma panel is composed of two sheets of glass with a series of ribs (like corrugated cardboard) filled with color phosphors in between. The top glass with embedded electrodes seals and forms a pixel where the junctions of the channels and the plate come together. Inside the sealed pixel, is a mixture of rare gases- typically argon and neon, although xenon has also been used. Actually a small electric capacitor has been created, with one electrode on the rear and a pair on the front. These three electrodes control the capacitor charge, sustain and discharge functions intrinsic to the plasma imaging process. The basic idea of a plasma display is to illuminate tiny, colored fluorescent lights to form an image. Each pixel is made up of three fluorescent lights—a red light, a green light and a blue light.

The xenon and neon gas in a plasma television is contained in hundreds of thousands of tiny cells positioned between two plates of glass. Long electrodes are also sandwiched between the glass plates, on both sides of the cells. The address electrodes sit behind the cells, along the rear glass plate. The transparent display electrodes, which are surrounded by an insulating dielectric material and covered by a magnesium oxide protective layer, are mounted above the cell, along the front glass plate.

SUMMARY

1. A display device is an output device for the presentation of information in visual form.
2. Digital displays are used in digital instrument to display the reading.
3. Accuracy is the largest allowable error that will occur under specific operating conditions.
4. The resolution of digital meters depends on the number of digits used in the display.
5. LEDs are diodes that will provide a limited amount of light when properly biased.
6. Multicolor LEDs contain two PN junctions that are connected is parallel.
7. Seven-segment displays are widely used in digital clocks, electronic meters, and other electronic devices for displaying numerical information.
8. A dot matrix display is a display device used to display information on machines, clocks, railway departure indicators etc.

GLOSSARY

Accuracy of Digital Meter: It indicates of how close the digital meter displayed measurements is to the actual value of the signal being measured.

Dot Matrix Display: The display consists of a matrix of lights or mechanical indicators arranged in a rectangular conFiguration. The rectangular arrangements are called arrays of LEDs.

Light Emitting Diode (LED): A PN junction diode, which emits light when forward biased

Nixie Tube or Cold Cathode Display: A nixie tube is an electronic device for displaying numerals or other information. It is a glass tube contains a wire-mesh anode and multiple cathodes.

Resolution of digital meter: It is the number of digit positions or simply the number of digits used in a meter

Segmental Display: A segment display is a form of electronic display device for displaying decimal numerals that is an alternative to the more complex dot-matrix displays.

Sensitivity of Digital Meter: This is the smallest change of the measured signal that can be detected.

NUMERICAL PROBLEMS

1. A $3\frac{1}{2}$ digit voltmeter is used for measurement voltage
   (*a*) Find the resolution of the instrument
   (*b*) How would a voltage of 14.53 be displayed on 10V scale?
   (*c*) How would a reading 14.53 be displayed on 100V scale?

   (**Ans.** (*a*) 0.001, (*b*) 14.53, (*c*) 014.5)

2. What is the resolution of a $4\frac{1}{2}$ digit display? How would 15.84 V be displayed on a 10 V range and 0.5243 V on 1 V and 10 V ranges?

   (**Ans.** 0.0001, 0.5243, 0.524)

DESCRIPTIVE QUESTIONS

1. What are the digital display methods? Discuss the types of display methods.
2. Describe the specification of digital meter display.
3. Explain the following terms as applied to digital displays
   (*a*) Resolution
   (*b*) Difference between $3\frac{1}{2}$ digits and 4 digits displays.
   (*c*) Sensitivity of digital meters
   (*d*) Accuracy specification

   (GBTU/MTU, 2008-09)

4. Explain the theory and working of an LED. Describe the advantage of LCDs.

(GBTU/MTU,2008-09)

5. Discuss the use of LED and LCD as display device.
6. Compare the various display devices.
7. What are the relative advantages of LCD display device over LED display device? Explain the working of seven segment LCD display.

(GBTU/MTU, 2003-04)

8. Explain the theory of LCD displays. Compare LCD displays with LED displays.

(GBTU/MTU, 2006-07)

9. Explain segmental display and dot matrices for numeric and alphanumeric displays. Draw the circuits for a seven segment display and a 5 × 7 matrix using LEDs.
10. Describe the dot matrix in display device. Discuss the types of dot matrix.
11. Write the short notes on
    - (c) Dot Matrix
    - (d) Nixie Tube
    - (e) Visual Display Unit
12. Define resolution and sensitivity of digital meter.

(GBTU/MTU, 2006-07)

13. Describe the principle of nixie tubes.

(PTU, May 2007)

14. Explain the construction and working of Nixie-tube.

(PTU, Dec 2006)

15. What do you mean by nixie tube?

(PTU, May 2006)

16. How are LCD displays advantages over LED displays?

(PTU, May 2009)

MULTIPLE CHOICE QUESTIONS

1. Resolution of 4-digital display is

   (*a*) $\frac{1}{4}$ (*b*) 1/1000 (*c*) 1/10,000 (*d*) 1 %

2. In a $3\frac{1}{2}$ digit 0-10 V digital meter, the most significant digit is

   (*a*) $\frac{1}{2}$ (*b*) 0 or 1 (*c*) 0 or 10 (*d*) 3

3. The resolution of the digital meter with 3 digit display is

   (*a*) 1/10000 (*b*) 1/1000 (*c*) 1/4 (*d*) 1/3

4. In its ohm range, a $3\frac{1}{2}$ digit digital multimeter can read maximum upto

   (*a*) 999 ohm (*b*) 1000 ohm (*c*) 1999 ohm (*d*) 9999 ohm

5. LED are fabricated from

   (*a*) Silicon (*b*) Germanium (*c*) Si or Ge (*d*) Gallium arsenide

6. The switching time of LEDs is of the order of

   (*a*) 1 s (*b*) 1 ms (*c*) 1 µs (*d*) 1 ns

7. LEDs emit light

   (*a*) Only in red colour (*b*) Only in yellow colour
   (*c*) Only in green colour (*d*) In red, green, yellow and amber colour

8. An LCD requires a power of

(*a*) 20 W (*b*) 20 mW (*c*) 20 μW (*d*) 20 nW

9. The turn ON and turn OFF times of a LCD are of the order of

(*a*) 1 s (*b*) 1 ms (*c*) 10 ms (*d*) 10 ns

10. A nixie tube requires

(*a*) 150 V-220 V (*b*) 100 V-150 V

(*c*) 150 mV-220 mV (*d*) 100 mV-150 mV

ANSWERS

1. (*c*) **2.** (*b*) **3.** (*b*) **4.** (*c*) **5.** (*d*) **6.** (*d*)
7. (*d*) **8.** (*c*) **9.** (*c*) **10.** (*a*)

Chapter 13

Signal Conditioning

Outline

Objectives

After completing this chapter, you should be able to:

- Know the purpose of signal conditioning.
- Explain the DC and AC signal conditioning.
- Describe the instrumentation amplifiers.
- Understand A/D and D/A conversion.
- Know about signal transmission.
- Explain the 4-20 mA current loop circuit.

13.1 Introduction

We have already discussed in the last article that the electrical generated by the transducer needs conditioning before it can be measured. The signal may require amplification, filtering linearization etc. The purpose every process in detail as explained below.

Amplification

It increases voltage level to better match the analog-to-digital converter (ADC) range, thus increasing the measurement resolution and sensitivity. In addition, using external signal conditioners located closer to the signal source, or transducer, improves the measurement signal-to-noise ratio by magnifying the voltage level before it is affected by environmental noise.

Attenuation

It is the opposite of amplification, is necessary when voltages to be digitized are beyond the ADC range. This form of signal conditioning decreases the input signal amplitude so that the conditioned signal is within ADC range. Attenuation is typically necessary when measuring voltages that are more than 10 V.

Isolation

It is a device that pass the signal from its source to the measurement device without a physical connection by using transformer, optical, or capacitive coupling techniques.

Filtering

Its reject unwanted noise within a certain frequency range. They are used to block out high-frequency noise in electrical measurements, such as 60 Hz power.

Excitation

It is required for many types of transducers. For example, strain gauges, accelerometers thermistors, and resistance temperature detectors (RTDs) require external voltage or current excitation. RTD and thermistor measurements are usually made with a current source that converts the variation in resistance to a measurable voltage.

Linearization

It is necessary when sensors produce voltage signals that are not linearly related to the physical measurement. Linearization is the process of interpreting the signal from the sensor and can be done either with signal conditioning or through software. Thermocouples are the classic example of a sensor that requires linearization.

Table 13.1

	Amplification	*Attenuation*	*Isolation*	*Filtering*	*Excitation*	*Linearization*	*CJC*	*Bridge Completion*
Thermocouple	✓		✓	✓		✓	✓	
Thermistor	✓		✓	✓	✓	✓		
RTD	✓		✓	✓	✓	✓		
Strain Gage	✓		✓	✓	✓	✓		✓
Load, Pressure, Torque (mV/V)	✓		✓	✓	✓	✓		
Load, Pressure, Torque (±5 V, ±10 V, 4-20 mA)	✓		✓	✓	✓	✓		
Accelerometer	✓		✓	✓	✓	✓		
Microphone	✓			✓	✓	✓		
Proximity								
Probe	✓			✓	✓	✓		
LVDT/RVDT	✓		✓	✓	✓	✓		
High Voltage		✓	✓					

Cold-Junction Compensation

It is a technology required for accurate thermocouple measurements. Thermocouples measure temperature as the difference in voltage between two dissimilar metals. Based on this concept, another voltage is generated at the connection between the thermocouple and terminal of your data acquisition device. CJC improves your measurement accuracy by providing the temperature at this junction and applying the appropriate correction.

Bridge Completion

It is required for quarter- and half-bridge sensors to comprise a four resistor Wheatstone bridge. Strain gage signal conditioners typically provide half-bridge completion networks consisting of high-precision reference resistors. The completion resistors provide a fixed reference for detecting small voltage changes across the active resistor(s).

Table 13.1 below shows a summary of common signal conditioning for different types of sensors and measurements.

13.2 Signal Conditioning

Fig 13.1 shows the block diagram of signal conditioning. The input device such as transducer is used to convert the quantity to be measured into an electrical signal. Signal inputs accepted by signal conditioners include DC voltage and current, AC voltage and current, frequency and electric charge. Sensor inputs can be accelerometer, thermocouple, thermistor, resistance thermometer, strain gauge or bridge, and LVDT or RVDT. Specialized inputs include encoder, counter or tachometer, timer or clock, relay or switch, and other specialized inputs. Outputs for signal conditioning equipment can be voltage, current, frequency, timer or counter, relay, resistance or potentiometer, and other specialized outputs.

The electrical output signal generated by a transducer often needs "conditioning" before it can be measured. The signal may require amplification, filtering, linearization and more before it can accurately read it. Additionally, some transducers require an excitation source or proper biasing to complete measurements.

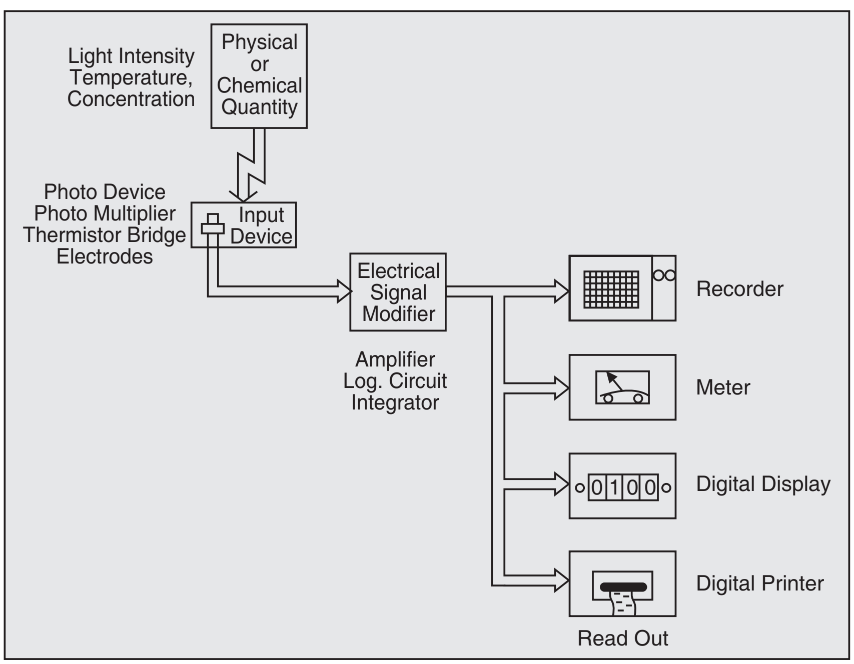


Fig. 13.1.

Some characteristics of each signal are related in a known way to the quantity to be measured. The measured quantity is now encoded as an electrical signal. Now the electrical signal from the input device is modified by suitable electronic circuit to make is suitable for operating a read-out device.

The output number is obtained from a readout device such as meter or chart recorder, where the position of a marker against a numbered scale is observed. The measurements of data are represented in an instrument at any instant by a physical quantity, chemical quantity or characteristics of an electrical signal. Each different characteristics or property used to represent data is called a data domain.

The signal conditioning equipment may be required to perform linear processes such as amplification, attenuation, integration, differentiation, addition or subtraction. They are also required to do non-linear processes such as modulation, demodulation, sampling, filtering, clipping and clamping, squaring and linearsing or multiplication by another function. These functions require proper selection of components and reproduction of the final output for the presentation stage.

The signal conditioning in many situation is an excitation and amplification system for passive transducer. For active transducers it may be amplification system. In both the application, the transducer output is brought upto sufficient level to make it useful for conversion, processing indicating and recording.

13.3 Types of Signal Conditioning

Excitation is needed for passive transducer because these transducers don't generate their own voltage or current depending upon the excitation source, a signal conditioning circuit may have AC and AD voltage source and according to these sources, signal conditioning circuit may be classification:

1. D.C Signal Conditioning System
2. A.C Signal Conditioning System

We will discuss each conditioning system one by one in the following pages.

13.4 D.C Signal Conditioning System

Fig. 13.2 shows the DC signal conditioning system. They are generally used for common resistance transducers such as potentiometer and strain gauges.

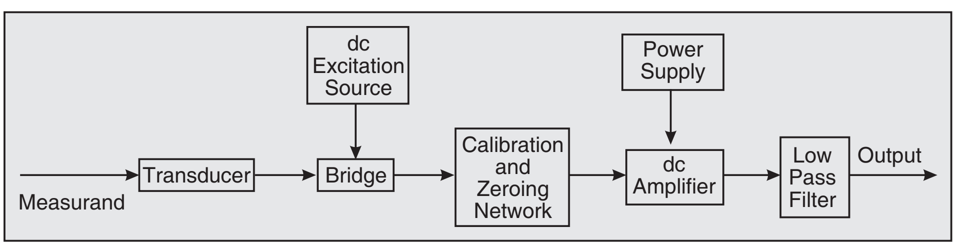


Fig. 13.2.

In the calibration and zeroing network unit the calibration of desired or required parameters like voltage, current, resistance is calibrated in terms of measured for example strain gauge is used in the dc bridge whose parameters found in terms of resistance but is calibrated in terms of force pressure displacement.

The zeroing network process for calibration such that only linear portion of the transducer characteristics is generated. Therefore zeroing network fixes the zero point and calibration starts from here.

In DC amplifer we have amplification, integration, addition, subtraction etc units. This unit works only when it is supplied by power supply. The low pass is used for filtering high frequency signal.

13.5 AC Signal Conditioning System

Fig. 13.3 shows the block diagram of AC signal conditioning system. It is used for variable reactance transducer and for systems where signals have to be transmitted via long cables to connect the transducer to the signal conditioning equipment.

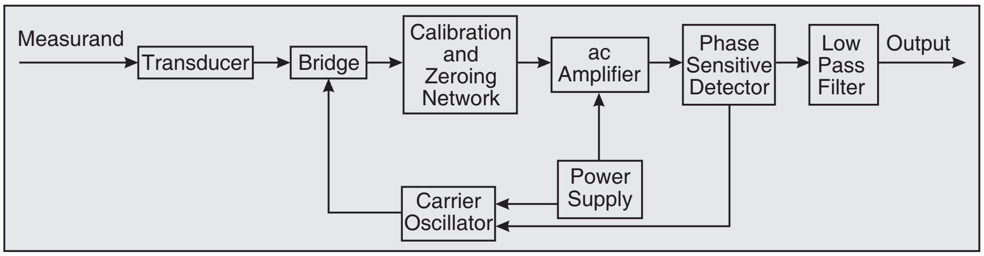


Fig. 13.2.

In this the purpose of calibration and zeroing network unit is same as in DC signal conditioning system. The carrier oscillator provides oscillating signal with certain frequency to run the AC bridge. This carrier signal is also provided to phase sensitive demodulator circuit to multiply the signal coming from the bridge via AC amplification. The phase sensitive demodulator senses the phase or the signal and demodulates the incoming signal. The low pass is used for filtering high frequency signal.

13.6 Amplifier

Op-amp is provided with two input terminals. One of the terminals, labeled '–' is known as *inverting input terminal*. The word "inverting" implies that if a signal is applied to the '–' terminal of the op-amp, it appears with the opposite polarity at the output, i.e., a sinusoidal signal will experience a phase shift of 180°. The other input terminal, labelled "+" is called the non-inverting input terminal. In other words, a signal applied to this terminal of the op-amp is amplified without inversion. The op-amp actually amplifies the difference between the voltages applied to its two input terminals.

13.7 Inverting Amplifier

Figure 13.4 shows the connection method for producing the inverted gain using op-amp. Such a configuration is called inverting amplifier. The op-amp circuit makes use of a single resistor (R_1) and a single feedback resistor (R_2). Notice that resistor R_1 is connected between the input terminal of the amplifier circuit and inverting input terminal (–) of the op-amp. While the resistor R_2 is connected between the inverting input terminal (–) and the output terminal of the op-amp. The non-inverting terminal (+) is connected to the ground. The inverting amplifier produces a 180° phase shift in voltage from input to output. Thus the input and output signals of the inverting amplifier are not in-phase with each other.

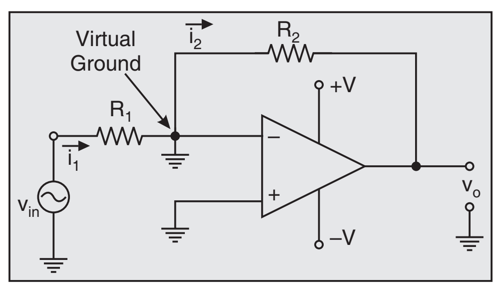


Fig. 13.4. Inverting amplifier.

Now we know that the op-amp gain without any feedback (called open-loop gain) is very high. This means that the voltage at the inverting (i.e., '–') terminal must be very small. As a matter of fact, the input voltage at the inverting terminal will be very nearly at the same potential as the non-inverting terminal. Now since the non-inverting input is grounded, the inverting input of an op-amp is also at the ground potential and is referred to as *virtual ground*.

Since the inverting terminal is virtual ground, therefore the entire input voltage appears across R_1 and the input current, $i_1 = v_{in}/R_1$. Moreover, the input resistance (R_{in}) of an op-amp is very high (ideally infinite), so very little current flows into the op-amp. Practically, the current drawn by the op-amp is negligible or nearly zero. Thus all the input current flows through R_2 (i.e. $i_1 = i_2$). And the voltage developed across R_2 is equal to the output voltage (v_o) of the circuit. Using this knowledge, let us develop expressions for the voltage gain, input resistance, output resistance and common mode rejection ratio of the inverting amplifier.

We have already mentioned above that the input voltage of an op-amp,

$$v_{in} = i_1 \cdot R_1, \text{ or } i_1 = v_{in}/R_1$$

And output voltage,

$$v_o = -\, i_2 \cdot R_2, \text{ or } i_2 = -\, v_o/R_2$$

The negative sign indicates the output is at a lower potential than that of a virtual ground. It is obvious because current through resistor R_2 is flowing from the side connected to the inverting input to the side connected to the output (see Figure 13.2). Since the input- and output-currents are equal (i.e. $i_1 = i_2$), because op-amp input current is negligible.

$$\therefore \qquad \frac{v_{in}}{R_1} = -\frac{v_o}{R_2}$$

or

$$v_o = \frac{R_2}{R_1} V_{in}, \text{ or } \frac{v_o}{v_{in}} = -\frac{R_2}{R_1} \qquad ...(i)$$

Now recall that voltage gain (A_v) of an amplifier is defined as the ratio of output voltage to the input voltage. Mathematically,

$$A_v = \frac{\text{Output voltage}}{\text{Input voltage}} = \frac{v_o}{v_{in}}$$

Substituting the value of (v_o/v_{in}) from equation (i) into the above equation, we get

$$A_v = \frac{R_2}{R_1}$$

The above equation indicates that voltage gain of an inverting amplifier can be determined by dividing the value of R_2 by R_1. The negative sign indicates that the inverting amplifier output is 180° out of phase with respect to the input.

13.8 Non-inverting Amplifier

Figure 13.5 shows the basic configuration of a non-inverting amplifier. Note that the input signal is applied to the non-inverting op-amp input and the resistor R_1 is returned to ground.

Let us develop expressions for amplifier voltage gain, input resistance, and output resistance in the same way as we did in the case of inverting amplifier.

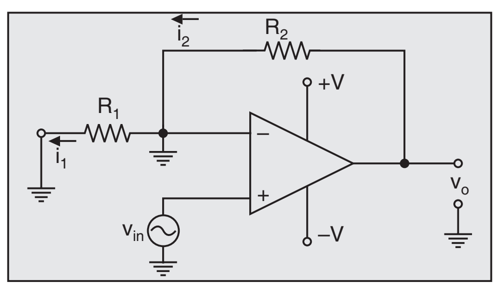


Fig. 13.5. A non-inverting amplifier

1. Voltage gain. We know that the op-amp gain without feedback (called open-loop gain) is very high. This means that voltage at the inverting terminal should nearly be the same as that at the non-inverting terminal. Since the non-inverting input is at a potential of v_{in}, therefore inverting input is also at the same potential. If i_1 is the current through resistor R_1, then its value,

$$i_1 = \frac{v_{in}}{R_1} \text{ or } v_{in} = i_1 \cdot R_1 \qquad ...(i)$$

Since the voltage drop across R_2 is equal to the difference between v_{in} and v_o, therefore, current through resistor R_2,

$$i_2 = \frac{v_o - v_{in}}{R_2} \quad \text{or } i_2 \cdot R_2 = v_o - v_{in}$$

$$\therefore \quad v_o = v_{in} + i_2 \cdot R_2 \qquad ...(ii)$$

Now recall that op-amp draws a negligible input current for its operation. For all practical purposes, its value is considered to be zero, therefore, $i_1 = i_2$.

Replacing i_2 by i_1 in equation (ii), we get

$$v_o = v_{in} + i_1 \cdot R_2$$

The amplifier voltage gain,

$$A_v = \frac{\text{Output voltage}}{\text{Input voltage}} = \frac{v_o}{v_{in}}$$

Substituting the value of v_o and v_{in} from equation (*ii*) and (*i*) into the above equation,

$$A_v = \frac{v_{in} + i_1 \cdot R_2}{i_1 \cdot R_1} = \frac{i_1 \cdot R_1 + i_1 \cdot R_2}{i_1 \cdot R_1} = \frac{R_1 + R_2}{R_1}$$

or

$$A_v = 1 + \frac{R_2}{R_1}$$

The above equation shows that voltage gain of a non-inverting amplifier will always be greater than the equivalent gain of the inverting amplifier by a value of 1. For example, if an inverting amplifier has a gain of 100, the equivalent non-inverting amplifier will have a gain of 101.

13.9 Differential Amplifier

Figure 13.6 shows the circuit of a differential amplifier. Notice that the voltages are applied at both the op-amp inputs (i.e., inverting and non-inverting inputs) through the resistors. And the difference between these two voltages is amplified.

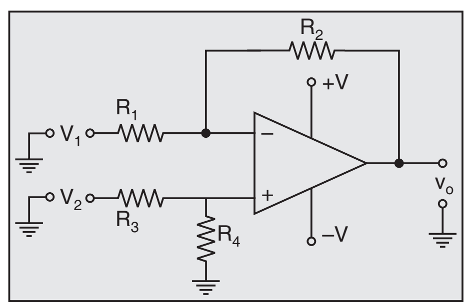


Fig. 13.6. A differential amplifier

Suppose that voltage '*v*' volts is applied to terminal 1 and zero volts to terminal 2. The difference in the potentials at the inverting and non-inverting op-amp terminals is very nearly zero. Therefore the inverting terminal must be at zero potential. This means that the input voltage v_1 is developed across resistor R_1.

$$\therefore \text{ Input current,} \quad i_1 = \frac{v_1}{R_1}$$

Since the input resistance of the op-amp is high, the current, (i.e., i_1) flows through resistor R_2. The voltage drop across R_2 which is the output voltage V_{out} of the circuit,

$$= -v_1 \cdot \left(\frac{R_2}{R_1}\right)$$

And the voltage gain of the circuit,

$$A_v = \frac{v_{out}}{v_1} = \frac{-v_1 \cdot (R_2 / R_1)}{v_1} = -\frac{R_2}{R_1}$$

Conversely if the voltage applied to input terminals 1 and 2 are respectively zero and v_2 volts, the voltage appearing at the non-inverting terminal

$$= v_2 \cdot \left(\frac{R_4}{R_3 + R_4}\right)$$

This voltage will also appear at the inverting terminals. So the voltage across resistor R_1,

$$= - v_2 \cdot \left(\frac{R_4}{R_3 + R_4}\right)$$

In this case, the output voltage of the circuit,

$$v_{out} = v_2 \cdot \left(\frac{R_4}{R_3 + R_4}\right) + \left\{\left(- v_2 \cdot \frac{R_4}{R_3 + R_4}\right) \times \left(- \frac{R_2}{R_1}\right)\right\}$$

And the voltage gain of the circuit,

$$A_v = \frac{v_{out}}{v_2} = \left(\frac{R_4}{R_3 + R_4}\right)\left(1 + \frac{R_2}{R_1}\right)$$

Lastly, if the voltages applied to the terminals 1 and 2 are v_1 and v_2 volts respectively, the difference between the two voltages is amplified. If $v_1 > v_2$, a voltage $(v_1 - v_2)$ is amplified $(-R_2/R_1)$ times. On the other hand, if $v_2 > v_1$, a voltage $(v_2 - v_1)$ is amplified by $[R_4/(R_3 + R_4)] \cdot [1 + (R_2/R_1)]$.

If $R_1 = R_3$ and $R_2 = R_4$, then the voltage gain,

$$A_v = \frac{v_{out}}{v_1 - v_2} = \frac{R_2}{R_1}; \quad \therefore v_{out} = \frac{R_2}{R_1}(v_2 - v_1)$$

3.10 Instrumentation Amplifier

An instrumentation amplifier is a type of differential amplifier. It is a differential voltage gain device that amplifies the difference between the voltages existing at its two input terminals. The main use of an instrumentation amplifier is for a low level amplification with high CMRR, high input impedance to avoid loading, low power consumption.

A basic instrumentation amplifier is shown in Fig. 13.7 Op-Amp A_1 and op-amp A_2 are non-inverting configurations that provide high input impedance and voltage gain. The overall voltage gain is

$$A_v = \frac{V_o}{(V_1 - V_2)} = 1 + \frac{2R}{R_P}$$

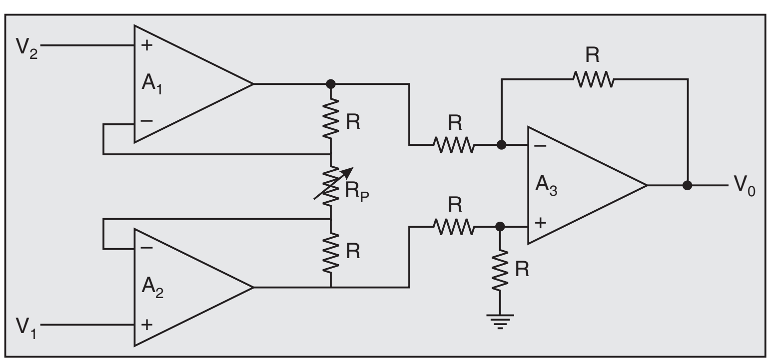


Fig. 13.7.

13.11 Instrumentation Amplifier Using Two Amplifiers

We have already discussed that the voltage follower amplifier has a very high input resistance. We can achieve the high input resistance with a variable voltage by using two op-amp instrumentation amplifier circuits. Figure 13.8 shows the instrumentation amplifier with two op-amps.

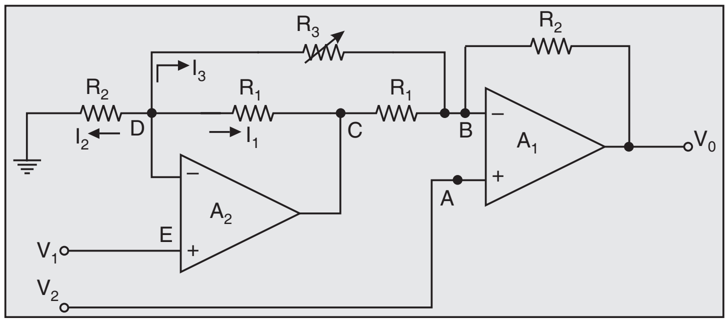


Fig. 13.8.

For amplifier 1 the voltage at node A is same as the node B, then

$$V_A = V_B = V_2$$

Similarly for the amplifier, voltage at node E is same as the node D.

$$V_E = V_D = V_1$$

$$I_2 = \frac{V_D}{R_2} = \frac{V_1}{R_2}$$

$$I_1 = \frac{V_D - V_C}{R_1} = \frac{V_1 - V_C}{R_1}$$

$$I_3 = \frac{V_D - V_B}{R_3} = \frac{V_1 - V_2}{R_3}$$

Applying KCL in node D,

$$I_1 + I_2 + I_3 = 0$$

$$\frac{V_1 - V_C}{R_1} + \frac{V_1}{R_2} + \frac{V_1 - V_2}{R_3} = 0 \qquad ...(i)$$

Applying KCL at node B, we get

$$\frac{V_B - V_D}{R_3} + \frac{V_B - V_C}{R_1} + \frac{V_B - V_0}{R_2} = 0 \qquad ...(ii)$$

From equation (i) and (ii) we get,

$$\frac{V_o}{V_2 - V_1} = 1 + \frac{R_2}{R_1} + \frac{2R_2}{R_3}$$

Here $(V_2 - V_1)$ is the difference of input voltage and V_o is the output voltage. Thus the voltage gain of this circuit is,

$$A_V = 1 + \frac{R_2}{R_1} + \frac{2R_2}{R_3}$$

Here the resistance R_3 is the variable resistance.

13.12 Instrumentation Amplifier Using Three Amplifiers

Instrumentation amplifier using three op-amps is shown in Fig. 13.9. This provides high input resistance for accurate measurement of signals. In this circuit a non-inverting amplifier is added to each of the basic difference amplifier inputs.

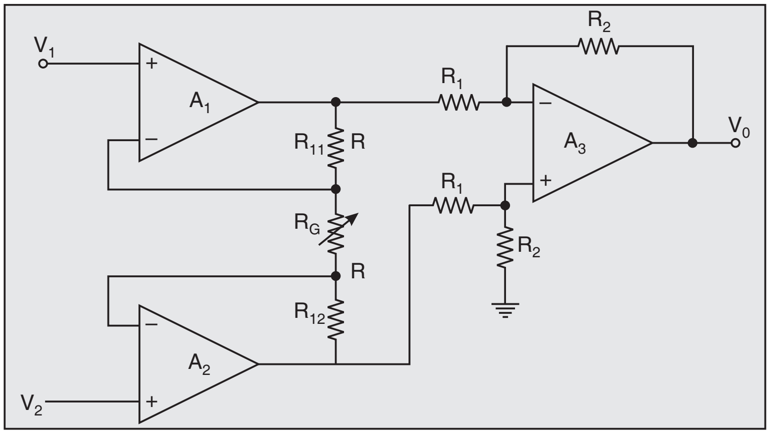


Fig. 13.9.

Here op-amps A_1 and A_2 are the non-inverting amplifiers forming the input or first stage of the instrumentation amplifier. The op-amp A_3 is the difference amplifier forming an output stage of the amplifier. The block diagram representation of the three op-amp instrumentation amplifier is shown in Fig. 13.10.

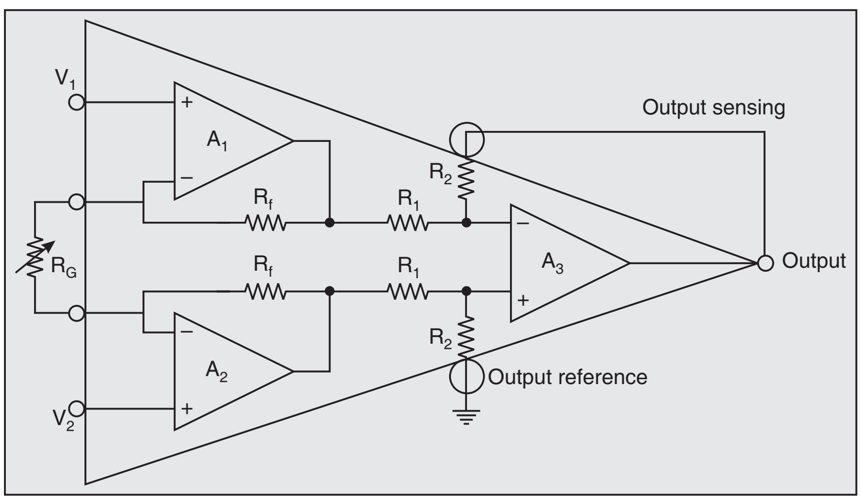


Fig. 13.10.

The output of the op-amp of the op-amp A_1 is V_{o1} and the output of the op-amp A_2 is V_{o2}. The output stage of a standard difference amplifier is,

$$V_o = \frac{R_2}{R_1}(V_{o2} - V_{o1})$$

Let find out the values of V_{o2} and V_{o1} from the instrumentation amplifier circuit shown in Fig. 13.11. The voltage at node A is equal to voltage V_1 and node voltage B is equal to node voltage A. And hence voltage of G is also equal to V_1. Similarly the voltage of H is V_2. Applying ohm's law between the node E and F we get,

$$I = \frac{V_{o1} - V_{o2}}{R_{f1} + R_G + R_{f2}}$$

Let $R_{f1} = R_{f2} = R_f$ then,

$$I = \frac{V_{o1} - V_{o2}}{2R_{f1} + R_G} \quad ...(i)$$

In node G and H,

$$I = \frac{V_G - V_H}{R_G} = \frac{V_1 - V_2}{R_G} \quad ...(ii)$$

From equation (i) and (ii), we get

$$\frac{V_{o1} - V_{o2}}{2R_{f1} + R_G} = \frac{V_1 - V_2}{R_G}$$

$$V_{o1} - V_{o2} = \frac{(2R_{f1} + R_G)}{R_G} (V_1 - V_2)$$

We know that the output voltage of the differential amplifier is given by

$$V_o = \frac{R_2}{R_1} (V_{o2} - V_{o1})$$

Substituting the value of $V_{o2} - V_{o1}$ we get,

$$V_o = \frac{R_2}{R_1} \cdot \left(1 + \frac{2R_f}{R_G}\right)(V_{o2} - V_{o1})$$

Above is the overall gain of the amplifier. If R_1 equal to R_2 then the overall gain of amplifier is given by,

$$V_o = \left(1 + \frac{2R_f}{R_G}\right) (V_{o2} - V_{o1})$$

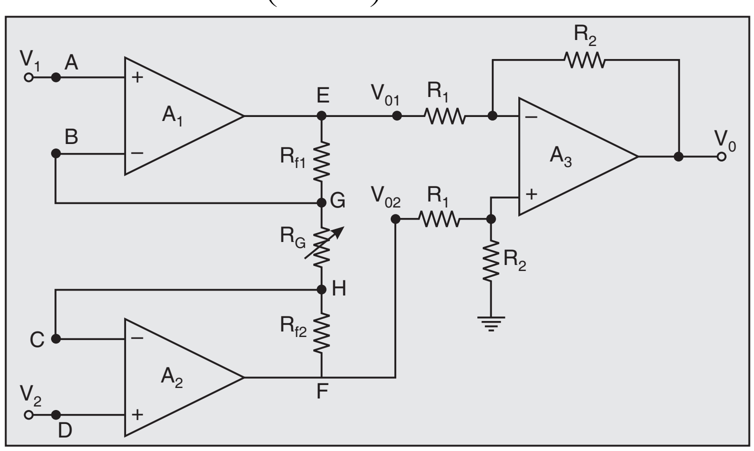


Fig. 13.11.

With the help of variable resistance the gain can be easily varied without disturbing the symmetry of the circuit. The gain depends in external resistances and hence can be adjusted accurately and made stable by selecting high quality resistances.

The AD620 Instrumentation Amplifier

You have seen that the output voltage of a Wheatstone bridge is too small to be used in any application. Hence, there is a need to amplify this voltage to a level where it can be utilized to turn on electrical loads such as an LED, a relay or a DC motor when a given amount of strain is applied to the strain gauge.

Now we will use the AD620 to amplify the output voltage of the Wheatstone bridge. The datasheet of the AD620 can be found in the Appendix I.

(*a*) Connect the circuit as shown in the diagram below.

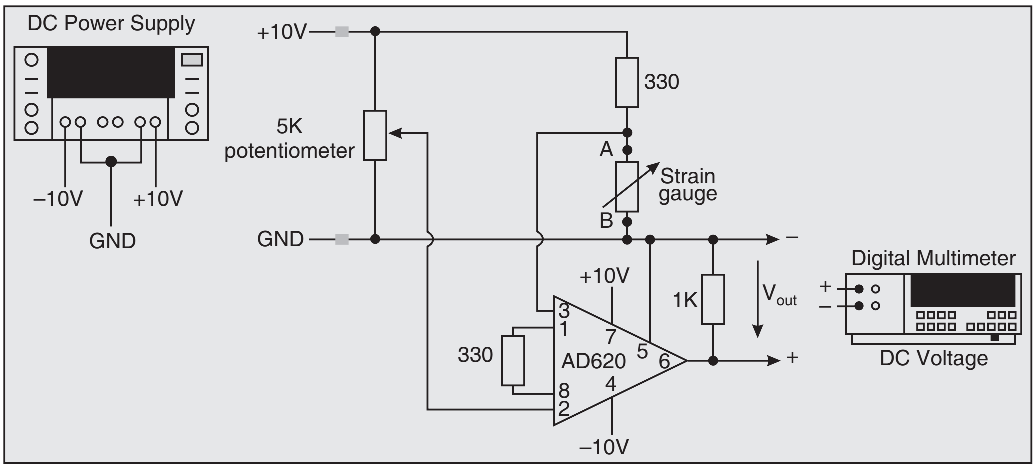


Fig. 13.12. Voltage amplification using the AD620

(*b*) Ensure that no objects are placed on the plastic ruler.

(*c*) If need to, adjust the 5k potentiometer until V_{out} is nearly zero in the unstrained condition.

(*d*) Apply force at the tip of the ruler and observe the change in V_{out}.

(*e*) Find out the gain of the AD620 instrumentation amplifier in Fig. 13.12.

Hint: Look at the *IC* specification datasheet.

4. Let us use the information we have gathered so far to design the Structural Health Monitoring system, assuming that a quarter-bridge circuit is used.

(*a*) Calculate the resistance of the strain gauge when strains is at design ultimate level.

(*b*) Determine the resistance of the strain gauge when strain is at normal working level.

(*c*) Find the output voltage of the Wheatstone bridge when strain is at design ultimate level/ normal working level.

There are countless different applications for strain gauges in Aerospace Engineering. They are ideally designed for the precise measurement of a static weight or a dynamic load or force.

One typical application of strain gauge is used for Structural health monitoring and impact detection for primary aircraft structures. A structural health monitoring (SHM) system that can evaluate the health of the airframe structure via measuring the strain distribution, monitoring deformation, and diagnosing damage is critical to ensure safe flight. At the very heart of the SHM system is a strain gauge to measure the strain at certain points.

Look at the pictures below and design a circuit to find out the strain for the SHM system. You can consider the strain gauge with a nominal resistance of 350 Ω and a gauge factor of 4.

The SHM system should have the following features:

1. Uses a strain gauge as a sensing element.

2. The design ultimate strain is 5000 με. Once strain exceeds the design limit, a red LED shall be on.
3. A green LED means strain is below normal working level, which is 3500 με.
4. When strain is between 3500 με and 5000 με, both green LED and red LED should be off.

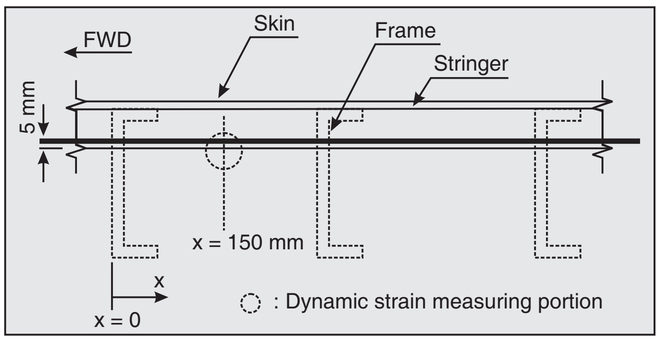


Fig. 13.13. Structural Health Monitoring System

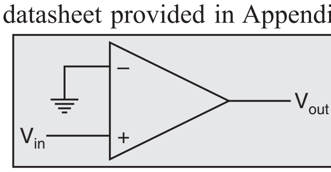
Design a circuit to amplify the output voltage of the Wheatstone bridge and to generate a signal to turn on the Red and Green LEDs based on the design specification.

Design Exercise

Based on what you have learned so far, design a circuit which can be used to turn on a red LED when strain exceeds the design limit. Under normal working level, a green LED shall be on.

You can use the following components to construct your circuit:

(*a*) A comparator (KA358, datasheet provided in Appendix I).



$$V_{out} = V_{CC} \text{ sign } (V_{in})$$

(*b*) A 5k potentiometer.
(*c*) Red LED.
(*d*) Green LED.
(*e*) 330 Ω current limiting resistor for the LED.
  (*i*) If green LED is to on be when AD620's output is below 1.5V, which input pin of the op-amp should set to 1.5V (Vref)?
  (*ii*) LF358 is a dual op-amp in one package, Use the other amplifier to drive the red LED. If red LED is to be on when AD620's output is > 3.0V, which input pin should set to 3.0V?

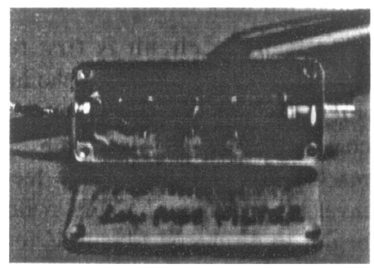
13.13 Filters

We have already discussed in Chapter 30, about tuned voltage amplifiers (or simply tuned amplifiers). Such amplifiers are designed to amplify only those frequencies that are within certain range. As long as the input signal is within the specified range, it will be amplified. If it goes outside of this frequency range, amplification will be drastically reduced. The tuned amplifier circuits using op-amp are generally referred to as active filters. Such circuits do not require the use of inductors. The frequency response of the circuit is determined by resistor and capacitor values.

We have already mentioned above that op-amps can be used to build active filter circuits. A filter circuit can be constructed using passive components like resistors and capacitors. But an active filter, in addition to the passive components makes use of an op-amp as an amplifier. The amplifier in the active filter circuit may provide voltage amplification and signal isolation or buffering.

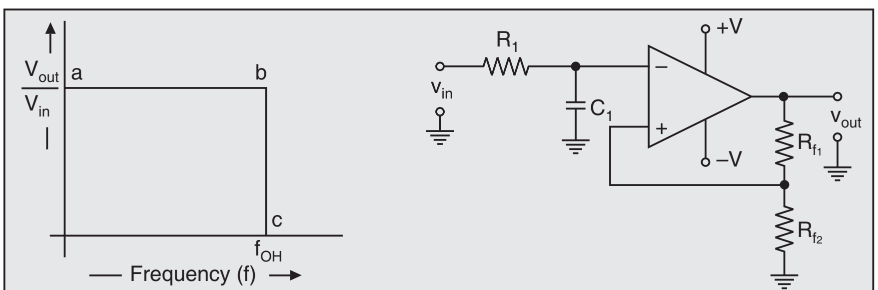
There are four major types of filters namely, low-pass filter, high-pass filter, and band-pass filter and band-stop or notch filter. All these four types of filters are discussed one by one in the following pages.

13.14 Low-Pass Filter



Low-Pass Filter

A filter that provides a constant output from dc up to a *cut-off frequency* (f_{OH}) and then passes no signal above that frequency is called an ideal low-pass filter. The ideal response of a low-pass filter is as shown in Fig. 13.14 (*a*). Notice that the response shows that the filter has a constant output (indicated by a horizontal line '*ab*') from dc or zero frequency up to a cut-off frequency (f_{OH}). And beyond f_{OH}, the output is zero as indicated by the vertical line '*bc*' in the figure.



(a) Ideal response of a low-pass filter. (b) Low-pass active filter circuit.

Fig. 13.14. Low-pass filter

Figure 13.14 (*b*) shows the circuit of a low-pass active filter using a single resistor and capacitor. Such a circuit is also referred to as first-order (or single-pole) low-pass filter. It is called first-order because it makes use of a single resistor and a capacitor. The response of such a first-order low pass filter is as shown in Fig. 13.15. Notice that the response below the cut-off frequency (f_{OH}) shows a constant gain (indicated by a horizontal line '*ab*').

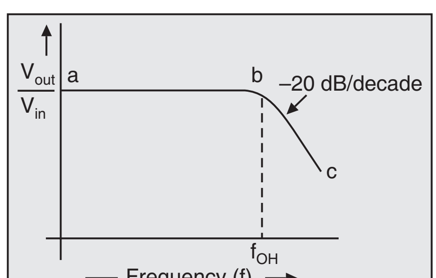


Fig. 13.15. Response of a first-order low-pass active filter.

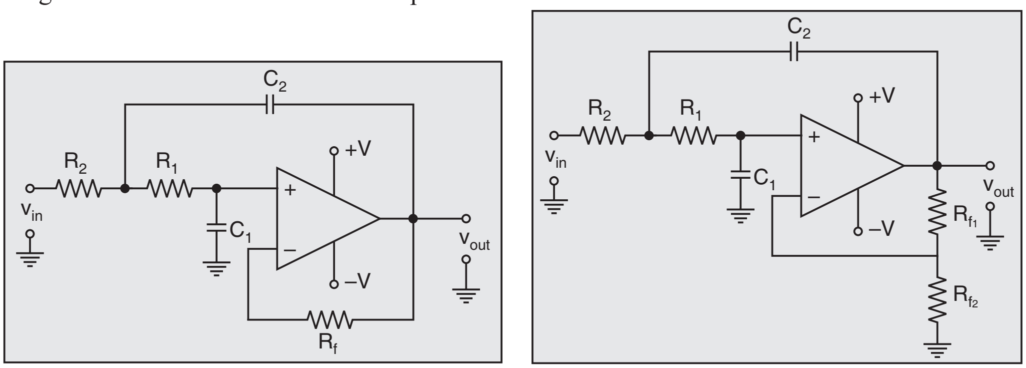
However, beyond the cut-off frequency, the gain does not reduce immediately to zero as expected in Fig. 13.14 (*a*) but reduces with a slope of 20 dB/decade (means that the output voltage reduces by a factor of 100 when the frequency increases by a factor of 10). The voltage gain for a low-pass filter below the cut-off frequency (f_{OH}) is given by the relation.

$$A_v = 1 + \frac{R_3}{R_1}$$

And the cut-off frequency is determined by the relation,

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

It is possible to connect two sections of the filter together as shown in Fig. 13.16 (*a*). Such a circuit is called second-order (or two-pole) low pass filter. Fig. 13.16 (*b*) shows another configuration of the second-order low-pass filter.



(a) Second order low-pass filter. (b) Another configuration of second-order low-pass filter.

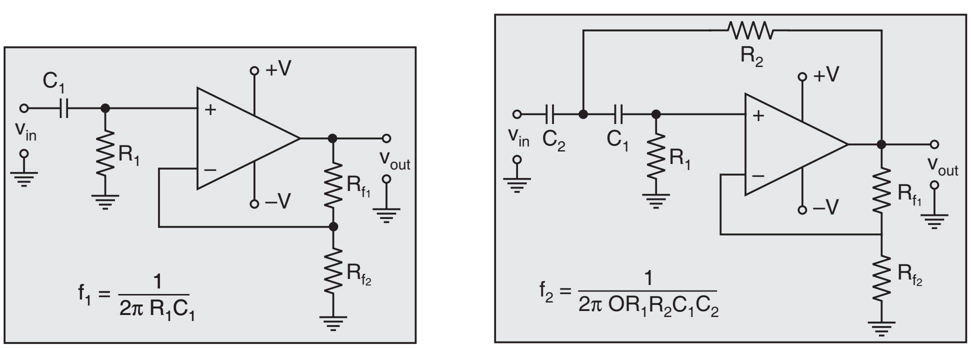
Fig. 13.16

Each circuit shown in Figure 13.16 has two *RC* circuits, $R_1 - C_1$ and $R_2 - C_2$. As the operating frequency increases beyond f_2, each circuit will be dropping the closed-loop gain by 20 dB, giving a total roll-off rate of 40 dB/decade when operated above f_2. The cut-off frequency for each of the circuit is given by,

$$f_2 = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

13.15 High-Pass Filter

As a matter of fact, there is very little difference between the high-pass filter and the low-pass



(a) A first-order high pass filter. (b) A second-order high pass filter.

Fig. 13.17.

filter. Figure 13.17 (*a*) shows the circuit of a first order (or single-pole) high-pass filter and Fig. 13.17 (*b*), the circuit of a second-order (or two-pole) high-pass filter. Notice that the only thing that has changed is the positions of the capacitors and resistors. The value of cut-off frequencies f_1 and f_2 is obtained by using the same equations we used for low-pass filter.

Figure 13.18 shows the gain versus frequency response of a high-pass filter. Notice that the solid line indicates the ideal response while the dashed line, corresponds to the actual response of the filter circuit. The ideal curve indicates that the filter has a zero output for the frequencies below f_{OL} (indicated by the line '*ab*'). And beyond f_{OL}, it has a constant output. The actual response curve may correspond to the roll-off gain by 20 dB/decade for first order or 40 dB/decade for second-order low-pass filters.

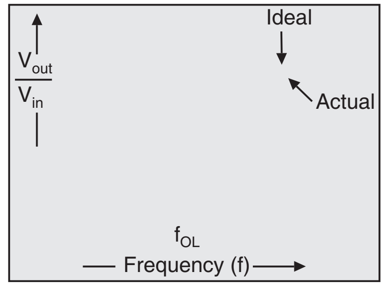


Fig. 13.18. Gain versus frequency response of a high-pass filter.

13.16 Band-Pass Filter

A band-pass filter is the one that is designed to pass all frequencies within its bandwidth. A simple way to construct a band-pass filter is to cascade a high-pass filter as shown in Fig. 13.19.

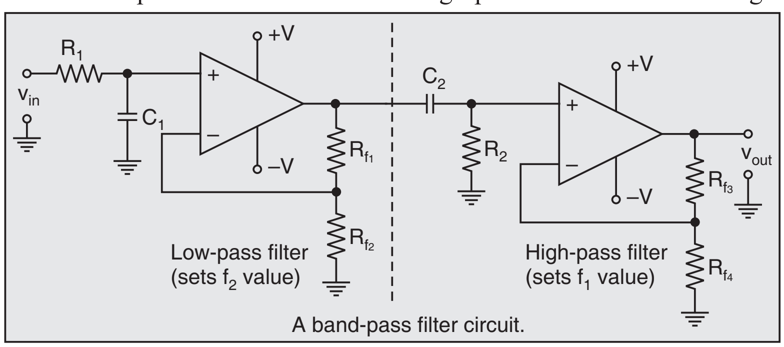


Fig. 13.19.

The first stage of the band-pass filter will pass all frequencies that are below its cut-off value, f_2. All the frequencies passed by the first stage will head into the second stage. This state will pass all frequencies above its value of f_1. The result of this circuit action is as shown in Fig. 13-20. Note that the only frequencies that will pass through the amplifier are those that fall within the pass band of both amplifiers. The values of f_1 and f_2 can be obtained by using the relations, $1/2\pi\ R_1C_1$ and, $1/2\pi\ R_2C_2$. Then bandwidth,

$$BW = f_2 - f_1$$

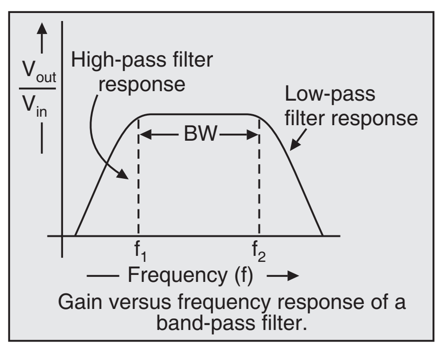


Fig. 13.20.

And the center frequency,

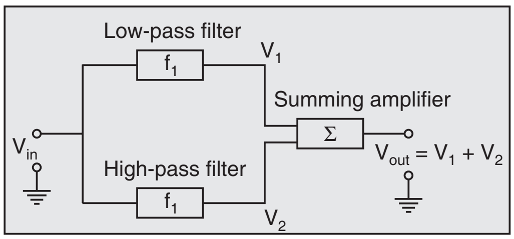
$$f_o = f_1 \cdot f_2$$

The Quality-factor (or *Q*-factor) of the band-pass filter circuit,

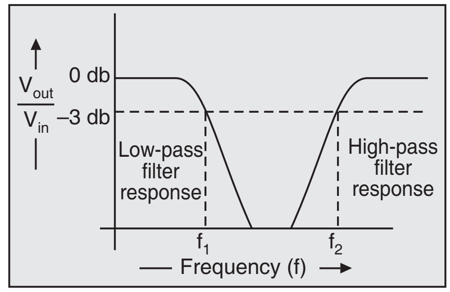
$$Q = \frac{f_o}{BW}$$

13.17 Notch Filter

The notch filter is designed to block all frequencies that fall within its bandwidth. Fig. 13.21 (*a*) shows a block diagram and 13.21 (*b*), the gain versus frequencies response curve of a multistage notch filter.



(a) Block diagram.



(b) Gain versus frequency response curve.

Fig. 13.21. Notch filter.

The block diagram shows that the circuit is made up of a high-pass filter, a low-pass filter and a summing amplifier. The summing amplifier produces an output that is equal to a sum of the filter output voltages. The circuit is designed in such a way so that the cut-off frequency, f_1 (which is set by a low-pass filter) is lower in value than the cut-off frequency, f_2 (which is set by high-pass filter). The gap between the values of f_1 and f_2 is the bandwidth of the filter.

When the circuit input frequency is lower than f_1, the input signal will pass through low-pass filter to the summing amplifier. Since the input frequency is below the cut-off frequency of the high-pass filter, v_2 will be zero. Thus the output from the summing amplifier will equal the output from the low-pass filter. When the circuit input frequency is higher than f_2, the input signal will pass through the high-pass filter to the summing amplifier. Since the input frequency is above the cut-off frequency of the low-pass filter, v_1 will be zero. Now the summing amplifier output will equal the output from the high-pass filter.

It is evident from the above discussion that frequencies below f_1 and those above f_2, have been passed by the notch filter. But when the circuit frequency between f_1 and f_2, neither of the filters will produce an output. Thus v_1 and v_2 will be both zero and the output from the summing amplifier will also be zero.

The frequency analysis of the notch filter is identical to the band-pass filter. First, determine the cut-off frequencies of the low-pass and the high-pass filters. Then using these calculated values, determine the bandwidth, center frequency and Q values of the circuit.

13.18. Analog-to-Digital (A/D) Conversion

Basically, an A/D conversion is a process of taking an analog voltage and converting to its equivalent digital code. The A/D conversion process is generally more complex and time-consuming than that of D/A process. The electronic device that does the A/D conversion is called A/D converter.

Many different methods have been developed for A/D conversion. We shall study some of these methods in detail. It may be carefully noted that although knowing different methods of A/D conversion may never be necessary to design or construct A/D converters, but they are used to provide a greater insight into the factors that determine the performance of A/D converters.

Figure 13.22 shows a block diagram of an A/D converter that utilizes a D/A converter as a part of their circuitry. As seen from this diagram, the A/D converter consists of an Op-Amp, a control unit, a register, and a D/A converter. The timing for the operation is provided by the input clock signal. The control unit contains the logic circuit for generating the proper sequence of operations in response to the *start command* which initiates the conversion process. The op-amp is used as a comparator. It has two analog inputs and a digital output. The digital output switches the states depending upon which analog input is greater.

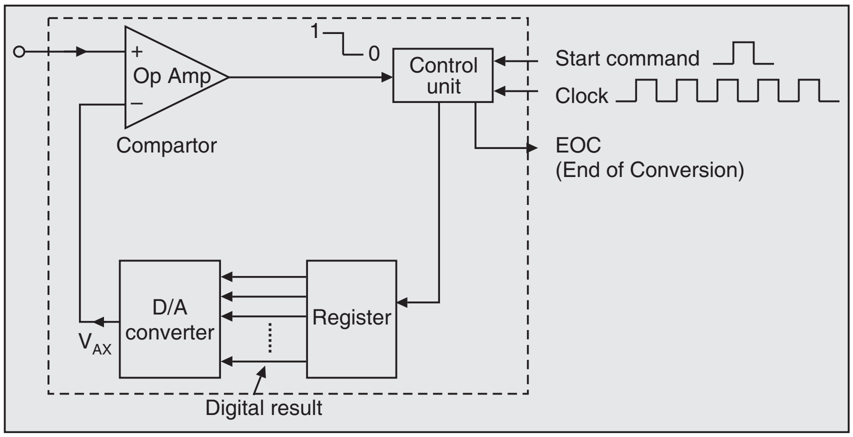


Fig. 13.22.

The basic operation of the A/D converter utilizing the D/A converter may be described as follows:

1. The "**Start Command**" pulse initiates the operation.
2. The control unit continually modifies the binary number stored in the register. The rate at which the number is modified is determined by the clock input.
3. The binary number in the register is converted to an analog voltage, V_{AX}, by the D/A converter.
4. The comparator compares V_{AX} with the analog input voltage V_A. As long as $V_{AX} < V_A$, the comparator output stays "High". When V_{AX} exceeds V_A by at least an amount equal to V_T (the threshold voltage), the comparator output goes "low" and stops the process of modifying the number in the register. At this point, V_{AX} is a close approximation to V_A. The digital number in the register, which is the digital equivalent of V_{AX}, is also the approximate digital equivalent of V_A, within the resolution and accuracy of the D/A converter.
5. The control logic activates the "**End-of-conversion**" signal, EOC, when the conversion is complete.

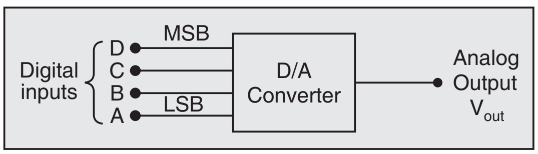
As a matter of fact, there could be several variations of this A/D conversion scheme. Every scheme may differ mainly in the manner in which the control section continually modifies the numbers in the register. However, the basic idea is the same with the register holding the required digital output.

13.19 Digital-to-Analog (D/A) Conversion

Most of the D/A and A/D converters utilize the D/A conversion process. Therefore we will study the D/A conversion first.

Basically, D/A conversion is the process of taking a value represented in digital code (such as BCD or a straight binary number) and converting it to a voltage or current that is proportional to the digital value.

Figure 13.23 (*a*) shows the symbol for a typical 4-bit D/A converter. We will not worry about the internal circuitry of the D/A converter at present. Rather let us focus on the relationship between various inputs and outputs. As seen from this figure, it has 4 digital inputs represented by *A*, *B*, *C* and *D* respectively. These outputs are obtained from the output register of a digital system. We know that these 4 inputs produce $2^4 = 16$ different binary numbers as shown in Fig. 13.23 (*b*). Notice that for each digital input number the D/A converter output voltage is a unique value. In this case, the analog output voltage (V_{out}) is equal in volts to the binary number. In actual practice, it could have been twice the binary number or any other value. In fact, the same idea would hold true of the D/A output were a current (I_{out}) instead of voltage.



(a)

D	C	B	A	V_{out} (Volts)
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

(b)

Fig. 13.23.

In general,

$$\text{Analog output} = K \times \text{Digital input}$$

where K = Proportionality factor. It is a constant value for a given D/A converter. Its value will be in voltage units when the D/A output is a voltage, and in current units when the D/A output is a current.

For a D/A converter in the present case, the value of K = 1 volt, therefore,

$$V_{out} = K \times \text{Digital input}$$
$$= (1) \times \text{Digital input} \qquad ...(i)$$

We can use equation (*i*) to calculate V_{out} for any value of digital input. For example, with a digital input of 1010 (decimal 12), the output voltage,

$$V_{out} = 1 \times 10 = 10V$$

13.20 Signal Transmission

There are a wide variety of sensors available to provide us with electrical signals representing many different parameters which we wish to measure. For example we can measure temperature with thermocouples and resistance thermometers, pH and conductivity with suitable electrodes, and mass with strain gauges.

All these devices have different characteristics of signal type, amplitude and linearity. To make use of them in an industrial environment it is useful to convert their signals into a standard signal which we can connect to our measuring and control equipment. We are then able to use the same measuring and control equipment to process many different physical parameters. The most popular standards worldwide are given below:

1. 0-5V
2. 0-10V

3. 1-5V
4. 2-10V
5. 1-5mA
6. 0-20mA
7. 4-20mA
8. 10-50mA

We will discuss the 4-20 mA signal transmission in detail.

13.21 4-20 mA Signal Transmission

The transmitter is a current sinking circuit, which means that it will attempt to draw a current from an external power supply. This is usually a 4-20 mA signal powered from 24V DC which is often an integral part of the measuring instrument to which the transmitter is connected. Unlike voltage transducers which are wired in parallel to measuring instruments, the current transmitter is wired in a series circuit.

Multiple series loads, wide variation in supply voltage, and some inherent noise immunity are advantages of current loop transmitters. Fig. 13.24 shows the basic internal circuit blocks of a 4-20 mA transmitter. These circuits provide the following functionality;

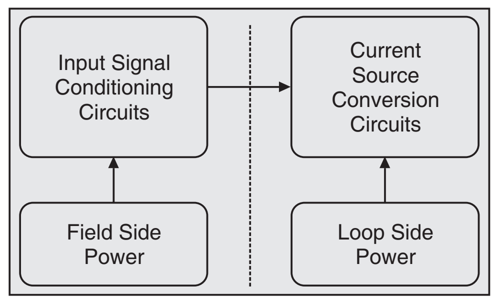


Fig. 13.24.

Input Signal conditioning circuits provide appropriate interfacing for all types of inputs, such as; thermocouples, RTDs, AC-DC voltages and currents, strain gauges. Many 4-20 mA modules have "smart" signal conditioning functionality that provides linearization, and mathematical manipulations.

Power circuits generate all the necessary internal voltages required and are energized from either a local power source or the actual current loop. Current conversion circuits establish the 4-20 mA current loop signal.

The dashed line in illustrates isolation between the field side and the output loop side. Isolation is an extremely important aspect of signal transmission. Signal loops, power supplies, and grounds should always be completely isolated from each other. There are basic three types of transmitter. They are discuss below:

1. **2-Wire Transmitter.** Fig. 13.25 shows a 2-wire transmitter energized by the loop current where the loop source voltage (compliance) is included in the receiver. The transmitter floats and signals ground is in the receiver.

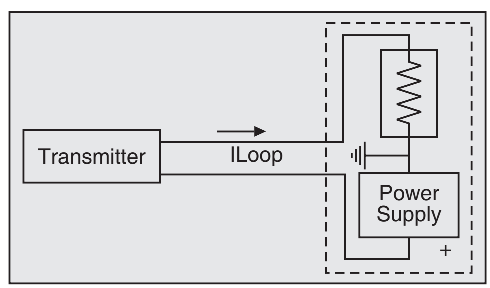


Fig. 13.25.

2. **3-Wire Transmitter.** Fig. 13.26 shows 3-wire transmitter energized by a supply voltage at the transmitter. The transmitter sources the loop current. Transmitter common is connected to receiver common.

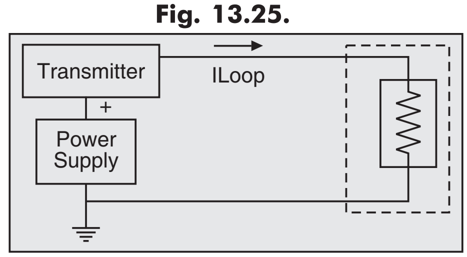


Fig. 13.26.

3. **4-Wire Transmitter.** Fig. 13.27 shows a 4-wire transmitter energized by a supply voltage at the transmitter. The transmitter sources the loop current to a floating receiver load.

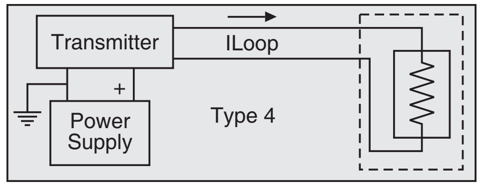


Fig. 13.27.

If a transmitter has field inputs, which provide signals referenced to field grounds potential ground loops exist. This potentially will cause signal gradation. In practical the field inputs are usually referenced to field grounds or in some cases actually connected to a field ground for example, the grounded thermocouple. Receiver grounds are rarely identical to field grounds, therefore, isolation is required to eliminate potential ground loop problems.

13.22 4-20 mA Current Loop

The 4-20 mA current loop is a very robust sensor signaling standard. Current loops are ideal for data transmission because of their inherent insensitivity to electrical noise. In a 4-20 mA current loop, all the signaling current flows through all components, the same current flows even if the wire terminations are less than perfect. All the components in the loop drop voltage due to the signaling current flowing through them. The signaling current is not affected by these voltage drops as long as the power supply voltage is greater than the sum of the voltage drops around the loop at the maximum signaling current of 20 mA.

In a 4-20 mA signal we always have at least 4 mA flowing in the loop. This means that if we can power our electronics from the 4 mA we can have our power supply and signal on the same pair of conductors. An instrument which transmits a 4-20 mA signal is usually referred to as a transmitter and if it derives its power from the 4 mA residual current it is called a loop powered transmitter. The two "Rwire" symbols represent the resistance of the wires running out to the sensors and back to the power supply and controller.

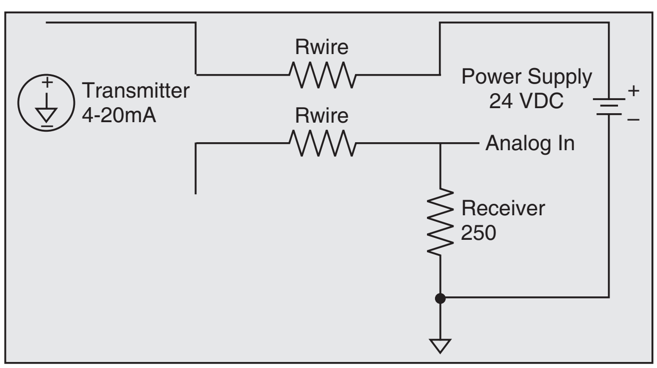


Fig. 13.28.

Fig. 13.28 shows a circuit of the simplest 4-20 mA current loop. The current supplied from the power supply flows through the wire to the transmitter and the transmitter regulates the current flow within the loop. The current allowed by the transmitter is called the loop current and it is proportional to the parameter that is being measured. The loop current flows back to the controller through the wire, and then flows through the Rreceiver resistor to ground and returns to the power supply. The current flowing through Rreceiver produces a voltage that is easily measured by an analog input of a controller. There are four components:

1. **The Power Supply.** Power supplies for 2-wire transmitters must always be DC because the change in current flow represents the parameter that is being measured. If AC power were used, the current in the loop would be changing all the time. Therefore, the change in current flow from the transmitter would be impossible to distinguish from change in current flow caused by the AC power supply. For 4-20 mA loops with 2-wire transmitters, common power supply voltages are 36 VDC, 24 VDC, 15 VDC and 12 VDC.
2. **The Transmitter.** The transmitter is the heart of the 4-20 mA signaling system. Here we use 2-wire transmitter. It converts a physical property such as temperature, humidity or pressure into an electrical signal. This electrical signal is a current, proportional to the temperature, humidity or pressure being measured. In a 4-20 mA loop, 4 mA represents the low end of the measurement range and 20 mA represents the high end. The lower voltage is the minimum voltage necessary to guarantee proper transmitter operation. The higher voltage is the maximum voltage the transmitter can withstand and operate to its stated specifications.
3. **The Receiver Resistor.** A receiver resistor that converts the current signal to a voltage. It is much easier to measure a voltage than it is to measure a current. Therefore, many current loop circuits use a Receiver Resistor (Rreceiver) to convert the current into a voltage.
4. **The Wire.** It sending current through a wire produces a voltage drop proportional to the length and thickness of the wire. All wire has resistance, usually expressed in Ohms per 1,000 feet. The voltage drop is calculated by using Ohm's law.

SUMMARY

In this chapter you have learned that:

1. Signal conditioning means manipulating an analog signal in such a way that it meets the requirements of the next stage for further processing.
2. An instrumentation amplifier is a type of differential amplifier.
3. Digital to analog conversion is the process of taking a value represented in digital code and converting it to a voltage or current that is proportional to the digital value.
4. ADC are used to convert the analog wave into numbers.
5. Filter is a device or process that removes unwanted components from a signal.
6. Transmitter converts a physical property such as temperature, humidity or pressure into an electrical signal.

GLOSSARY

AC Signal Conditioning System. It is used for variable reactance transducer and for systems where signals have to be transmitted via long cables to connect the transducer to the signal conditioning equipment.

A/D Converter. It is used to convert analog or continuous voltage signal to an digital form.

D/A Converter. It is used to convert digital data from the system to an analog form.

DC Signal Conditioning System. They are generally used for common resistance transducers such as potentiometer and strain gauges.

Instrumentation Amplifier. It is a differential voltage gain device that amplifies the differences between the voltage at its two input terminals.

Receiver Resistor. A receiver resistor that converts the current signal to a voltage.

Signal Amplification. Signal amplification performs two important functions increases the resolution of the input signal and increases its signal-to-noise ratio.

Transmitter. It is a transducer which responds to a measured variable.

DESCRIPTIVE QUESTIONS

1. What is signal conditioning and why it is required? Draw the block diagram of a DC signal conditioning system and explain the functions of each block.
2. Draw the block diagram of a AC signal conditioning system and explain its working.

   (Nagpur University, Summer 2008, Winter 2009)
3. Draw the block diagram of a AC signal conditioning system and explain function of each block.

   (Nagpur University, Summer 2010)
4. Explain ADC converter.
5. What is sample and hold circuit?
6. What is transmitter?
7. Explain the two-wire transmitter.
8. Explain AC and DC signal conditioning system with help of block diagram.

   (Nagpur University, Winter 2008)
9. Explain the working of 4-20 mA current loop converter.

   (Nagpur University, Winter 2008)
10. Explain the reason for using 4-29 mA current loop in the 2-wire transmitter.
11. Draw neat diagram of instrumentation amplifier and derive its gain equation.

    (Nagpur University, Summer 2010, Winter 2008, Summer 2008)
12. Derive gain equation of instrumentation amplifier and explain its importance features.

    (Nagpur University, Summer 2011)
13. What is signal conditioning and why is it required?

Chapter 14

Transducers for Measurement of Electrical Quantities

Outline

Objectives

After completing this chapter, you should be able to:

- Understand the transducers.
- Know the various types of transducers.
- Explain the inductive and capacitive transducers.
- Understand the opto-electronics transducers.

14.1 Introduction

We need an instrument to sense the wide ranges of different non-electrical energy forms such as movement, electrical signals, radiant energy, thermal or magnetic energy etc. The input quantity of the most instruments is a non-electrical quantity. To use electrical method and techniques for measurement we have to convert non-electrical energy into electrical energy. A device that converts non-electrical energy into electrical energy is known as transducers.

14.2 Transducer

Transducer is a device that converts one type of energy into one type of energy into other type for the purpose of measurement or transfer of information. For example, a microphone as an input device converts sound waves into electrical signals for the amplifier to amplify, and a loudspeaker as an output device converts the electrical signals back into sound waves as shown in Fig. 14.1.

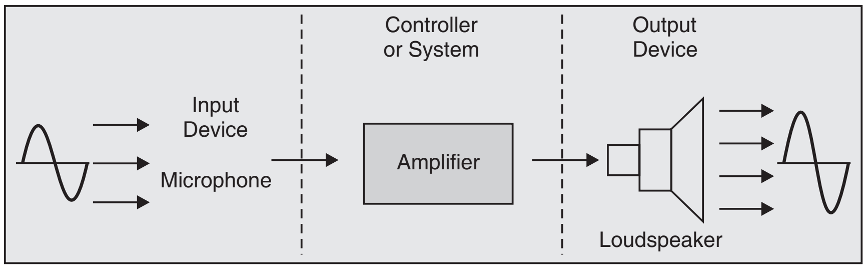


Fig. 14.1.

14.3 Classification of Transducer

The classification of transducers may be explained as follows:

1. Based on the physical phenomenon
   (*a*) Primary transducer
   (*b*) Secondary transducer

On the basis of application transducer may be classified as primary and secondary transducer. When the input signal is directly sense by the transducer, the non-electrical energy is converted into electrical energy directly then, this type of transducer is known as primary transducer. For example thermistor, senses the temperature directly and causes the change in resistance with the change in temperature.

When the input signal is first sensed by some sensor or detector, then its output signal is feed to the other instrument as an input. The output of this instrument is given as the input of transducer for converting into electrical energy. This type of transducer is in secondary transducer classification. For example in the case of pressure measurement, we use bourdon tube to convert pressure into displacement, then the pressure is converter into output voltage with the help of LVDT. Here the secondary transducer is LVDT. We will discuss the bourdon tube and LVDT in this chapter.

2. Based on the power type
   (*a*) Active transducer
   (*b*) Passive transducer

Active transducer does not require any auxiliary power source to produce their output. It is also called self generating type transducer.

Active and Passive Transducers

Active transducer is also known as self generating type transducer. It develops their own voltage or current from the physical phenomenon being measured. Active transducers generate electric current or voltage directly in response to environmental stimulation. Examples of active transducers are thermocouples and piezoelectric accelerometers. Thermocouples produce a voltage related to a temperature of two metals and if the two junctions are at different temperatures, electricity is generated.

Passive transducers is also known as externally powered transducers. It derive the power required for energy conversion from an external power source. Passive transducers produce a change in some passive electrical quantity, such as capacitance, resistance, or inductance, as a result of stimulation. These usually require additional electrical energy for excitation. A simple example of a passive transducer is a device containing a length of wire and a moving contact touching the wire. The position of the contact determines the effective length of the wire, varying the resistance of the length of wire. Other examples of passive transducers are strain gauges, resistance temperature detectors (RTDs), and thermistors.

3. Based on the type of output
- (*a*) Analog transducer
- (*b*) Digital transducer

4. Based on the electrical phenomenon
- (*a*) Resistive transducer
- (*b*) Capacitive transducer
- (*c*) Inductive transducer
- (*d*) Photoelectric transducer
- (*e*) Photovoltaic transducer

5. Based on the non-electrical phenomenon
- (*a*) Linear displacement
- (*b*) Rotary displacement

6. Based on the transduction phenomenon,
- (*a*) Transducer
- (*b*) Inverse transducer.

14.4 Requirements of a Good Transducers

Following are the key requirements for good transducers:
- (*a*) Smaller in size and weight.
- (*b*) High sensitivity.
- (*c*) Ability to withstand environmental conditions.
- (*d*) Low cost.

14.5 Characteristics of Transducer

A known values of the measured (input) are applied to a sensor (measurement system) for the purpose of observing the sensor (system) output. The main characteristics of transducer are given below:

1. **Sensitivity.** It can be defined as the ratio of the *incremental output* and the *incremental input*. While defining the sensitivity, we assume that the input-output characteristic of the instrument is approximately linear in that range.
2. **Range.** The range of the sensor is the maximum and minimum values of applied parameter that can be measured.
3. **Precision.** The concept of precision refers to the degree of *reproducibility* of a measurement. In other words, if exactly the same value were measured a number of times, an ideal sensor would output exactly the same value every time. But real sensors output a range of values distributed in some manner relative to the actual correct value.
4. **Resolution.** The smallest difference between measured values that can be discriminated. For example, it correspond to the last stable figure on a digital display. This specification is the smallest detectable incremental change of input parameter that can be detected in the output signal. Resolution can be expressed either as a proportion of the reading (or the full-scale reading) or in absolute terms.

5. **Accuracy.** The accuracy of the sensor is the maximum difference that will exist between the actual value and the indicated value at the output of the sensor. Again, the accuracy can be expressed either as a percentage of full scale or in absolute terms.

6. **Linearity.** The linearity of the transducer is an expression of the extent to which the actual measured curve of a sensor departs from the ideal curve. Fig. 14.2 shows a somewhat exaggerated relationship between the ideal, or least squares fit, line and the actual measured or *calibration* line. Linearity is often specified in terms of *percentage of non-linearity*, which is defined as,

$$\text{Non-linearity (\%)} = \frac{\text{Maximum input deviation}}{\text{Maximum full scale input}} \times 100$$

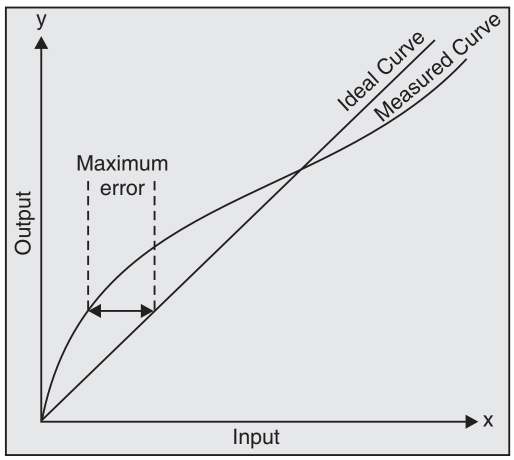


Fig. 14.2.

7. **Hysteresis.** Hysteresis exists not only in magnetic circuits, but in instruments also. For example, the deflection of a diaphragm type pressure gage may be different for the same pressure, but one for increasing and other for decreasing, A transducer should be capable of following the changes of the input parameter regardless of which direction the change is made, hysteresis is the measure of this property. Fig. 14.3 shows a typical hysteresis curve.

$$\text{Hysteresis} = \frac{H}{O_{max} - O_{min}} \times 100$$

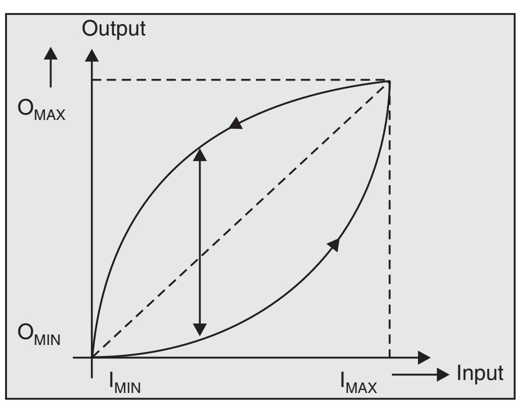


Fig. 14.3.

14.6 Selection of Transducer

Following are the factors which need to be considered while selecting a transducer

1. High input impedance and low output impedance, to avoid loading effect.
2. Good resolution over is entire selected range.
3. Highly sensitive to desired signal and insensitive to unwanted signal.
4. Preferably small in size.
5. High degree of accuracy and repeatability.
6. Selected transducer must be free from errors.

14.7 Strain Gauge

Strain is expressed as the ratio of total deformation to the initial dimension of the material body in which the forces are being applied. Mathematically, strain,

$$e = \frac{\Delta L}{L} = \frac{l - L}{L}$$

where L = the original length of the material body

l = Final length and

ΔL = Change in length.

A strain gauge is a device used to measure the strain of an object. It consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor.

The most popular electrical elements used in force measurements include the resistance strain gage, the semiconductor strain gage, and piezoelectric transducers. The strain gage measures force indirectly by measuring the deflection it produces in a calibrated carrier. Pressure can be converted into a force using an appropriate transducer, and strain gage techniques can then be used to measure pressure. Flow rates can be measured using differential pressure measurements which also make use of strain gage technology.

The change in the value of resistance by straining the gauge may be partly explained by elastic material. Figure 14.4 shows a strip of elastic material, if the tension is applied, if longitudinal dimension will increase while there will be a reduction in the lateral dimension. When its positive strain, its length increase while its area of cross-section decreases.

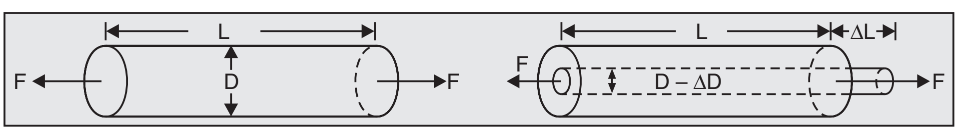


Fig. 14.4.

The resistance of the conductor is proportional to its length and inversely proportional to its area of cross-section. The resistance of the gauge increase with positive strain.

Let us consider a strain gauge made of circular wire. The wire has a resistivity ρ, the resistance of unstrained gauge,

$$R = \rho \frac{L}{A}$$

where L = length of conductor

A = area of conductor

Lets the tensile stress is applied to the wire. The length is increase and area is decrease as shown in Fig. 14.4.

Lets differentiate the R with respect to stress S, we get,

$$\frac{dR}{dS} = \frac{\rho}{A}\frac{\partial L}{\partial S} - \frac{\rho L}{A^2}\frac{\partial A}{\partial S} + \frac{L}{A}\frac{\partial \rho}{\partial S}$$

Let divide the above equation with $R = \rho\frac{L}{A}$,

$$\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{1}{A}\frac{\partial A}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S} \qquad ...(i)$$

From the above equation we see that the per unit change in resistance is due to per unit change in length, per unit change in area and per unit change in resistivity.

$$A = \frac{\pi}{4}D^2$$

$$\frac{\partial A}{\partial S} = 2.\frac{\pi}{4}D.\frac{\partial D}{\partial S}$$

$$\frac{1}{A}\frac{\partial A}{\partial S} = \frac{(2\pi/4)\,D}{(\pi/4)\,D^2}.\frac{\partial D}{\partial S}$$

$$= \frac{2}{D}.\frac{\partial D}{\partial S}$$

Substituting the above value in equation (i) we get,

$$\frac{1}{R}\frac{dR}{dS} = \frac{1}{L}\frac{\partial L}{\partial S} - \frac{2}{D}\frac{\partial D}{\partial S} + \frac{1}{\rho}\frac{\partial \rho}{\partial S} \qquad ...(ii)$$

The Possion's ratio is given by

$$v = \frac{\text{lateral strain}}{\text{longitudinal strain}}$$

$$= -\frac{\partial D/D}{\partial L/L}$$

$$\frac{\partial D}{D} = -v \times \frac{\partial L}{L}$$

Substituting the value of $\frac{\partial D}{D}$ in equation (ii) we get,

$$\frac{\Delta R}{R} = \frac{\Delta L}{L} + 2v\frac{\Delta L}{L} + \frac{\Delta \rho}{\rho}$$

The gauge factor of material is defined as the ratio of per unit change in resistance to per unit change in length.

$$\text{Gauge factor} = G_f = \frac{\Delta R/R}{\Delta L/L}$$

$$\frac{\Delta R}{R} = G_f\frac{\Delta L}{L}$$

$$= G_f \times \in$$

where $\in$ = strain = $\frac{\Delta L}{L}$

The Poisson's ratio of all metals is between 0 and 0.5.

Example 14.1. *A thin wire of soft iron has a gauge factor of 3.5. Determine the Passion's ratio of the soft iron.*

Solution. Given: $G_f = 3.5$.

We know that the Passion's ratio,

$$v = \frac{G_f - 1}{2} = \frac{3.5 - 1}{2} = 1.25 \textbf{ Ans.}$$

Example 14.2. *A resistance wire strain gauge uses a soft iron wire of small diameter. The gauge factor is ± 4.2. Neglecting the piezoresistive effects, calculate the Poisson's ratio.*

Solution. Given: $G_f = 4.2$.

We know that,

$$G_f = 1 + 2v$$

$$v = \frac{G_f - 1}{2} = \frac{4.2 - 1}{2} = 1.6 \textbf{ Ans.}$$

Example 14.3. *A resistance, wire strain gauge with a gauge factor of 2 is bonded to a steel structural member subjected to a stress of 100 MN/m*^{2}*. The modulus of elasticity of steel is 200 GN/m2. Calculate the percentage in value of the gauge resistance due to the applied stress. Comment upto the results.*

Solution. Given: $s = 100$ MN/m^2; $E = 200$ GN/m^2 and $G_f = 2$.

We know that,

$$\in = \frac{s}{E} = \frac{100 \times 10^6}{200 \times 10^9} = 500 \times 10^{-6} = 500 \text{ microstrain}$$

We also know that,

$$\frac{\Delta R}{R} = G_f \in = 2 \times (500 \times 10^{-6}) = 0.001 = 0.1\% \textbf{ Ans.}$$

14.8 Electrical Resistance Strain Gauge

In an electrical resistance strain gauge the device consists of a thin wire placed on a flexible paper tissue and is attached to a variety of materials to measure the strain of the material. The gauge position will be in such a manner that the gauge wires are aligned across the direction of the strain to be measured. When a force is applied on the wire, there occurs a strain that increases the length and decreases its area. Thus, the resistance of the wire changes. This change in resistance is proportional to the strain and is measured using a Wheatstone bridge. There are three different ways of connecting strain gauge in bridge circuit they are given below:

1. Full Bridge

Figure 14.5 shows a full bridge circuit. It has all four of its gauges active. A full bridge circuit is used in applications where complimentary pair of strain gauges is to be bounded to the test specimen. A full bridge circuit is said to be more linear than other circuits.

2. Half Bridge

Figure 14.6 shows a half bridge. It has two of its gauges active and thus uses two precise value resistors. A half-bridge configuration is one where two strain gauges are mounted on opposite surface of the test specimen with one in stretched strain and the other as compressed strain. The other two are dummy resistance that experience no strain and are temperature insensitive Therefore, the effects of temperature change will be cancelled, and the circuit will suffer minimal temperature-induced error.

3. Quarter Bridge

Figure 14.7 shows a quarter bridge. It has only one gauge and the rest of the resistors will be precise in value. The bonding is difficult in a quarter bridge circuits. It is mostly used for strain gauge measurements.

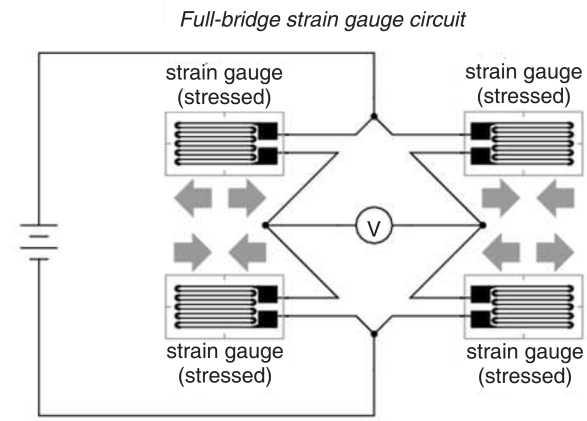


Fig. 14.5.

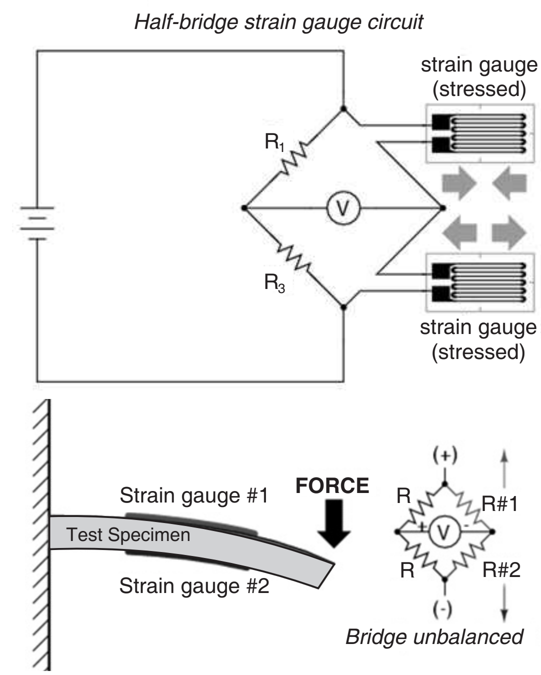


Fig. 14.6.

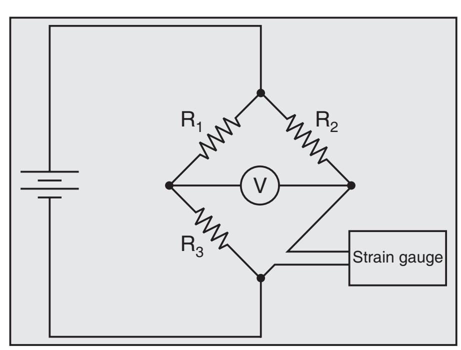


Fig. 14.7.

In practice a half bridge and full bridge circuit has more sensitivity than the quarter bridge circuit. The strain gauges are used for measurement of strain and stress.

14.9 Types of Wire Strain Gauge

There are two type of wire strain gauges:

(*i*) unbonded metal strain gauge and

(*ii*) bonded strain gauge.

1. Unbonded Metal Strain Gauge

The unbonded metallic strain gauge is based on the principle that the electrical resistance of a metallic wire changes due to the change in the tension of the wire. This type of strain gauge consists of a stationary frame and a movable platform. Relative motion between the platform and the frame increases the tension in two loops, while decreasing tension in the other two loops. These four elements are connected approximately to a four arm Wheatstone bridge. These type of strain gauges are used for measurement of acceleration, pressure, force etc.

Figure 14.8 shows the unbonded metal strain gauge. It consists of stretch wire between two points in an insulating medium such as air, and a stationary frame with an armature supported at centre of the frame. The armature can move only in one direction. It travels in that direction and is limited by four filaments of strain sensitive wires. The wire made up of copper, nickel, chrome nickel or nickel iron alloys.

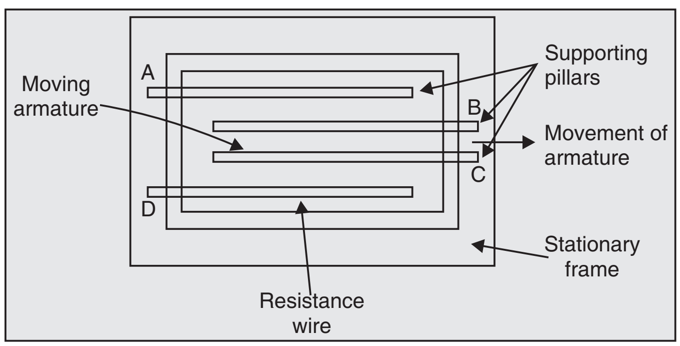


Fig. 14.8.

2. Bonded Strain Gauge

Bonded strain gauge is connected to a paper or a thick plastic film support. The measuring leads are soldered or welded to the gauge wire. The bonded strain gauge with the paper backing is connected to the elastic member whose strain is to be measured. Bonded strain gauges are of two type wire type or a foil type they are explained below:

(i) Bonded Metal Wire Strain Gauge

The bonded metallic type of strain gauge consists of a strain sensitive conductor (wire) mounted on a small piece of paper or plastic backing. In us this gauge is cemented to the surface of the structural member to be tested. The wire grid may be flat type or wrap-around. In the flat type after attaching the lead wires to the ends of the grids, a second piece of paper is cemented over the wire as cover. In the wrap-around type, the wire is wound around a cylindrical core in the form of a close wound helix. This core is then flattened & cemented between layers of paper for the purpose of protection and insulation. Formerly only wrap-around gauges were available, but generally flat grid gauges are preferred as they are superior to wrap-around gauge in terms of hysterisis, creep, elevated temperature, performance, stability & current carrying capacity.

Figure 14.9 shows the bonded metal wire strain gauge. It consists of grid of a resistive element which is cemented to the base which may be thin sheet of paper. A thin sheet made up of Bakelite or Teflon. It used for both stress analysis and for construction of transducers. The spreading of wire permits a uniform distribution of stress over the grid.

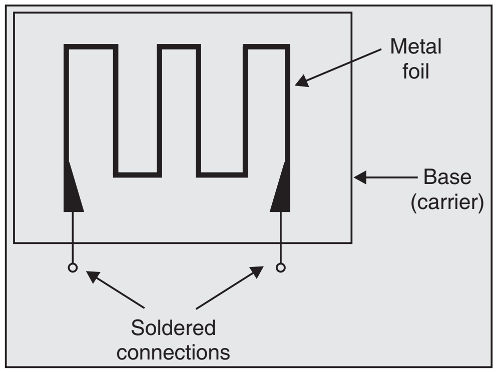


Fig. 14.9.

(ii) Bonded Metal Foil Strain Gauge

This is the extension of the bonded metal wire strain gauges. In this the strain is detected using metal foil. The metal and alloys used for the foil and wire are nichrome, constantan, isoelastic, nickel and platinum. Fig. 14.10 show the construction of strain gages. The fine-wire strain gages are used for special purposes, such as at high temperatures. Foil strain gages are usually made by a printed-circuit process. Since the foil used in a strain gage must be very fine or thin to have a sufficiently high electrical resistance. Some foil use has been made of wire filaments in strain gages, but this type of gage is seldom used except in special or high temperature applications. In order to handle this foil, it must be provided with a carrier medium or backing material, usually a piece of paper, plastic, or epoxy. The backing material performs another very important function in addition to providing ease of handling and simplicity of application. The cement provides so much lateral resistance to the foil that it can be shortened significantly without buckling; then compressive as well as tensile strains can be measured. Lead wires or connection terminals are often provided on foil gages A protective coating, recommended or supplied by the manufacturer, is usually applied over the strain gage, especially where the lead wires are attached.

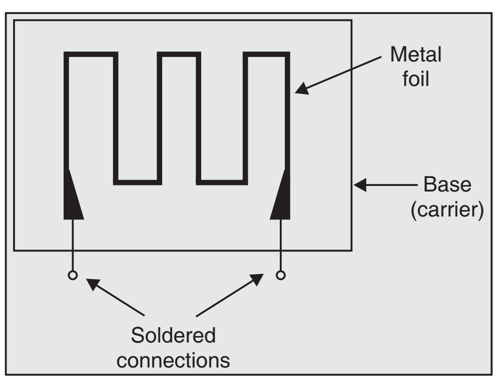


Fig 14.10.

Figure 14.10 shows the foil strain gauge, it made up of thinner than comparable wire units. Also they are more flexible. The foil can be mounted in remote and restricted places and especially on curved surface.

14.10 Resistive Transducers

In such material the resistances of the transducer get varied according to the measured. The resistance of any metal conductor is expressed by a simple equation,

$$R = \rho \frac{L}{A}$$

where, L = length of the conductor

A = Cross Section area of the conductor

ρ = resitivity of conductor

From the above equation we see that the resistance of the material depends on L, A and ρ. Any method of varying one of the quantities involved in the above relationship can be the design basic of electrical resistive transducer.

14.11 Inductive Transducers

The inductive transducers work on the principle of the magnetic induction of magnetic material. The induction of the magnetic material depends on a number of variables like the number of turns of the coil on the material, the size of the magnetic material, and the permeability of the flux path. In the inductive transducers the magnetic materials are used in the flux path and there are one or more air gaps. The change in the air gap also results in change in the inductance of the circuit and in most of the inductive transducers it is used for the working of the instrument. There are two type of inductive transducers, they are given below:

1. Linear Variable Differential Transformer
2. Rotary Variable Differential Transformer

We will discuss each transducer one by one in the following pages.

14.12 Linear Variable Differential Transformer

Linear Variable Differential Transformer (LVDT) is an inductive type position sensor which works on the same principle as the AC transformer that is used to measure movement. It is a very accurate device for measuring linear displacement and whose output is proportional to the position of its moveable core.

It basically consists of three coils wound on a hollow tube former, one forming the primary coil and the other two coils forming identical secondaries connected electrically together in series but 180° out of phase either side of the primary coil. A moveable soft iron ferromagnetic core which is connected to the object being measured, slides or moves up and down inside the tube. A small AC reference voltage called the "excitation signal" is applied to the primary winding which in turn induces an EMF signal into the two adjacent secondary windings.

Figure 14.11 show that if the soft iron magnetic core armature is exactly in the centre of the tube and the windings the null position indicate. The two induced emf in the two secondary windings cancel each other out as they are 180° out of phase, so the resultant output voltage is zero. As the core is displaced slightly to one side or the other from this null or zero position this the induced voltage in one of the secondaries will be become greater than that of the other secondary and an output will be produced. The polarity of the output signal depends upon the direction and displacement of the moving core. The greater the movement of the soft iron core from its central null position the greater will be the resulting output signal. The result is a differential voltage output which varies linearly with the core position. Therefore, the output signal has both an amplitude that is a linear function of the cores displacement and a polarity that indicates direction of movement. The differential output voltage is given by,

$$E_0 = E_{S_1} - E_{S_2}$$

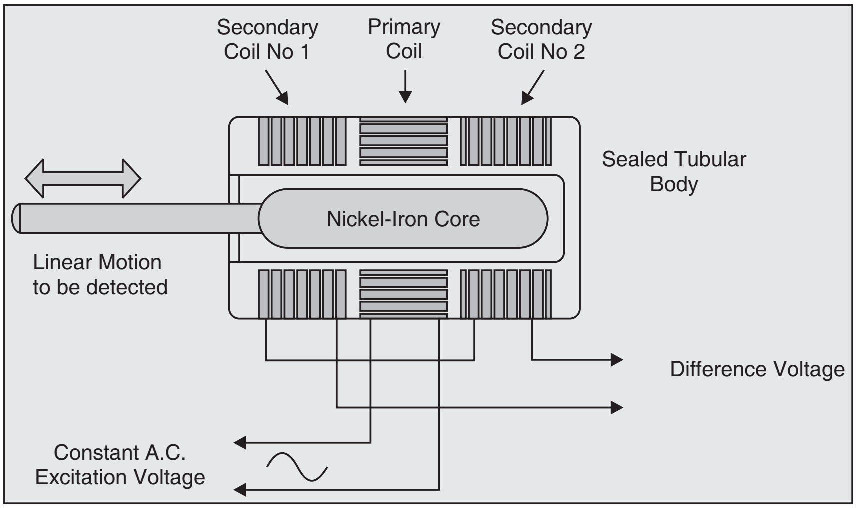


Fig. 14.11.

Example 14.4. *An LVDT produces an rms output voltage of 2.6 V for displacement of 0.4 μm. Calculate the sensitivity of LVDT.*

Solution: Given V_{rms} = 2.6 V and displacement = 0.4 μm.

We know that the sensitivity is given by,

$$\text{Sensitivity} = \frac{V_{rms}}{\text{Displacement}}$$

$$= \frac{2.6}{0.4} = 6.5 \text{ V/}\mu\text{m} \textbf{ Ans.}$$

Example 14.5. *An LVDT has a secondary voltage of 5.0 V for a displacement of ± 12.5 mm. Determine the output voltage for a core displacement of 8.0 mm from its central position.*

Solution: Given: V_S = 5.0 V; displacement = ± 12.6 mm and displacement from its central position = 8.0 mm.

We know that the sensitivity,

$$S = \frac{V_S}{\text{Displacement}}$$

$$= \frac{5}{12.5} = 0.4 \text{ V/mm}$$

The output voltage for a core displacement of 8.0 mm is

$$= S \times 8.0$$

$$= 3.2 \text{ V } \textbf{Ans.}$$

14.13 Rotary Variable Differential Transformer

Figure 14.12 shows the circuit diagram of rotary variable differential transformer (RVDT). It is used for measuring angular displacements, and operates in the same manner as a LVDT. The core of this transducer is cylindrical iron core and may be rotated between the windings by means of a shaft.

When the core is in null position the output voltage of secondary winding S_1 and S_2 are equal and opposite. Therefore at this position the net output voltage is zero. If any angular displacement in the core occurs from the null position its changes the differential output voltage. The greater angular displacement the greater will be the differential output voltage.

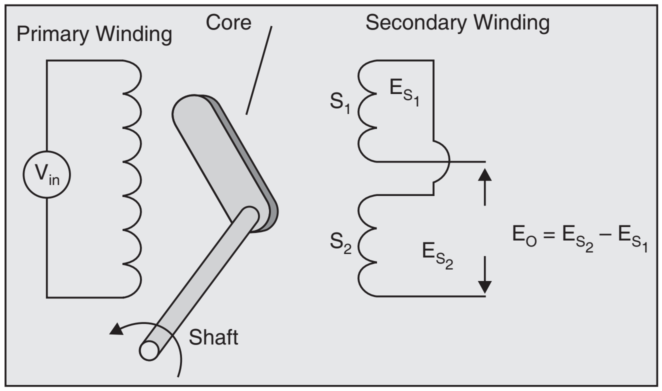


Fig. 14.12.

The clockwise rotation of the core produces an increasing voltage of a secondary winding of one phase while the counter-clockwise rotation produces an increasing voltage of opposite phase.

14.14 Capacitive Transducers

The capacitive transducer is the capacitor with variable capacitance. The capacitive transducer comprises of two parallel metal plates that are separated by the material such as air, which is called as the dielectric material. In the parallel plate capacitor as shown in Fig. 14.13 the distance between the two plates is fixed, but in variable capacitance transducers the distance between the two plates is variable.

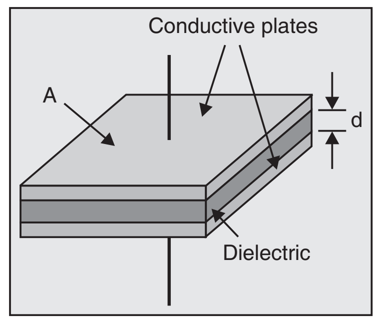


Fig. 14.13.

Value of capacitance is given by,

$$\text{Capacitance} = \in \frac{A}{d}$$

where, A = overlapping area of plate

d = Distance between two plates

$\in$ = permittivity of medium

In the instruments using capacitance transducers the value of the capacitance changes due to change in the value of the input quantity that is to be measured. The capacitive transducer is used extensively for the measurement of displacement, pressure etc.

From the above equation we see that the capacitance of the capacitive transducer depends on the area of the plates and the distance between the plates. The capacitance of the capacitive transducer also changes with the dielectric constant of the dielectric material used in it.

Thus the capacitance of the variable capacitance transducer can change with the change of the dielectric material, change in the area of the plates and the distance between the plates. Depending on the parameter that changes for the capacitive transducers, there are three types of capacitive transducers they are given below:

1. Changing Area of the Plates of Capacitive Transducers

The capacitance of the variable capacitance transducer also changes with the area of the two plates. The capacitance is directly proportion to the area of plates, thus the capacitance changes linearly with change in area of plates. This type of transducer is used for measurement of displacement. Fig. 14.14 show the parallel plate capacitor, in which one plate of the capacitor is fixed while other plate moves according to the displacement apply. The capacitance is given by,

$$C = \in \frac{A}{d} = \in \frac{xw}{d}$$

where x = is the length of overlapping part of plates
w = width of overlapping part of plates

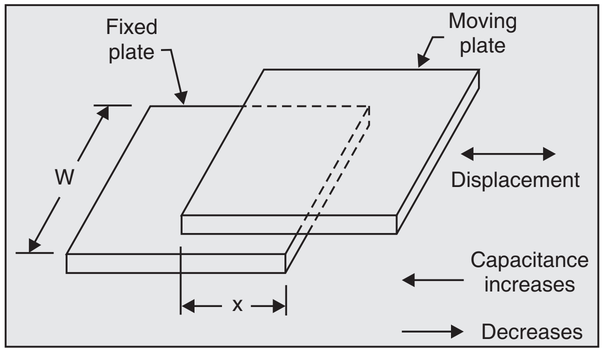


Fig. 14.14.

sensitivity of the transducer is given by,

$$S = \frac{\partial C}{\partial x} = \in \frac{w}{d}$$

From above equation its show that the sensitivity is constant and therefore there is linear relationship between capacitive and displacement. The sensitivity for a fractional change in capacitance,

$$S' = \frac{\partial C}{C\partial x} = \frac{1}{x}$$

This type of capacitance transducer is suitable for measurement of linear displacements.

Figure 14.15 show the cylindrical capacitance. D_2 is the inner diameter of outer cylindrical electrode and D_1 is the outer diameter of inner cylindrical electrode. The capacitance of cylindrical capacitor is given by,

$$C = \frac{2\pi \in x}{\log_e \left(\frac{D_2}{D_1}\right)}$$

and the sensitivity,

$$S = \frac{\partial C}{\partial x} = \frac{2\pi \in}{\log_e \left(\frac{D_2}{D_1}\right)}$$

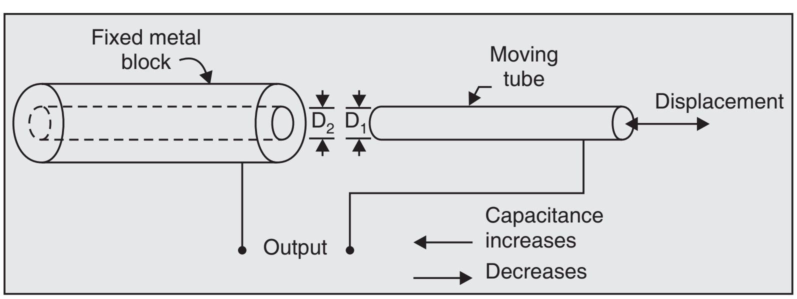


Fig. 14.15.

The sensitivity is constant and the relationship between capacitance and displacement is linear as shown in Fig. 14.16.

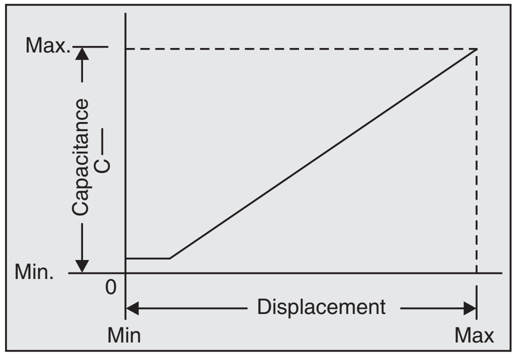


Fig. 14.16.

The principle of change of capacitance with change in area can be employed for measurement of angular displacement. Fig. 14.17 show a two plate capacitor. One plate is fixed and the other is movable. The angular displacement changes the effective area between the plates and thus the capacitance changes. The capacitance is maximum when two plate overlap with each other at angular displacement θ = 180°. Maximum value of capacitance is given by,

$$C = \in \frac{A}{d} = \frac{\pi \in r^2}{2d}$$

Capacitance at angle θ is given by,

$$C = \frac{\pi \, \theta \, r^2}{2d}$$

and sensitivity,

$$S = \frac{\partial C}{\partial \theta} = \frac{\pi \, r^2}{2d}$$

The sensitivity is constant and the relationship between capacitance and angular displacement is linear as shown in Fig. 14.17.

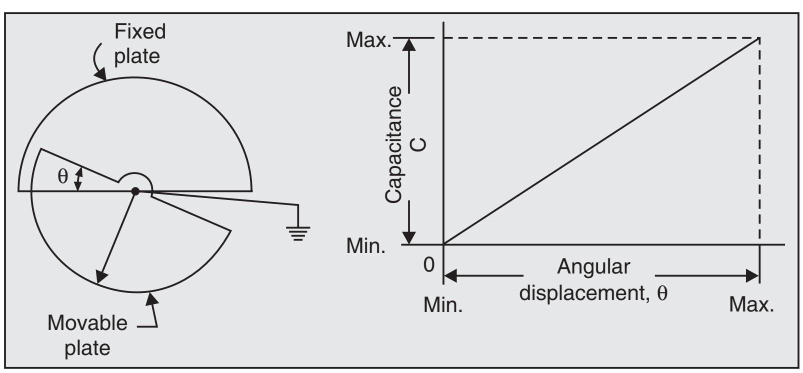


Fig. 14.17.

2. Changing Distance between the Plates of Capacitive Transducers

In these capacitive transducers the distance between the plates is variable, while the area of the plates and the dielectric constant remain constant. This is the most commonly used type of variable capacitance transducer.

Figure 14.18 show that the measurement of the displacement of the object, one plate of the capacitance transducer is kept fixed, while the other is connected to the object. When the object moves, the plate of the capacitance transducer also moves, this results in change in distance between the two plates and the change in the capacitance. The capacitance varies inversely proportional to the distance between the plates. The response of the transducer is not linear as shown in Fig. 14.19.

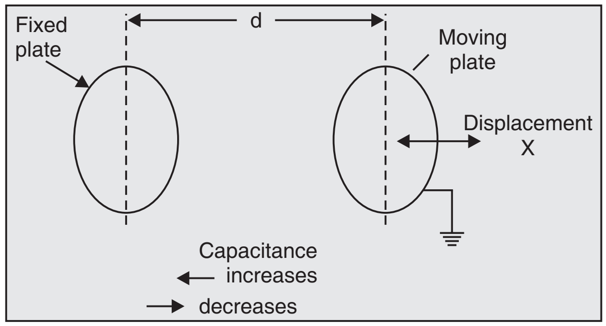


Fig. 14.18.

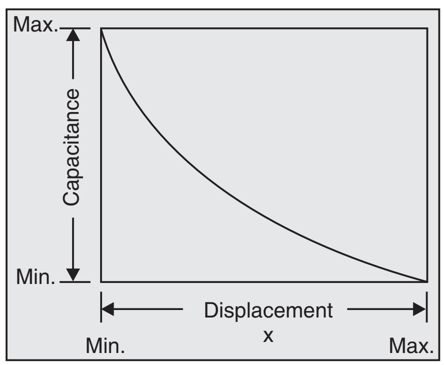


Fig. 14.19.

Sensitivity of the transducer,

$$S = \frac{\partial C}{\partial x} = \frac{\partial C}{\partial x}\left(\in \frac{A}{x}\right) = -\frac{\in A}{x^2}$$

The sensitivity of this transducer is not constant but varies over the range of the transducer. The relationship between capacitance C and the distance between plates x is hyperbolic. This is linear over the small range of displacement.

When the displacement is applied to the cantilever type spring plate. It moves the cantilever plate towards the second plate. The distance between plate decreases, it increases the capacitance of the capacitor. The capacitance of air-dielectric capacitor does not vary linearly with change in distance between the plates. Therefore, this arrangement is fundamentally non-linear. However the linearity can be closely approximated by keeping the change in the distance small or by having a medium of high dielectric constant in the space between the two plates.

3. Changing Dielectric Constant Type of Capacitive Transducers

In this capacitive transducer the dielectric material between the two plates changes, due to which the capacitance of the transducer also changes. When the input quantity to be measured changes the value of the dielectric constant also changes so the capacitance of the instrument changes. This capacitance, calibrated against the input quantity, directly gives the value of the quantity to be measured.

Figure 14.20 shows a capacitive transducer for measurement of linear displacement. It has dielectric of relative permittivity $\in_r$. Initial capacitance of transducer,

$$C = \in_o \frac{wl_1}{d} + \in_o \in_r \frac{wl_2}{d} = \in_o \frac{w}{d}(l_1 + \in_r l_2)$$

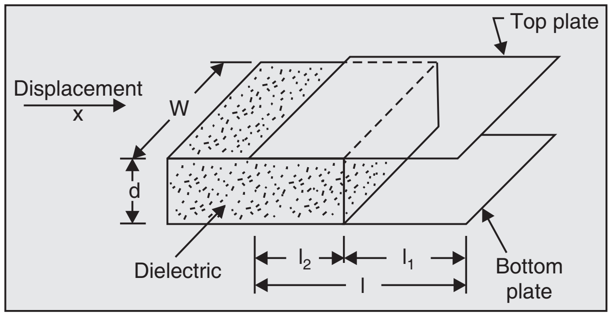


Fig. 14.20.

Lets the dielectric is moved through the distance x in the direction indicated,

$$C + \Delta C = \frac{w}{d}(l_1 - x) + \in_o \in_r \frac{w}{d}(l_2 + x)$$

$$= \in_o \frac{w}{d}[(l_1 - x) + \in_r (l_2 + x)]$$

$$= \in_o \frac{w}{d}(l_1 + \in_r l_2) + \in_o \frac{wx}{d}(\in_r - 1)$$

$$= C + \in_o \frac{wx}{d}(\in_r - 1)$$

Change in the capacitance,

$$\Delta C = \in_o \frac{wx}{d}(\in_r - 1)$$

This transducer is used for measurement of level in the hydrogen container, where the change in level of hydrogen between the two plates results in change of the dielectric constant of the capacitance transducer. Apart from level, this principle can also be used for measurement of humidity and moisture content of the air.

14.15 Advantages of Capacitive Transducer

Some of the main advantages of capacitive transducer are given below:

1. They are very sensitive.
2. Good frequency response.
3. The force requirement of capacitive transducer is very small and therefore it require small power to operate.

14.16 Disadvantage of Capacitive Transducer

The disadvantages of capacitive transducer are given below:

1. The capacitive transducer are temperature sensitive.
2. The instrumentation circuit is very complex.

Example 14.6. *A capacitive transducer using five plates. The dimensions of each plate are 25 × 25 mm and the distance between plates is 0.25 mm. This arrangement is to be used for* *measurement of displacement by observing the change in capacitance with distance x. Calculate the sensitivity of the devise. Assume that the plates are separated by air. The permittivity of air is* 8.85×10^{-12} *F/m.*

Solution. Given: $A = 25 \times 25$ mm; $\in_o = 8.85 \times 10^{-12}$ F/m and $d = 0.25$ mm $= 0.25 \times 10^{-3}$ m.

We know that for five plates transducers forms four capacitors connected in parallel,

$$C = 4C' = \frac{4\in_o (l - x)w}{d}$$

Sensitivity of transducer,

$$\frac{\partial C}{\partial x} = \frac{-4\in_o w}{d} = -\frac{4 \times (8.85 \times 10^{-12}) \times (25 \times 10^{-3})}{0.25 \times 10^{-3}}$$

$$= -3540 \text{ pF/m } \textbf{Ans.}$$

14.17 Piezoelectric Transducers

The piezoelectric transducers work on the principle of piezoelectric effect. When mechanical stress or forces are applied to some materials along certain planes, they produce electric voltage. This electric voltage can be measured easily by the voltage measuring instruments, which can be used to measure the stress or force.

There are certain materials that generate electric potential or voltage when mechanical strain is applied to them or when the voltage is applied to them, they tend to change the dimensions along certain plane. This effect is called as the piezoelectric effect. This effect was discovered in the year 1880 by Pierre and Jacques Curie. Some of the materials that exhibit piezoelectric effect are quartz, Rochelle salt, polarized barium titanate, ammonium dihydrogen, ordinary sugar etc.

The physical quantities like stress and force cannot be measured directly. In such cases the material exhibiting piezoelectric transducers can be used. The stress or the force that has to be measured is applied along certain planes to these materials. The voltage output obtained from these materials due to piezoelectric effect is proportional to the applied stress or force. The output voltage can be calibrated against the applied stress or the force so that the measured value of the output voltage directly gives the value of the applied stress or force.

The piezo-electric effect can be made to response mechanical deformations of the material in many different modes. The modes can be thickness expansion, transverse expansion, thickness shear and face shear. The mode of motion effected depends on the shape of the body relative to the crystal axis and location of the electrodes. The mechanical deformation generates a charge and this charge appears as a voltage across the electrodes.

Figure 14.21 shows the piezo-electric crystal. The magnitude and polarity of the induced surface are proportional to the magnitude and direction of the applied force F. The polarity of induced charge depends upon the direction of applied force. The charge is given by,

$$Q = d \times F$$

where d = charge sensitivity of crystal

F = applied force

Modes of Operation of Piezo-electric Crystals

There are different mode of operation they are given below:

1. Thickness shear
2. Face shear
3. Thickness expansion
4. Transverse Expansion

All these modes are shown in Fig. 14.21.

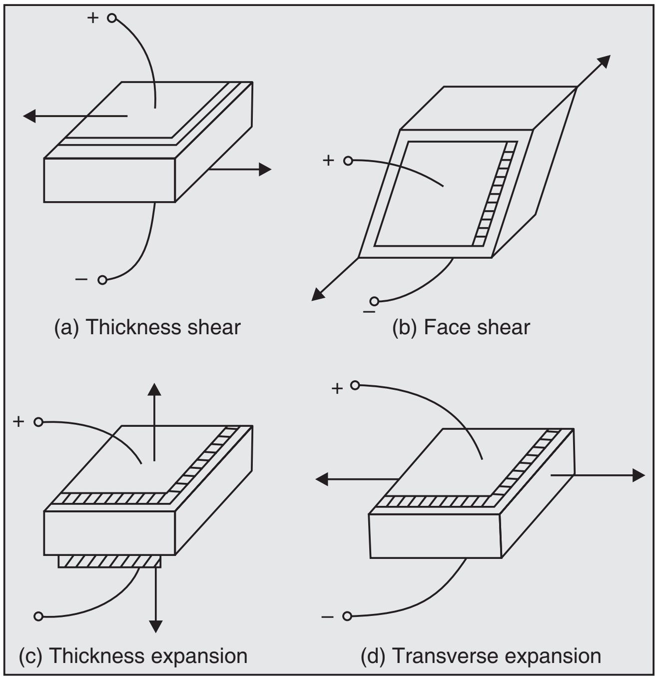


Fig. 14.21.

14.18 Equivalent Circuit of Piezo-electric Transducers

Figure 14.22 shows the piezo-electric transducer. The source is the charge generator. The value of charge is $Q = dF$. The charge generator can be replaced by an equivalent voltage source, it is connected across the capacitor C_P of the crystal and leakage resistance R_P. The voltage is given by,

$$E = \frac{Q}{C_P} = \frac{d \times F}{C_P}$$

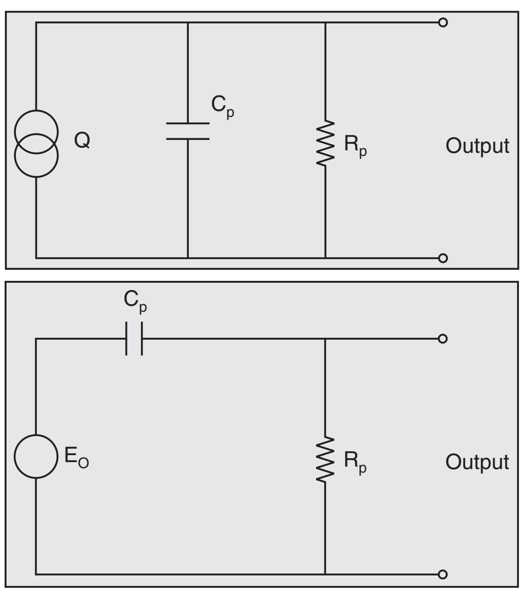


Fig. 14.22.

Application

They are used for quality assurance, process control and for research and development in many different industries.

14.19 Hall Effect Transducer

This transducer works on the principle of Hall Effect. Figure 14.23 show the hall effect element when a current conducting material is placed in the transverse magnetic field then the difference of potential is produced between the opposite edges of the conductor. This effect is known as Hall Effect. The magnitude of the voltage depends upon the current, the strength of magnetic field and the property of the conductor.

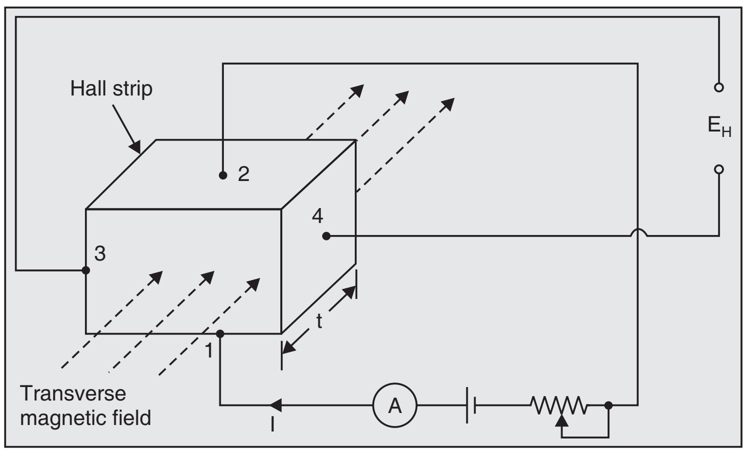


Fig. 14.23.

Let the current pass through edge 1 and 2 of the conductor and the output leads is connected to edge 3 and 4. The edge 3 and 4 are at same potential when there is no transverse magnetic field passing through the conductor. When a transverse magnetic field passing through the conductor, an output voltage appears across the output leads. This output voltage is proportional to the current and the field strength. The output voltage is given by,

$$E_H = \frac{K_H I B}{t}$$

where K_H = Hall effect constant

t = thickness of the conductor

I = current in the circuit

B = Flux density

The voltage produces may be used for measurement of the current I or the magnetic field strength B.

14.20 Application of Hall Effect Transducers

Main applications of the Hall Effect transducers are given below:

1. Magnetic to Electric Transducer

This transducer is used as a magnetic to electrical transducer. A semiconductor plate is inserted into the magnetic field to be measured. The magnetic lines of force are perpendicular to the semiconducting plate. The transducer gives and output voltage which is proportional to the magnetic field density B. Also the element gives out a continuous electric signal in direct response to the magnetic field strength.

2. Measurement of Displacement

The hall effect is used for measurement of the location or displacement of the elements. Fig….. shows in which a ferro-magnetic structure having a permanent magnet. The hall effect transducer is located in the gap adjacent the permanent magnet. The field strength produced in the gap, adjacent to the permanent magnet in the gap, where the hall effect element is located, is varied by changing the position of a ferro-magnetic plate. The output voltage of the hall effect transducer is proportional to the field strength in the gap which is a function of the position of the ferro-magnetic plate from the structure.

3. Measurement of Current

The hall effect transducer used to measure the current in conductor without the need for interrupting the circuit and without making electrical connection between the conductor and the meter. The current pass through the conductor and sets up a magnetic field surrounding the conductor. The magnetic field is proportional to the current.

Example 14.7. *A Hall Effect transducer is used for the measurement of a magnetic field of 0.5 Wb/m^2. The 2 mm thick slab is made of Bismuth for which the hall coefficient is –1 × 10^{-6} Vm and the current is 3 A.*

Solution. Given: $K_H = -1 \times 10^{-6}$ Vm; $I = 3$ A; $B = 0.5$ Wb/m^2 and $t = 2$ mm $= 2 \times 10^{-3}$ m.

We know that,

$$E_H = \frac{K_H BI}{t} = \frac{(-1\times 10^{-6})\times 3\times 0.5}{2\times 10^{-3}}$$

$$= 0.75 \times 10^{-3} \text{ V} = 0.75 \text{ mV } \textbf{Ans.}$$

14.21 Opto-Electronics Transducers

The energy absorption by semiconductor produces movable charges or a change of mobility of the charge carries in the semiconductors. There are following types of opto-electronic transducers, they are given below:

14.22 Photodiodes

A photodiode is a two terminal PN junction device, which *operates in a reverse bias*. It has a transparent window, which allows light to strike the PN junction. Figure 14.24 (*a*) and (*b*) shows structure and schematic symbol of a photodiode. The basic biasing arrangement of a photodiode as shown in Fig. 14.24 (*c*).

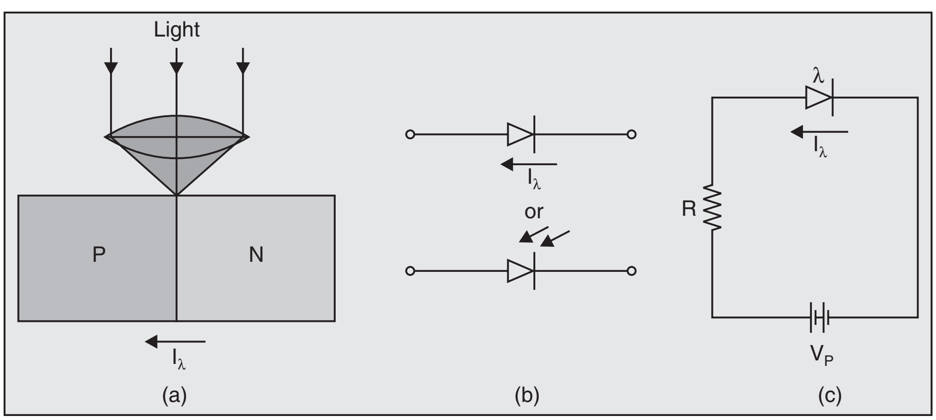


Fig. 14.24. Photodiode

We know that a rectifier diode has a very small reverse-current, when it is reverse biased. The same is true for a photodiode also. The reverse biased current is produced by thermally generated electron-hole pairs in the depletion layer, which are swept across the junction by the electric field created by the reverse voltage. In a rectifier diode, the reverse-current increases with the temperature due to an increase in the number of electron-hole pairs.

A photodiode differs from a rectifier diode in a sense that its reverse current increases with the light intensity at the PN junction. When there is no incident light, the reverse current is almost negligible and is called the dark current. An increase in the amount of light energy produces an increase in the reverse current for a given value of reverse-bias voltage. Figure 14.25 shows the characteristic curves for a typical diode.

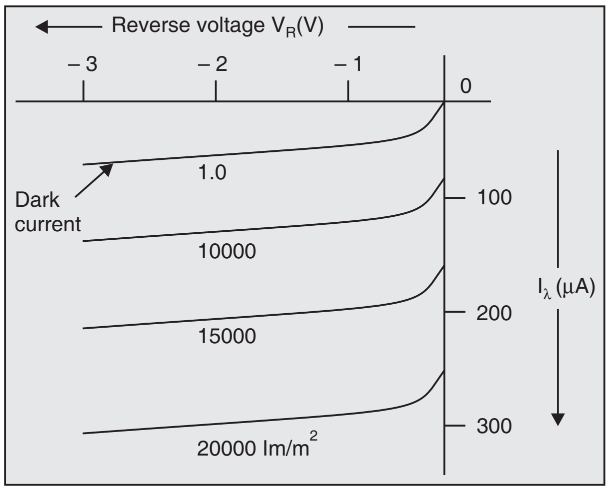


Fig. 14.25. Characteristic curves of a photodiode

It may be noted from the characteristic curve that the dark current, for this particular device, is approximately 250 mA at a reverse bias voltage of 3 V. Therefore, resistance of the device with the incident light,

$$r_R = \frac{3}{25 \times 10^{-6}} = 120\ 000\ \Omega = 120\ \text{k}\Omega$$

At 20 000 lm/m^2, the current is approximately 300 μA at 3 V. The resistance under this condition

$$r_R = \frac{3}{300 \times 10^{-6}} = 10\ 000\ \Omega = 10\ \text{k}\Omega$$

These calculations show that the photodiode can be used as a variable resistance device controlled by light intensity. A photodiode can be used to switch on the current at a very fast rate (in nanosecond). Thus it is one of the fastest photo detectors.

Commercially Available Photodiodes

Figure 14.26 (*a*) through (*b*) shows a variety of photodiodes in different types, shapes and sizes. Photodiode shown in (*a*) is a general purpose photodiode. It is suitable for applications in modulated light detectors, hight-speed punched card readers etc. The photodiode shown find its application in analytical and medical instrumentation, smoke detectors and photographic passing. The photodiode shown in (*c*) is ideal for low light level applications where a hight signal-speed ratio is needed such as light monitoring and control circuit. The photodiode shown in (*d*) has signal high gain low noise amplifier housed in a lensed housing TO5 package. The lens increases signal to noise ratio making it ideal for electrically noisy environments. The applications for this include instrumentation, photometry and light monitoring.

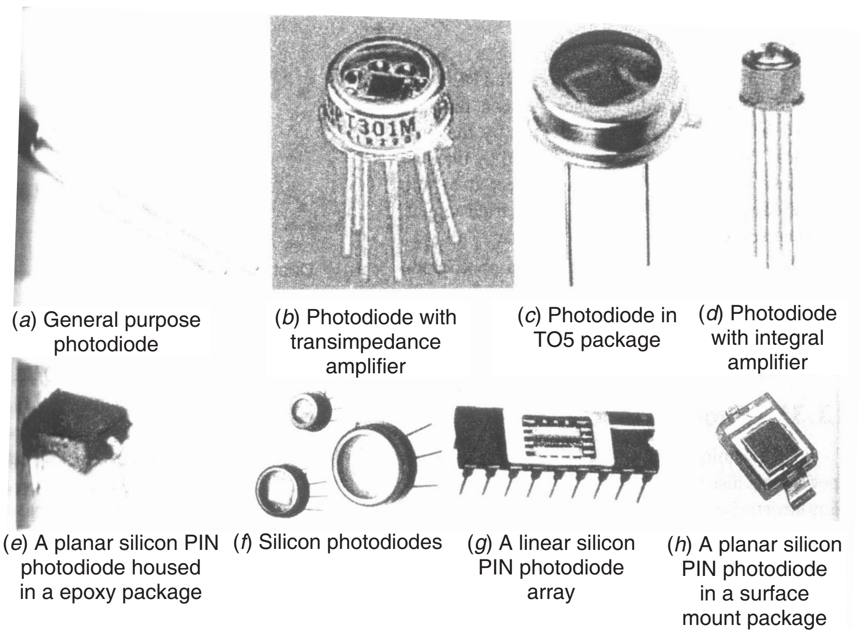


Fig. 14.26. Photodiodes of different shapes and sizes.

The photodiode shown in (*e*) is 7 mm^2 planar silicon PIN photodiode housed in a two pin epoxy package with a integral daylight cut-off filter. The device is a low noise, high speed and operates over a wide temperature range. The applications for this photodiode include remote controls, light curtains, data transmission and measurement and control. The photodiodes shown in (*f*) are silicon photodiodes deal for use in general photometric applications. Both these devices have integral colour correction alter. The device shown in (*g*) is a 16-element linear silicon PIN photodiode array housed in a ceramic dual in-line (DIL) package. This high speed device consists of 16 individual elements arranged on a mm pitch in common cathode configuration. This array is ideal for linear position sensing, wide temperature detection and edge and hole detection in strip materials. The device shown in (*h*) is a 7 mm^2 planar silicon PIN photodiode housed in a surface mount package. The application of this device are the same as that of the photodiode shown in (*e*), i.e., in remote controls, light curtains, data transmission and measurement and control.

14.23 Photodiode Applications

Some of the important applications of a photodiode are as follows:

1. Photo detection (Both visible and invisible)
2. Demodulation
3. Logic circuits
4. Switching
5. Optical communication systems
6. Character recognition
7. Encoders etc.

14.24 Dust Sensor

Figure 14.27 shows a combination of an LED and a photodiode used as a dust sensor. As seen, the light emitted from the LED gets reflected by the dust particles. The reflected light is collected by the dust particles. The reflected light is collected by the photodiode and is converted into an electrical signal. The dust sensor is employed in cleaners.

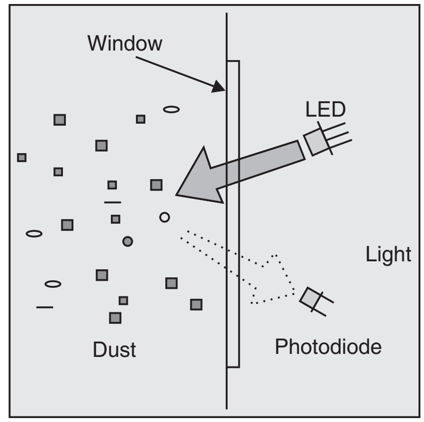


Fig. 14.27.

The combination of an LED and a photodiode is also used as : (1) a paper sensor in facsimile machines, (2) as a tape-end sensor in videotape recorders/players, and (3) as a dirt detector for rinsing in washing machines.

14.25 Photoconductive Cell

It is a semiconductor device whose resistance varies inversely with the intensity of light falls upon it. It is also known as *photoresistive* cell or *photoresistor* because it operates on the principle of photoresistivity.

The resistivity (and, hence, resistance) of a semiconductor depends on the number of free charge carriers available in it. When the semiconductor is not illuminated, the number of charge carriers is small and, hence, resistivity is high. But when light in the form of photons strikes the semiconductor each photon delivers energy to it. If the photon energy is greater than the energy band gap of the semiconductor, free mobile charge carriers are liberated and, as a result, resistivity of the semiconductor is decreased.

Photoconductive cells are generally made of cadmium compounds such as cadmium sulphide (CdS) and cadmium selenide (CdSe). Spectral response of CdS cell is similar to the human eye, hence such cells are often used to simulate the human eye. That is why they find use in light metering circuits in photographic cameras.

The construction of a typical photoconductive cell and its two alternative circuit symbols are shown in Fig. 14.28 (*a*) and (*b*) respectively. As seen, a thin layer of photosensitive semiconductor material is deposited in the form of a long strip zig-zagged across a disc-shaped ceramic base with protective sides. For added protection, a glass lens or plastic cover is used. The two ends of the strip are bought out to connecting pins below the base.

The terminal characteristic of a photoconductive cells is shown in Fig. 14.29. It depicts how the resistance of the cell varies with light intensity. Typically, the dark resistance of the cells is 1 MΩ or larger. Under illumination, the cell resistance drops in a value between 1 and 100 kΩ depending a surface illumination.

A photoconductive cell is an expensive and simple detector which is widely used in OFF/ON circuits, light-measurement and light-detecting circuits.

Example 14.8. *A relay is controlled by a photoconductive cell which has resistance of 100 kΩ when illuminated and 1 kΩ when at the dark. The realy is supplied with 10 mA from a 30-V supply when cell is in illuminated and is required to be de-energized when the cell is in the dark sketch a suitable circuit and calculate the required series resistance and value of dark current.*

(Optoelectronic Devices, Gujarat Univ. 1993)

Solution: The circuit is as shown in Fig. 14.30 where R is a current-limiting resistor.

The current through the circuit,

$$I = \frac{30}{R + r}$$

where 'R' is the series resistance and 'r' is the cell resistance. Rearranging the equation (i),

$$R = \left(\frac{30}{I} - r\right)$$

When illuminated, from equation (ii),

$$R = \left(\frac{30}{10 \times 10^{-3}} - (1 \times 10^3)\right) = 2 \times 10^3\ \Omega = 2\ \text{k}\Omega\ \textbf{Ans.}$$

From equation (i), the dark current,

$$I_d = \frac{30}{\left((2 \times 10^3) + (100 \times 10^3)\right)} = 0.3 \times 10^{-3}\ \text{A or } 0.3\ \text{mA}\ \textbf{Ans.}$$

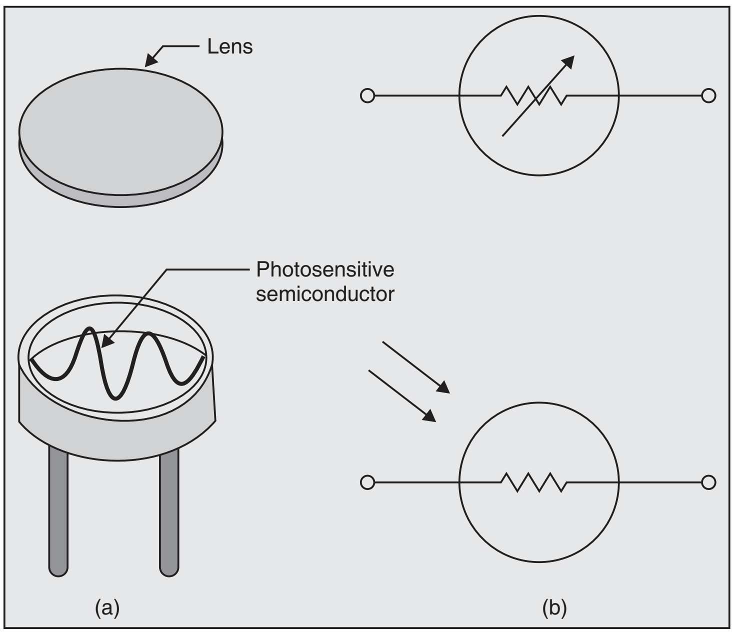


Fig. 14.28.

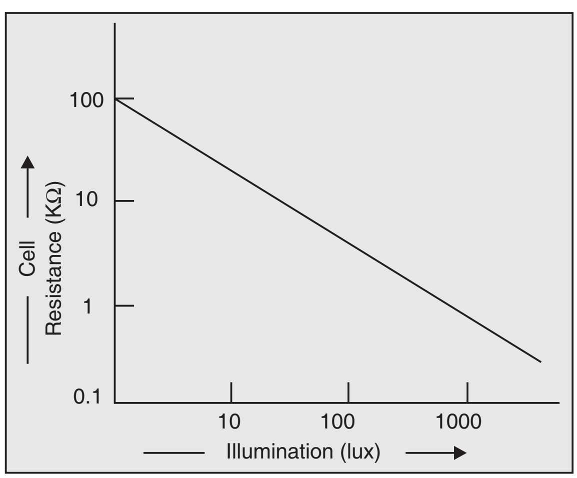


Fig. 14.29.

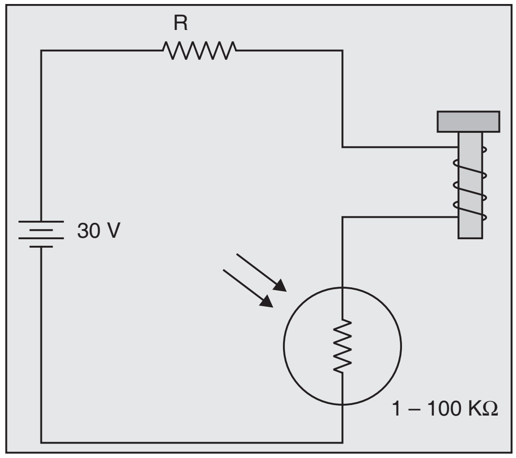


Fig. 14.30.

14.26 Photovoltaic or Solar Cell

Such cells operate on the principle of photovoltaic action i.e. conversion of light energy into electrical energy. This action occurs in all semiconductors which are constructed to absorb energy.

As shown in Fig. 14.31 (*a*), a basic solar cell consists of *P*-type and *N*-type semiconductor material (usually, silicon or selenium) forming a *P*-*N* junction. The bottom surface of the cell (which is always away from light) covered with a continuous conductive contact to which a wire lead to attached. The upper surface has a maximum area exposed to light with a small contact either along the edge or around the perimeter. The surface layer of *P*-type material is extremely thin (0.5 mm) so that light can penetrate to the junction.

Although silicon is commonly used for fabricating solar cells, another construction consists of *P*-type selenium covered with a layer of *N*-type cadmium oxide *P*-*N* junction as shown in Fig. 14.31 (*b*). Two alternative circuit symbols are shown in Fig. 14.31 (*c*). Power solar cells are also fabricated in flat strips to form efficient coverage of available surface area. Incidentally, the maximum efficiency of a solar cell in converting sunlight into electrical energy is nearly 15 per cent at the present.

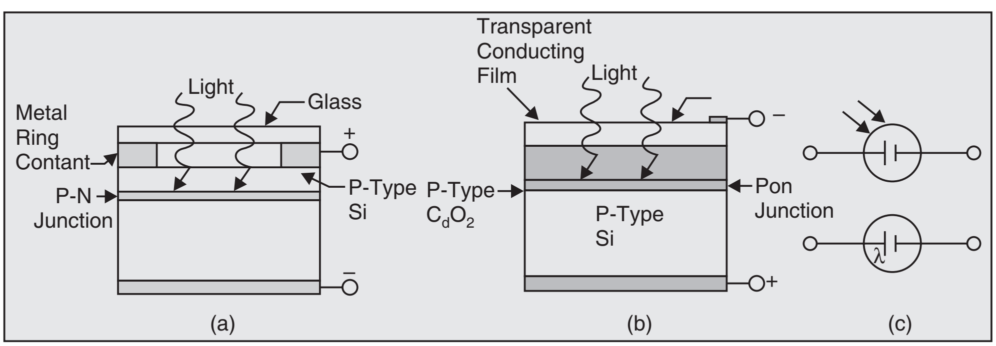


Fig. 14.31.

When the *P*-*N* junction of a solar cell is illuminated, electron-hole pairs are generated in much the same way, as in photovoltaic cell. An electric field is established near the *P*-*N* junction by the positive and negative ions created due to the production of electron-hole pairs which leads to the development of potential across the junction. Since the number of electron-hole pairs far exceeds the number exceeds for thermal equilibrium, many of the electrons are pulled across the junction by the force of the electric field. Those that cross the junction contribute to the current in the cell and through the external load. The terminal voltage of the cell is directly proportional to the intensity of the incident light. The voltage may be as high as 0.6 V depending on the external load. Usually a large number of cells are arranged in an array in order to obtain higher voltages and currents as shown in Fig. 14.32 (*a*).

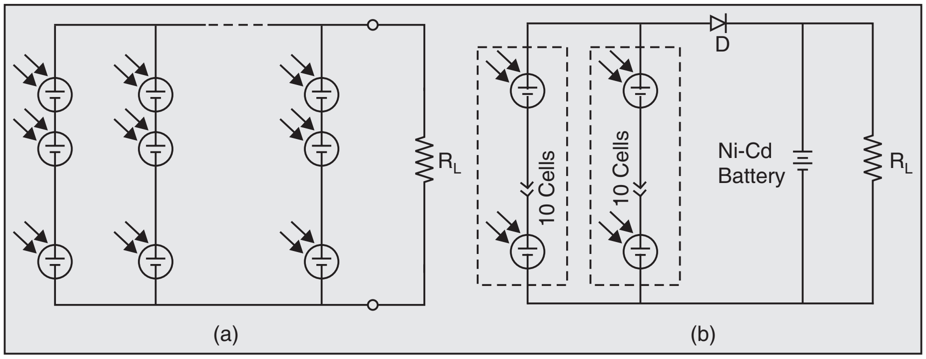
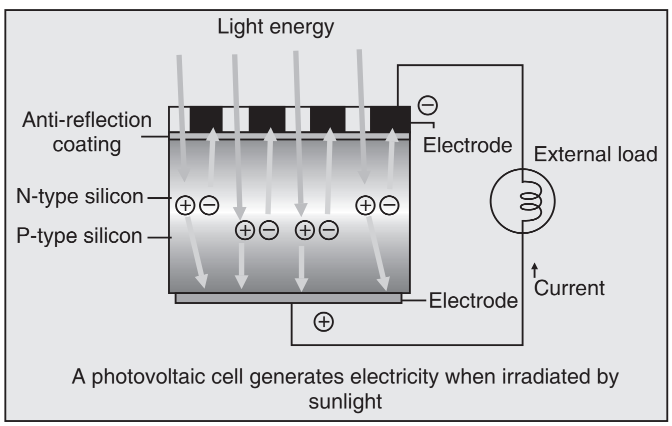


Fig. 14.32.

Solar cells act like a battery when connected in series or parallel. Figure 14.32 (*b*) show two groups of 10 series cells connected a parallel with each other. If each cell provides 0.5 V at 150 mA, the overall value of the solar bank is 5 V at 150 mA. The two parallel solar links provides 5 V at 300 mA. This solar power source supplies the load and also charges the Ni-Cd battery. The battery provides power in the balance of light. A blocking diode *D* is used to isolate the solar cells from Ni-Cd battery otherwise in the absence of light, the battery will discharge through the cells thereby damaging them.



A photovoltaic cell generates electricity when irradiated by sunlight

A solar cell operates with fair efficiency, has unlimited, life, can be easily mass-produced and has a high power capacity per weight. It is because of these qualities that it has becomes an important source of power for earth satellites.

Example 14.9. *An earth satellite has on board 12-V battery which supplies a continuous current of 0.5 A. Solar cells are used to keep the battery charged. The solar cells are illuminated by the sun for 12 hours in every 24 hours. If during exposure, each cell gives 0.5 V at 50 mA, determined the number of cells required.*

(Optoelectronics Devices, Gujarat Univ., 1994)

Solution: The solar cell battery-charging circuit is shown in Fig. 14.33. The cells must be connected in series to provided the necessary voltage and such groups must be connected in parallel to provide the necessary current. The charging voltage has to be greater than the battery voltage of 12 V. Allowing for different drops, let the solar bank voltage be 13.5 V.

Number of series connected solar cells = 13.5/0.5 = 27

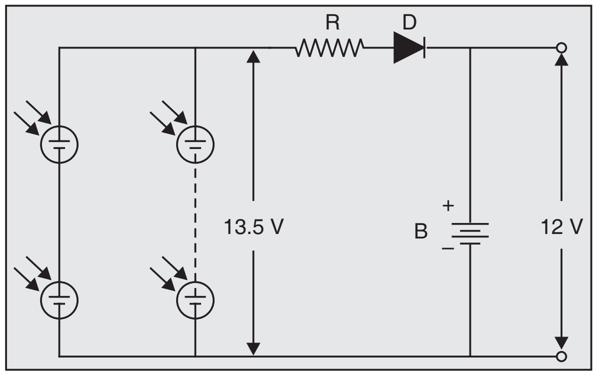


Fig. 14.33.

The charge given out by batteries during a 24 hour period = 12 × 0.5 = 6 Ah. Hence, solar cells must supply this much charge over the same period. However, solar cells deliver current only when they illuminated i.e., for 12 hours in every 24 hours. Necessary charging current required from the solar cells = 6 Ah/12 h = 0.5 A.

Total number of groups of solar cells required to be connected in parallel is

$$= \text{output current/cell current} = 0.5/50 \times 10^{-3} = 10$$

∴ total number of solar cells required for the earth satellite = 27 × 10 = **270**

14.27 Digital Displacement Transducers

Any transducer that presents information as discrete samples and that does not introduce a quantization error, when the reading is represented in the digital form may be classified as a digital transducer. Any transducer that generates a coded of a measurement can be termed an digital encoder. Digital encoder transducer enable a linear or rotary displacement to be directly converted into digital form without intermediate forms of analog to digital conversion. There are following types of digital encoder transducer, they are given below:

1. **Tachnometer Encoders.** This transducer has only a single output signal which consists of a pulse for each increment of displacement. Figure 14.34 shows the tachnometer encoder. If the motion is always in one direction, a counter could accumulate these pulses to determine the displacement form a known starting point. Any motion in opposite direction would also produce identical pulses, which would produce errors. Therefore this digital transducer is usually used for measurement of speed.

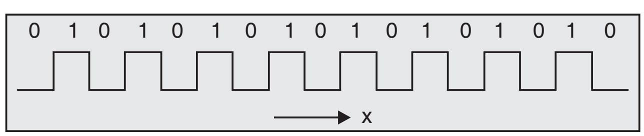


Fig. 14.34.

2. **Incremental Encoders.** In this transducer the increment encoder uses at least two signal generating elements. The two tracks in the case incremental encoder are mechanically shifted by ¼ cycle relative to each other. This allows detection of motion which signal rises first. Thus an up down pulse counter can be used to subtract pulses whenever the motion reverse. A third output, which produces one pulse per revolution at a distinct point, it sometimes provide for zero reference.

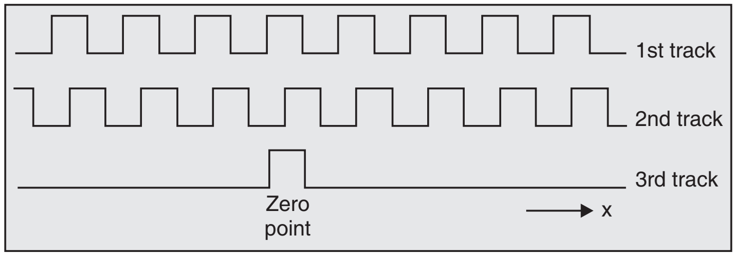


Fig. 14.35.

3. **Absolute Encoders.** It generally limited to measurement of a single revolution. They use multiple tracks and outputs, which are readout in parallel to produce a binary representation of the angular shaft input position. There is a one-to-one correspondence between binary output, position data are recovered when power is restored after an outage. The transient electric noise causes only transient measurement errors.

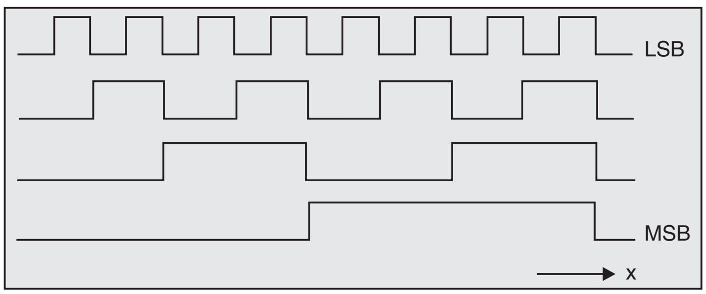


Fig. 14.36.

14.28 Digital Optical Encoder

Any Transducer that generates a coded reading of a measurement can be termed an encoder. Optical Encoder uses an opaque disk with one or more circular tracks with some arrangement of identical transparent windows (slit) in each track. An optical light source and light sensors are used to obtain the output of the system.

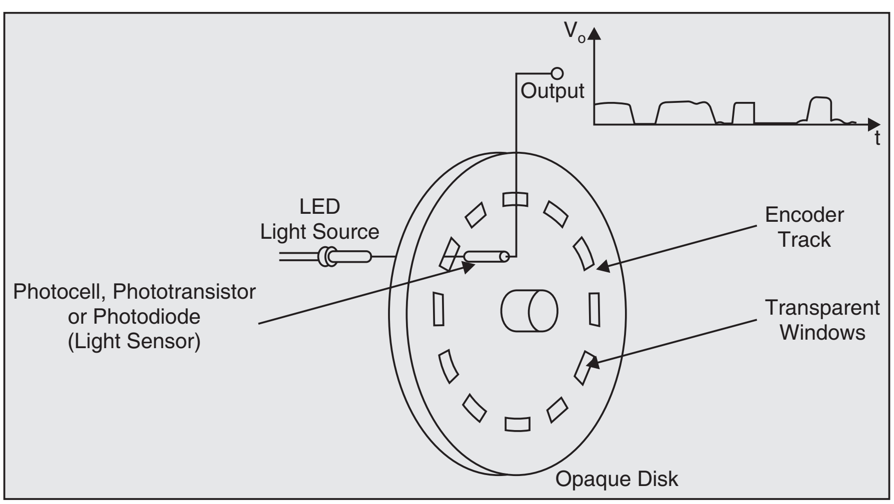


Fig. 14.37.

Figure 14.37 shows the optical encoder using an opaque disk that has one or more circular tracks, with some arrangement of identical transparent windows. A parallel beam of light is projected to all tracks from one side of the disk. The light sensor could be a silicon photodiode, a phototransistor, or a photovoltaic cell. The light from the source is interrupted by the opaque areas of the track, the output signal from the probe is a series of voltage pulses.

14.29 Proximity Sensor

A proximity sensor is a device that sense the other object when one object is close to another object. Mostly proximity sensors indicate only the presence or absence of an object within their sensing region. Proximity sensors detect the presence of objects without physical contact. There are wide ranges of proximity sensors to meet all types of applications. Typical applications include the detection, position, inspection and counting on automated machines and manufacturing systems.

In inductive and capacitive type operating principle is based on a high frequency oscillator that creates a field in the close surroundings of the sensing surface. The presence of a metallic object (inductive) or any material (capacitive) in the operating area causes a change of the oscillation amplitude. The rise or fall of such oscillation is identified by a threshold circuit that changes the output state of the sensor. The operating distance of the sensor depends on the actuator's shape and size and is strictly linked to the nature of the material. A screw placed on the back of the capacitive sensor allows regulation of the operating distance. This sensitivity regulation is useful in application, such as detection of full containers and non-detection of empty containers. Figure 14.38 show a inductive proximity sensor.

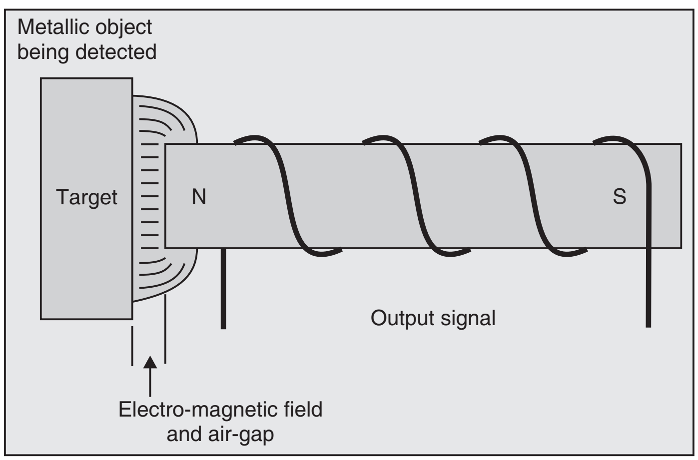


Fig. 14.38.

In photoelectric type it use light sensitive elements to detect objects and are made up of an emitter (light source) and a receiver. Three types of photoelectric sensors are available. Direct Reflection-emitter and receiver are housed together and use the light reflected directly off the object for detection. Reflection with Reflector-emitter and receiver are housed together and requires a reflector. An object is detected when it interrupts the light beam between the sensor and reflector. Thru Beam-emitter and receiver are housed separately and detects an object when it interrupts the light beam between the emitter and receiver.

In magnetic type the sensors are actuated by the presence of a permanent magnet. Their operating principle is based on the use of reed contacts, which consist of two low reluctance ferro-magnetic reeds enclosed in glass bulbs containing inert gas. The reciprocal attraction of both reeds in the presence of a magnetic field, due to magnetic induction, establishes an electrical contact.

14.30 Fiber Optic Sensor

Fiber optic sensor technology offers the possibility of sensing different parameters like strain, temperature, pressure in harsh environment and remote locations. These kinds of sensors modulates some features of the light wave in an optical fiber such as intensity and phase or use optical fiber as a medium for transmitting the measurement information. The advantages of fiber optic sensors in contrast to conventional electrical ones make them popular in different applications and now a day they consider as a key component in improving industrial processes, quality control systems, medical diagnostics, and preventing and controlling general process abnormalities.

Figure 14.39 show the general structure of an optical fiber sensor system. It consists of an optical source such as Laser, LED, Laser diode etc and optical fiber, sensing or modulator element, an optical detector and processing electronics (oscilloscope, optical spectrum analyzer etc).

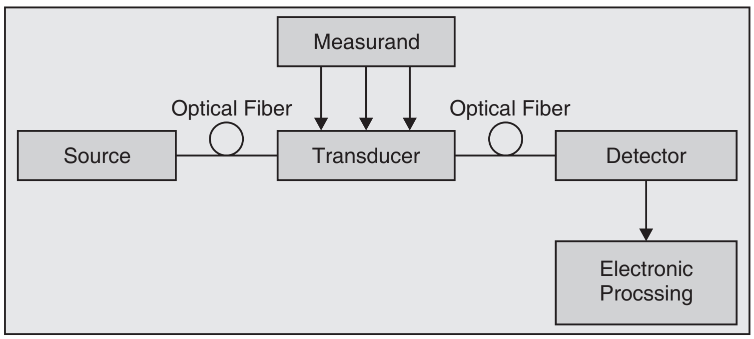


Fig. 14.39.

Fiber optic sensors can be classified under three categories: The sensing location, the operating principle, and the application. Based on the sensing location, a fiber optic sensor can be classified as extrinsic or intrinsic. In an extrinsic fiber optic sensor, the fiber is simply used to carry light to and from an external optical device where the sensing takes place. In this case the fiber just acts as a means of getting the light to the sensing location. In an intrinsic fiber optic sensor one or more of the physical properties of the fiber undergo a change.

Applications of Fiber Optic Sensors

Following are the main application of fiber optic sensors:

1. Measurement of physical properties such as strain, displacement, temperature, pressure, velocity, and acceleration in structures of any shape or size.
2. Monitoring the physical health of structures in real time.
3. Buildings and Bridges: Concrete monitoring during setting, crack.

14.31 Intelligent Sensor

Intelligent sensor takes some predefined action when it senses the appropriate input (light, heat, sound, motion, touch, etc.). They are capable of logic function, they can make their own decisions.

When a sensor device is packaged together with a CPU it is called a "smart sensor." The sensors really become smart when the tight integration of sensing and processing results in an adaptive sensing system that can react to environmental conditions and consistently deliver useful measurements to a robotic system even under the harshest of the conditions.

Figure 14.40 shows the basic structure of an intelligent sensor. The process is sensed by the sensor device. Then it is applied to the analog signal conditioning. After an Analog Digital Conversion (ADC) the process value is stored inside the memory of a controller (typically micro controller) where also some digital signal conditioning algorithms may run. Via a bus coupling device the value or a value being calculated can be read out from the bus. Whereas conventional sensors only support data traffic in one direction from the sensor to the host or to the coupling field bus box but in intelligent sensors its allow data to be send in both direction.

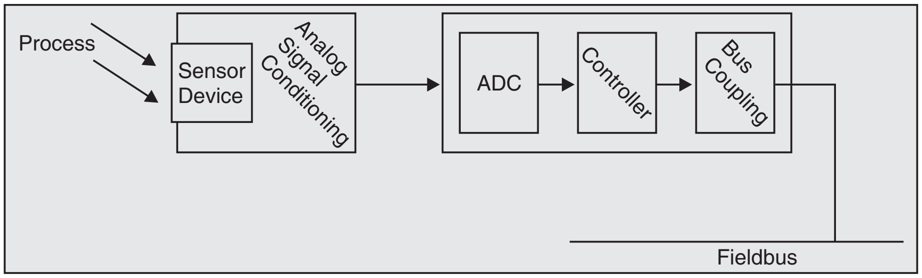


Fig. 14.40.

14.32 Load Cell (Pressure Cell)

A load cell is a transducer that converts mechanical force into electrical signals. There are many different types of load cells that operate in different ways, but the most commonly used load cell today is the strain gage (or strain gauge) load cell. A strain gage load cells use an array of strain gages to measure the deformation of a structural member and convert it into an electrical signal.

Figure 14.41 shows the load cell. A length of bar is used as the active element. The weight of the load is applies a particular stress to the bar. As the stress is applied along the direction of *S*, the steel bar experiences a compression along that axis and an expression along the *X* and *Y* axes. As a result gauge experiences a decrease in resistance while gauge *B* undergoes an increase in resistance. When these two gauges and the gauge on the two remaining sides of steel are connected to form a bridge circuit, four times the sensitivity of a simple gauge bridge is obtained. This makes the load cell sensitive to very small values of applied stress as well as to extremely heavy loads.

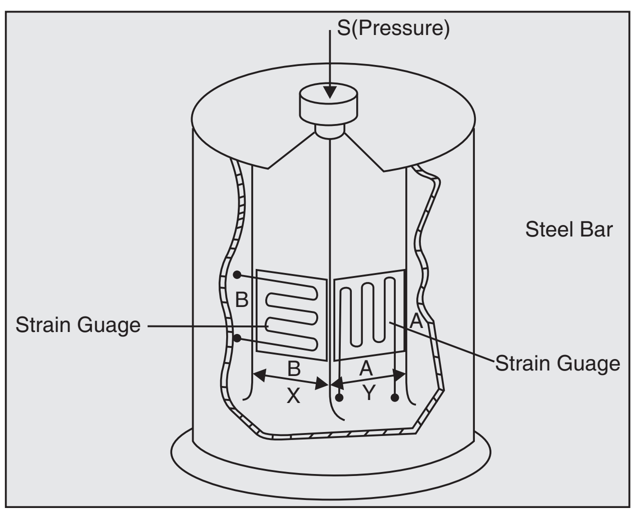


Fig. 14.41.

Other types of load cell include piezoelectric useful for dynamic measurements of force and vibrating wire load cells which are useful in geomechanical applications due to low amounts of drift.

SUMMARY

In this chapter you have learned that:

1. A transducer can be defined as a device capable of converting energy from one form into another.
2. Transducers can be found both at the input as well as at the output stage of a measuring system.
3. In an electrical resistance strain gauge the device consists of a thin wire placed on a flexible paper tissue and is attached to a variety of materials to measure the strain of the material.
4. The induction of the magnetic material depends on a number of variables like the number of turns of the coil on the material, the size of the magnetic material, and the permeability of the flux path.
5. When a current conducting material is placed in the transverse magnetic field then the difference of potential is produced between the opposite edges of the conductor. This effect is known as Hall Effect.
6. Active transducers is also known as self generating type transducers.
7. Passive transducers is also known as externally powered transducers.

GLOSSARY

Hall Effect Transducer: This transducer works on the principle of Hall Effect

Inductive Transducers: The inductive transducers work on the principle of the magnetic induction of magnetic material.

Piezoelectric Transducers: The piezoelectric transducers work on the principle of piezoelectric effect. When mechanical stress or forces are applied to some materials along certain planes, they produce electric voltage.

Strain Gauge: A strain gauge is a device used to measure the strain of an object.

Transducer: A transducer is a device that converts one form of energy to another.

NUMERICAL PROBLEMS

1. A strain gauge has a gauge factor of 4. If the strain gauge is attached to a metal bar that stretches from 0.25 m to 0.255 m when strained. What is the percentage change in resistance? If the unstrained value of gauge is 120 Ω what is resistance value of gauge after application of strain?

   (**Ans.** 8%, 129.6 Ω)
2. An 8-plate transducer has plates of dimensions 25 mm × 25 mm and a separation of 0.2 mm between the plates. The arrangement is to be used for displacement measurement. Determine the sensitivity of the arrangement for air medium.

   (**Ans.** 7.75 PF/m)
3. An Hall effect element used for measuring a magnetic field strength gives an output voltage of 10.5 mV. The element is made of silicon and is 2.5 mm thick and carries a current of 4 A. The Hall coefficient is 4.1×10^{-6} Vm/A – Wb/m^2.

   (**Ans.** 1.6 Wb/m^2)
4. A strain gauge has a resistance of 120 Ω unstrained and the gauge factor is –12. What is the resistance value if the strain is 1%.

   (**Ans.** 105.6 Ω)
5. A strain gauge with a gauge factor of 4 has a resistance of 500 Ω. It is to be used in a test in which the strain to be measured may be as low as 5×10^{-6}. What will be the charge in resistance of gauge?

   (**Ans.** 10×10^{-3} Ω)

6. Strain gauge and resistor vary with temperature. Most of the time the spec on strain gauge or resistor comes with a specification that state 50 ppm/°C, 100 ppm/°C or 1000 ppm/°C.
   (*a*) What is ppm?
   (*b*) Calculate the strain gauge resistance when temperature rises to 40°C with the specification says it has a nominal resistance of 100 Ω and temperature tolerance of 200 ppm/°C at ambient temperature of 25°C.

DESCRIPTIVE QUESTIONS

1. What is a transducer?
2. Give classification of transducers.
3. Define electrical transducers?
4. What are Inverse transducers?
5. What are variable inductance type transducers?
6. Differentiate between Transducers and Inverse transducers?
7. What is a strain gauge?
8. What are the types of strain gauges?
9. Give other classification of strain gauges.
10. What is a semiconductor strain gauge?
11. What is Hall Effect transducers, how it can be used for measuring displacement?
12. What are the possible applications of Hall Effect Transducers?
13. What are the points to be considered for selecting transducer?
14. What is LVDT?
15. Define Gauge Factor of a strain gauge.
16. Mention applications of a resistance strain gauge for measurement of non electric quantities.
17. What are the different types of strain gauges? Name four resistance materials used in wire and foil gauges.
18. Mention major applications of LVDTs?
19. Enlist advantages' of LVDT.
20. What are the advantages of semiconductor strain gauge?
21. Mention one disadvantage of LVDT.
22. What are primary and secondary transducers?
23. What are the advantages of an electrical transducer?
24. What is the basic principle of operation of INDUCTION TYPE transducers?
25. What are Analog and Digital transducers?
26. What is a Piezeoelectric transducer?
27. Write a note on 'selection of transducer.'
28. What are the basic requirement of a transducer?
29. Enlist advantages of Electrical transducers.
30. Describe elements and requirements of transducers.
31. Describe the construction and working of LVDT.
    (PTU, May 2004)
32. Discuss piezoelectric and electric transducer.
    (PTU, May 2004)
33. What is gauge factor? Give gauge factor for any two materials
    (PTU, Dec. 2005)
34. Give three basic requirement of a transducer?
    (PTU, Dec., 2005)

35. Explain the construction of wire wound strain gauges and derive expression for gauge factor.
(PTU, Dec. 2005)

36. What are capacitive transducers? What are their disadvantages and disadvantages? Explain the use of the capacitive transducer for measurement of liquid level.
(PTU, Dec. 2005)

37. Explain the construction and feature of working of linear voltage different transformer.
(PTU, May 2005)

38. How capacitive transducers are superior to other transducers.
(PTU, May 2006)

39. What are the capacitive transducers? Explain the use o capacitive transducers for measurement of liquid level.
(PTU, May 2006)

40. Discuss the major source of error in potential transformer. How to reduce them.
(PTU, May 2006)

41. Why the secondary windings of LVDT are connected in series opposition?
(PTU, Dec. 2006)

42. What are the basic principle of strain gauge instruments.
(PTU, Dec. 2006)

43. Explain the measurement of displacement using LVDT.
(PTU, Dec. 2006)

44. Explain the construction of wire wound strain gauges and derive the expression for gauge factor.
(PTU, Dec. 2006)

45. Why piezoelectric transducers cannot be used for static displacement instrument.
(PTU, May 2007)

46. Define a transducer and distinguish between a sensor and a transducer.
(PTU, Dec. 2008)

47. What is an LVDT? What quantities can be measured by using LVDT?
(PTU, Dec. 2008)

48. What are the basic requirements of a transducer?
(PTU, Dec. 2010)

49. Describe the different modes of operation of piezoelectric transducer and give its applications.
(PTU, Dec. 2010)

50. Discuss working principle of LVDT.
(PTU, Dec. 2010)

51. Define transducer. Give its classification.
(Nagpur University, Summer 2011)

52. Write short notes on:
(*a*) Rotary variable differential transformer
(*b*) Piezoelectric accelerometer
(*c*) Various types of thermistors
(Nagpur University, Summer 2011)

53. Write short notes on:
(*a*) Load cell
(*b*) Hall effect transducer
(*c*) Temperature compensation in strain gauge.
(Nagpur University, Summer 2010)

54. Explain working principle of LVDT and state advantages and disadvantages of LVDT.

(Nagpur University, Summer 2011)

55. What is the gauge factor? Derive its expressions. What are the situations in which semiconductors strain gauge is used?

(Nagpur University, Summer 2011)

56. Describe active and passive transducers.

(Nagpur Univrsity, Summer 2010)

57. Describe analog and digital mode of operation of transducers.

(Nagpur University, Summer 2010)

58. Prove that the Gauge factor:

$$G = 1 + 2v + \frac{\Delta\rho/\rho}{\varepsilon}$$

(Nagpur University, Summer 2010, 2011)

59. Differentiate between active and passive transducers.

(Nagpur University, Summer 2010)

60. What are piezoelectric materials? Explain piezoelectric accelerometer in detail.

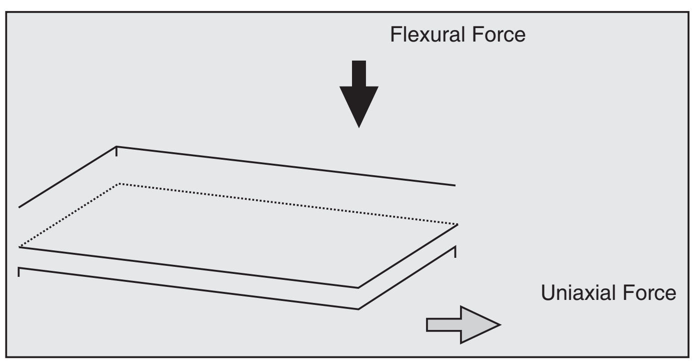
(Nagpur University, Summer 2010)

61. Explain RVDT in brief with neat sketch.

(Nagpur University, Summer 2010)

62. Besides strain, the behaviour of a strain gauge may also be affected by other phenomena such as temperature. Hence, it is important to ensure that your design is immune to temperature fluctuations. How can this be achieved?

63. The force applied exerted to the strain gauge can be from uniaxial or flexural loading. There are different ways to configure or place the strain gauge. Do a research to find out some of the common methods used for detection of uniaxial or flexural loading and temperature compensation. How do each of them effects the strain gauge bridge circuit calculation?



MULTIPLE CHOICE QUESTIONS

1. The piezoelectric crystal sensitivity is defined as,

(IES, 2001)

(*a*) Voltage developed per unit stress (*b*) Field developed per unit stress
(*c*) Voltage developed per unit force (*d*) Field developed per unit force

2. Which one of the following transducers requires power supply for its operation,

(IES, 2005)

(*a*) Thermocouple (*b*) Photovoltaic Cell
(*c*) Piezoelectric Crystal (*d*) Thermistor

3. In an LVDT, there are two secondary coils which are connected for a single output. Which one of the following is correct?

(IES, 2008)

(*a*) The coils are in series and in phase opposition
(*b*) The coils are in parallel and in phase opposition
(*c*) The coils are in series and in the same phase condition
(*d*) The coils are in parallel and in the same phase condition.

4. Which one of the following is a passive transducer?

(IES, 2008)

(*a*) Piezoelectric (*b*) Thermocouple
(*c*) Photovoltaic cell (*d*) LVDT

5. Which of the following transducers is classified as an active transducers,
(*a*) Metallic strain gauge (*b*) Capacitive microphone
(*c*) LVDT (*d*) Piezoelectric transducers

6. The strain gauges should have low,
(*a*) Gauge factor (*b*) Resistance temperature coefficient
(*c*) Resistance (*d*) All of the above

7. LVDT can be used for,
(*a*) Vibration measurement (*b*) Angular velocity measurement
(*c*) Force measurement in a beam (*d*) Load measurement on a column

8. The principle of operation of LVDT is based on vibration of,
(*a*) Self inductance (*b*) Mutual inductance
(*c*) Reluctance (*d*) Permeance

9. In a LVDT the two secondary voltages,
(*a*) Are independent of the core position
(*b*) Vary unequally depending on the core position
(*c*) Vary equally depending on the position
(*d*) Are always in phase quadrature

10. In an LVDT, the output quantity,
(*a*) Is algebraically summed to zero
(*b*) Is difference to the two current flowing in the two secondary
(*c*) Depends upon its rating
(*d*) None of these

11. Capacitive transducers are normally employed for,
(*a*) Static measurements (*b*) Dynamic measurements
(*c*) Both static and dynamic measurements (*d*) Transient measurements

12. Piezoelectric crystal can be used to measure,
(*a*) Static pressure only (*b*) Dynamic pressure only
(*c*) Both static and dynamic pressures (*d*) None of the above

13. Piezoelectric crystals are used for the measurement of,
(*a*) Temperature (*b*) Velocity
(*c*) Sound (*d*) None of the above

14. Hall effect transducers are used for measuring,
(*a*) Magnetic field (*b*) Current
(*c*) Electric Field (*d*) Pressure

15. A photoelectric transducer converts,
- (*a*) Electric current to voltage
- (*b*) Kinetic energy of electrons into potential energy
- (*c*) Light intensity to voltage
- (*d*) None of the above

16. Increment encoder use,
- (*a*) One channel only
- (*b*) Two channels
- (*c*) Two channels and sometimes three
- (*d*) Four channels

ANSWERS

1. (*b*)	**2.** (*d*)	**3.** (*a*)	**4.** (*d*)	**5.** (*d*)	**6.** (*b*)
7. (*c*)	**8.** (*b*)	**9.** (*b*)	**10.** (*b*)	**11.** (*b*)	**12.** (*c*)
13. (*a*)	**14.** (*a*)	**15.** (*c*)	**16.** (*c*)		

Chapter 15

Transducers for Measurement of Non-Electrical Quantities

Outline

15.1 Introduction

Transducer are used for converting non-electrical signal into electrical signal and this electrical signal is processed by the circuit and then supplied to the output devices.

15.2 Measurement of Temperature

Temperature is a physical property of any matter that quantitatively expresses the common notions of hot and cold. Heat spontaneously flows from bodies of a higher temperature to bodies of lower temperature, at a rate that increases with the temperature difference and the thermal conductivity. No heat will be exchanged between bodies of the same temperature; such bodies are said to be in "thermal equilibrium".

Many methods have been developed for measuring temperature. Most of these rely on measuring some physical property of a working material that varies with temperature. One of the most common devices for measuring temperature is the glass thermometer. This consists of a glass tube filled with mercury or some other liquid, which acts as the working fluid. Temperature increase causes the fluid to expand, so the temperature can be determined by measuring the volume of the fluid. Such thermometers are usually calibrated so that one can read the temperature simply by observing the level of the fluid in the thermometer.

But in industries we use different type of temperature measurement instrument for measuring temperature. When measuring the temperature we ensure that the measuring instrument (thermometer, thermocouple, etc.) is really the same temperature as the material that is being measured. Under some conditions heat from the measuring instrument can cause a temperature gradient, so the measured temperature is different from the actual temperature of the system. In such a case the measured temperature will vary not only with the temperature of the system, but also with the heat transfer properties of the system. We will discuss each type of measuring instrument one by one in the following pages.

15.3 Thermoelectric Effects

Thermoelectric thermometry is based on thermoelectric effects or thermoelectricity discovered in the 19th century. Seebeck effect was discovered by Thomas Johann Seebeck in 1821 after some year Peltier effect discovered by Jean Charles Peltier in 1824 and Thomson effect discovered by William Thomson in 1847, the thermoelectric effects are explained below:

1. **Seebeck Effect.** Two wires of different metals A and B are joined together to form two functions and if the two junctions are at different temperatures, an electric current will flow around the circuit. This is the Seebeck effect. If metal A is of copper and metal B of iron, then the current flows from copper to iron at the hot junction and from iron to copper at the cold junction as shown in Fig. 15.1.

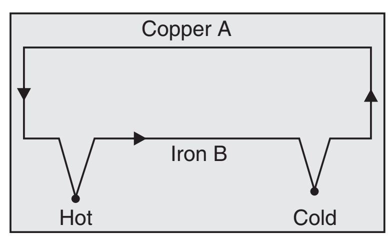


Fig. 15.1.

2. **Peltier Effect.** This is the reverse phenomenon of Seeback effect, if an external source of emf is connected and a current is forced to flow through the junctions. It is observed that heat is absorbed when the current flows across the iron-copper junction from copper to iron and liberated if the flow of current is reversed. The amount of heat liberated or absorbed is proportional to the quantity of electricity that across the junction, and the

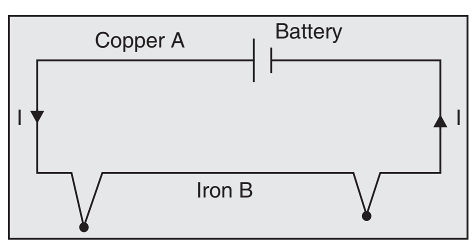


Fig. 15.2.

amount of heat liberated or absorbed when one ampere passes for a second is called the Peltier coefficient.

3. **Thompson effect.** According to the Thompson effect, when a current flows through a copper conductor having thermal gradient along length of the conductor, heat is released at a point where current is in the direction same as the heat flow; while heat is absorbed at a point where current flows in the direction opposite to that of heat flow.

15.4 Laws of thermoelectric Circuit

There are three laws of thermoelectric circuits which are given below:

1. **Law of homogenous materials.** A thermoelectric current cannot be sustained in a circuit of a single homogenous material however it varies in cross section by the application of heat alone.
2. **Law of intermediate materials.** The algebraic sum of the thermoelectric forces in a circuit composed of any number of dissimilar materials is zero if all the junctions are at the same temperature. The Seebeck emf E developed is independent of the fact that a third material C forms two junctions with the + and – materials as shown in the first part of Fig. 15.3. Since the material C is isothermal the situation is equivalent to a single measuring junction between the + and – materials as indicated in the latter part of the figure.

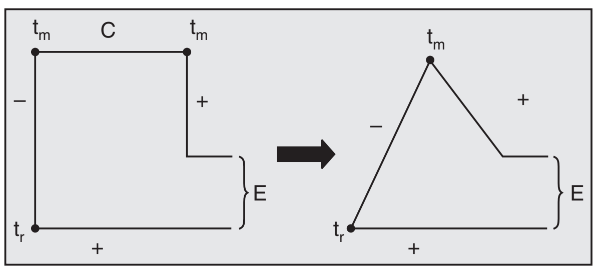


Fig. 15.3.

3. **Law of successive or intermediate temperatures.** The seebeck voltage is E_1 with the measuring junction at t_1 and the reference junction at t_2. The seebeck voltage is E_2 with the measuring junction at t_2 and the reference junction at t_3. Then the seebeck voltage is $E_3 = E_1 + E_2$ with the measuring junction at t_1 and the refencence junction at t_3 as show in Fig. 15.4.

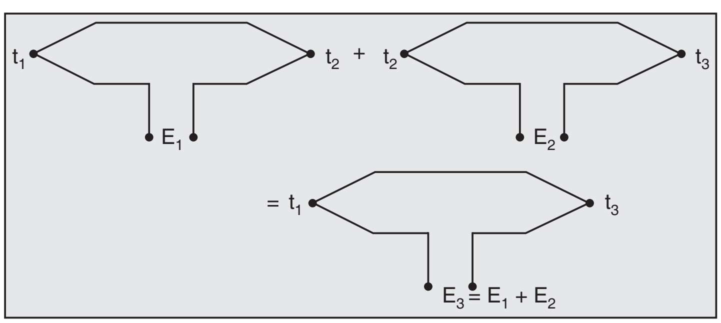


Fig 15.4.

15.5 Resistance Temperature Detectors

Resistance Temperature Detectors (RTDs) are used to measure temperature by correlating the resistance of the RTD element with temperature. The resistance of a conductor changes when its temperature is changed. The variation of resistance R with temperature T can be represented by the following relationship,

$$R = R_o\,(1 + \alpha_1 T + \alpha_2 T^2 + ... + \alpha_n T^n)$$

Where R_o = resistance at T = 0 K

$\alpha_1, \alpha_2 + ... + \alpha_n$ = constants

Fig. 15.5 shows the RTD. The resistances of certain metals are changing with the different temperature ranges.

By increasing the temperature, the electrical resistance of different metals increases in the direct relation to the rise of temperature. The basic element of RTD is very simple. Its construction consists of a wire piece wrapped around a ceramic or glass core. Because of their compact size, when the space is limited then RTD elements are commonly used. It is made of very thin metal surface as much as possible to keep the contact is better. The change in resistance caused by changes in temperature are detected by Wheatstone bridge as shown in Fig. 15.6. The temperature sensing element which may be nickel, copper or platinum contained in a bulb or well, along with the balancing bridge form the essential components of a temperature measuring system based upon this principle.

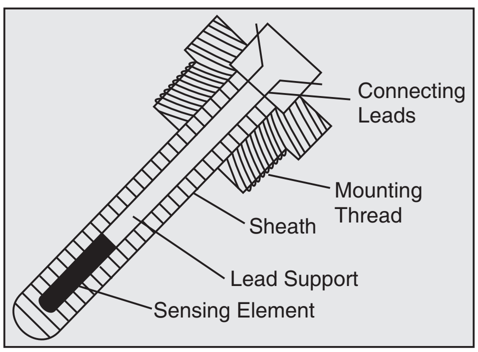


Fig. 15.5.

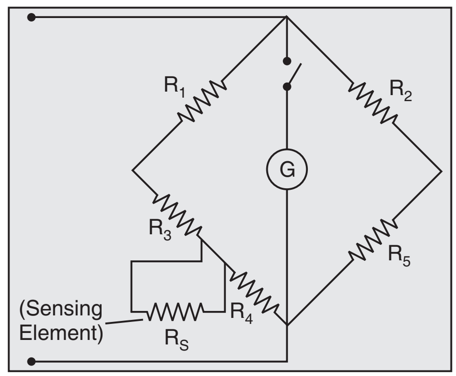


Fig. 15.6.

The sensing element Rs is made of a material having a high temperature coefficient, and R_1, R_2 and R_5 are made of resistances that are practically constant under normal temperature changes. When no current flows through the galvanometer, the normal principle of Wheatstone's bridges states the ratio of resistances is,

$$\frac{R_1}{R_2} = \frac{R_s}{R_5}$$

The sensing element is away from the indicator and its leads have a resistance, R_3, R_4, then,

$$\frac{R_1}{R_2} = \frac{R_3 + R_s + R_4}{R_5}$$

Now its resistance R_s change cannot be maintained and the galvanometer shows a deflection, which can be calibrated to give a suitable temperature scale. The RTD element is made from a pure material whose resistance at various temperatures has been documented. The material has a predictable change in resistance as the temperature changes; it is this predictable change that is used to determine temperature.

The requirements of a conductor material to be used in RTD are given below:

1. The change in resistance of material per unit change in temperature should be as large as possible
2. The material should have a high value of resistivity so that minimum volume of material is used for the construction of RTD.

3. The resistance of materials should have a continuous and stable relationship with temperature.

Common RTD elements constructed of platinum, copper or nickel have a unique, and repeatable and predictable resistance versus temperature relationship and operating temperature range.

15.6 Thermocouple

A thermocouple consists of a pair of dissimilar conductors welded or fused together at one end to form the hot or measuring junction with other end available for connection to the cold or reference junction. A thermocouple is a thermoelectric device that converts thermal energy into electrical energy. The thermocouple is used as a primary transducer for measurement of temperature, converting temperature changes directly into emf.

There are two types of effects that arise when two dissimilar metals are brought in contact with each other and the temperature is changed at the junction. One effect produces an electrical potential (Seeback effect) when heat is applied and the other effect is to cool the junction when a current is passed through the junction in the proper direction (Peltier effect). These two effects can be very useful. Since the voltage at the junction depends upon the temperature of the end points, we may generate a voltage by heating one junction while holding the other constant in temperature. This effect make a cooling device, a refrigerator, by passing a current through the junction in the proper direction.

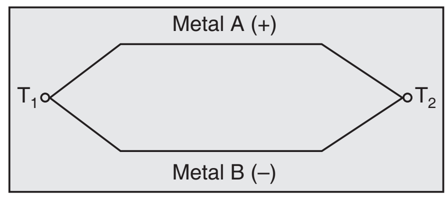


Fig. 15.7.

There are two junctions T_1 and T_2. The junction T_2 is kept at constant reference temperature and referred as cold junction while the junction T_1 is referred as hot junction. When the hot junction temperature is greater as compared to the cold junction an emf is generated due to the temperature gradient. The magnitude of the emf depends on the material used for the wires and temperature difference between the two junctions. A meter or recorder is used to measures emf as shown in Fig. 15.8.

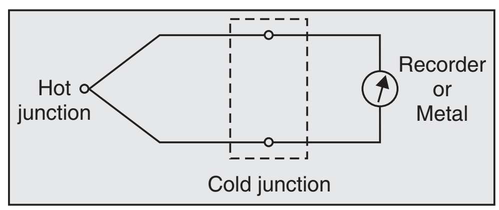


Fig. 15.8.

15.7 Types of Thermocouple

There are several types of thermocouples are available, and different types are designated by capital letters that indicate their composition according to American National Standards Institute (ANSI) conventions. For example, a J-Type thermocouple has one iron conductor and one constantan (a copper-nickel alloy) conductor. The list of thermocouples in given in Table. 15.1.

Table 15.1.

Thermocouple Type	*Conductors – Positive*	*Conductors – Negative*
B	Platinum-30% rhodium	Platinum-6% rhodium
E	Nickel-chromium alloy	Copper-nickel alloy
J	Iron	Copper-nickel alloy
K	Nickel-chromium alloy	Nickel-aluminum alloy
N	Nickel-chromium-silicon alloy	Nickel-silicon-magnesium alloy
R	Platinum-13% rhodium	Platinum
S	Platinum-10% rhodium	Platinum
T	Copper	Copper-nickel alloy

Fig. 15.9 shows the thermal emfs for some common thermocouple materials. The values are based on a reference temperature of 32°F.

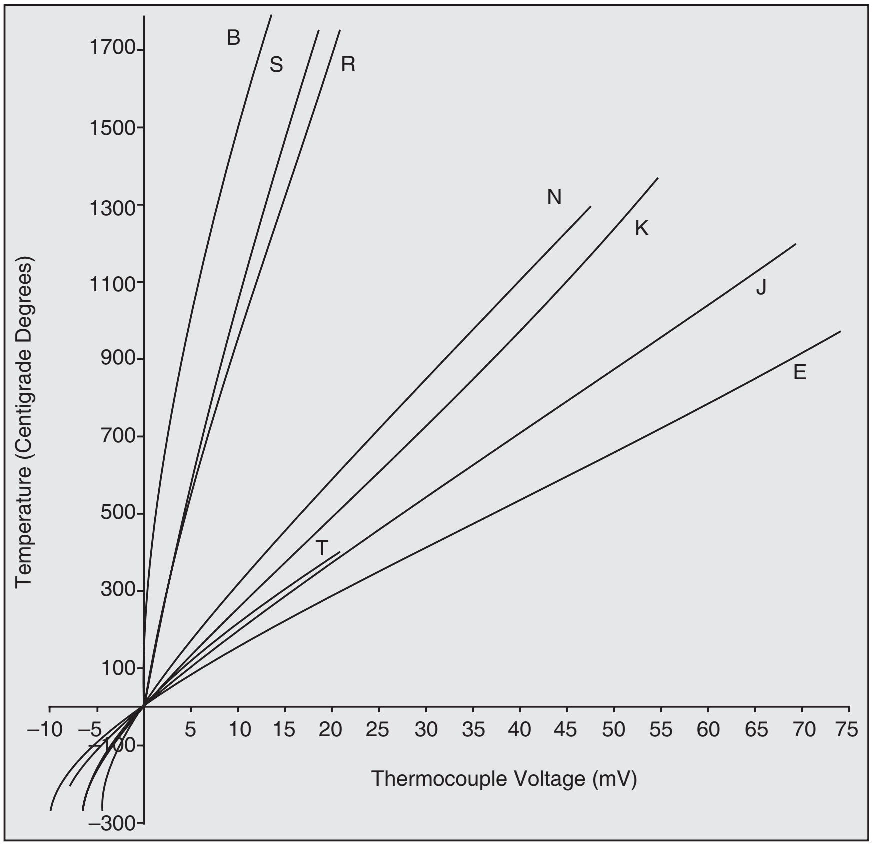


Fig. 15.9.

15.8 Measurement of Temperature with Thermocouple

T Type Thermocouple. Fig. 15.10 shows a T type , uses copper and constantan. Copper used is an element and constantan use is an alloy of nickel and copper. The copper side is positive and constant side is negative. Assuming copper wires used to connect the thermocouple to the next stage and second copper-constantan junction is produced. The junction is called as reference junction. It generates a seeback voltage that oppose the voltage generated by the sensing junction. When the both junction are at the sane temperature the output voltage is zero. If the sensing junction is at high temperature the output voltage is proportional to the difference between the two junction temperatures.

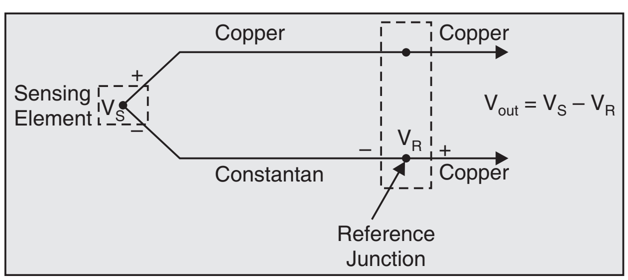


Fig. 15.10.

With Cold Junction Compensation. The temperature cannot be delivered directly from the output voltage, it may cause an error produced by the reference junction. This error is overcome by placing the reference junction in the ice bath of known temperature as shown in Fig. 15.11. This process is called as cold junction compensation. The reference voltage is maintained at 0°C. The reference voltage is now predictable from the calibration curve of the T type thermocouple.

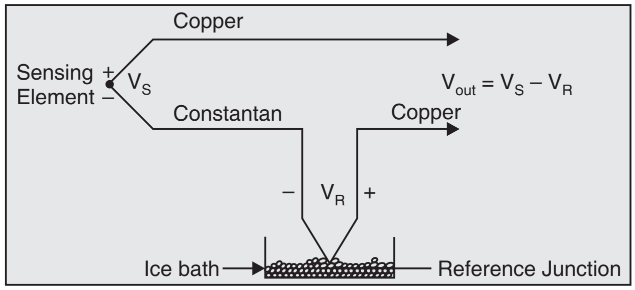


Fig. 15.11.

For accurate measurement of hot junction temperature the cold junction or reference junction must kept at 0°C. If the cold junction is at ambient temperature then a voltage corresponding to this temperature must be added to the measurement to obtain accurate reading.

The standard calibration data for all thermocouples are based on cold junction temperature. In practice it may not be possible to keep cold junction at zero degree temperature. Hence standard data need to be corrected. One way is to add the environmental temperature to the value of temperature determined by thermocouple measurement. In another method, thermistor may be put in the thermocouple circuit. The voltage drop across thermistor depends on environmental temperature which then compensates for the error.

J Type Thermocouple Using Isothermal Block. When the copper us not one of the thermocouple metal then the four junction circuit is formed as show in Fig. 15.12. This is J type thermocouple uses iron and constantan as the two elements, When it is connected to copper wires, two iron copper junction, reference junction and sensing junction are formed. Here we used isothermal block. This block is made of materials that have poor conductor of electricity but a good conductor of heat. Both iron-copper junctions will be at same temperature and generate the same seeback voltage and hence these two voltages will cancel. In industry it is not possible to use the ice-baths method so we use different method for cold junction compensation. The isothermal block contains two reference junctions and a thermistor. The resistance of the thermistor is function of temperature. The circuit is used to sense the resistance of thermistor and to compensate for the voltage introduced by the two reference junctions. An isothermal block with one temperature sensor can provide compensation for several units.

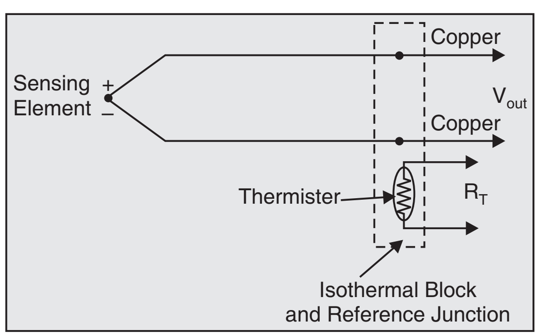


Fig. 15.12.

15.9 Types of Junction in Thermocouples

When thermocouples are assembled into metal-sheathed thermocouples, there are the following ways to assemble the thermocouple junction.

1. **Grounded Junction.** Fig. 15.13 shows the grounded junction when assembling the thermocouple into protective metal sheath, the thermocouples junction are weld directly to the inside tip of the sheath. Grounded thermocouples temperature sensors are widely used, because it offer faster respond time, more accurate reading at short distant. It is a preferred junction type for high temperature applications. Precaution for ground loop at long distances and at low temperature usage.

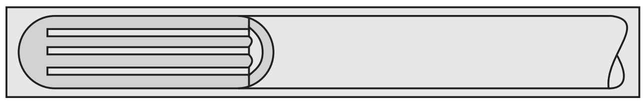


Fig. 15.13.

2. **Ungrounded Junction.** Fig. 15.14 shows the ungrounded junction this is similar to the grounded junction except it is isolated from the metal sheath. Ungrounded thermocouples are used primarily for isolating the control system from the sensor and to prevent ground loop. It is more inaccurate and slow respond time.

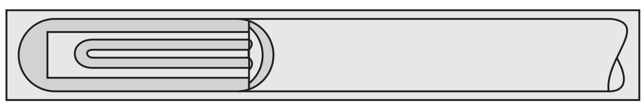


Fig. 15.14.

3. **Exposed Junction.** Fig. 15.15 shows the exposed junction. The junction is directly exposed to the material being heated, the junction responds is very quickly to temperature changes. There is no sheath or insulation to slow down heat transfer.

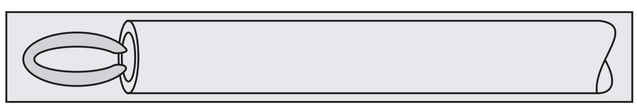


Fig. 15.15.

Materials for Thermocouple

Some of the property of material used for thermocouple are given below:

1. Melting point of thermocouple materials must be higher than the measuring temperature.
2. The dissimilar materials on joining should be able to produce large emf for accuracy of measurements.
3. Temperature is determined indirectly i.e. through calibrations of emf with temperature. As for as possible, the linear variation of emf with temperature is desired.
4. Thermocouple materials should be resistant to atmospheres in furnaces.

Advantages of Thermocouple

Some of the advantages of thermocouples are given below:

1. The thermocouple junction may be grounded and brought into direct contact with the material being measured.
2. The thermocouples is rugged in construction
3. It cover a wide range of temperature form –270° C to 2700° C.
4. Using extension leads and compensating cables, long distances transmission for temperature measurement is possible.

Disadvantages of Thermocouple

Some of the main disadvantages of thermocouple are given below:

1. Temperature measurement with a thermocouple requires two temperatures be measured, the junction at the work end (the hot junction) and the junction where wires meet the instrumentation copper wires (cold junction).
2. Thermocouples operation are relatively complex with potential sources of error.
3. They have a lower accuracy and hence they cannot be used for precision work.

15.10 Thermistor

Thermistor are the semiconductor type resistance thermometers. They have high sensitivity but highly nonlinear characteristics. It also having positive temperature coefficients but generally the resistor having negative temperature coefficient are called Thermister. Their characteristics can be expressed as,

$$R_T = R_o e^{\beta\left(\frac{1}{T} - \frac{1}{T_o}\right)}$$

Where R_T = resistance at temperature T(K)

R_0 = resistance at temperature T_0

T_0 = reference temperature at 25°C

β = constant

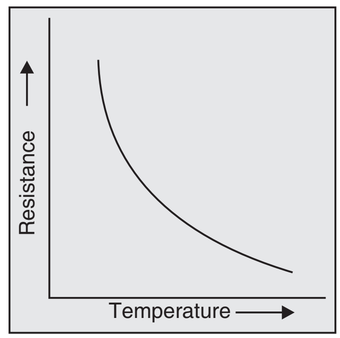


Fig. 15.16.

Fig. 15.16 shows the characteristics of NTC thermistors. The resistance of the thermistor decrease as the operating temperature increases. They are made from oxides of iron, manganese, magnesium etc.

The nonlinear characteristics of thermistors often creates problem for temperature measurement. The resistance temperature characteristics of the equivalent resistance would be more linear, but at the cost of sensitivity.

Voltage-Current characteristics

Fig. 15.17 shows the voltage current characteristics of thermistor. As the current increase the voltage across the thermistor increase after reaching the peak value voltage start decreasing, and the negative resistance region starts.

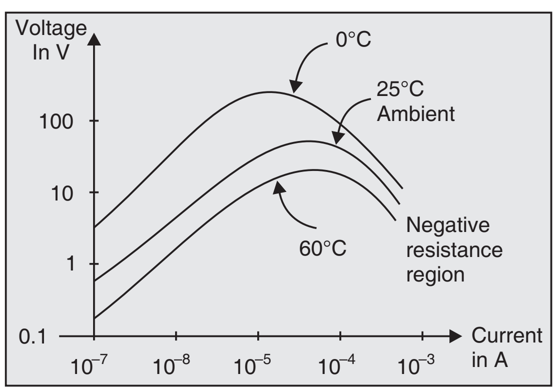


Fig. 15.17.

15.11 Current Time Characteristics

At very low voltages the thermistor takes long time to reach peak current. As the voltage level increase the time to reach peak current decreases. These characteristics are shown in Fig. 15.18 its also known as current time characteristics.

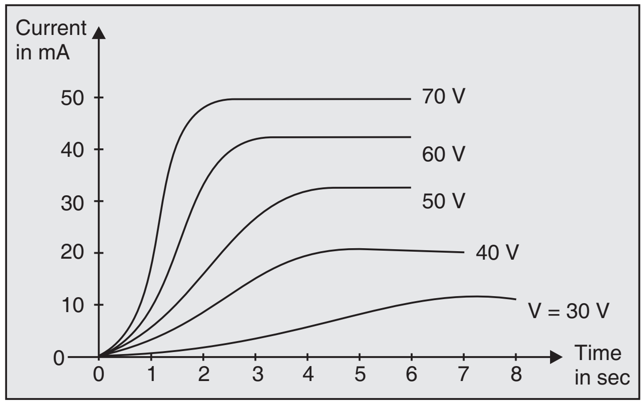


Fig. 15.18.

Types of thermistor

Different types of thermistor are given below:

1. **Bead thermistors.** Smallest Thermistors are in the form of heads with a diameter of 0.15mm to 1.25mm. This is the most familiar type of Thermistor usually glass coated.

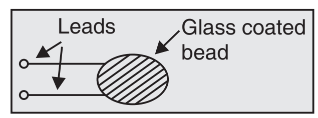


Fig. 15.19.

2. **Probe Thermistor.** Beads may be sealed in the tips of soild glass rods to form probes. Glass probe have a diameter of about 2.5mm. the probes are used for measuring temperature of liquids.

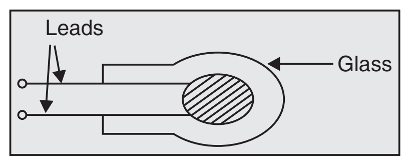


Fig. 15.20.

3. **Disc Thermistor.** Discs are made by pressing material under high pressure into cylindrical flat shapes with a diameters ranging from 2.5mm to 25mm. they are mainly used for temperature control.

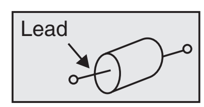


Fig. 15.21.

4. **Washer type Thermistor.** Washer type is usually long cylindrical units. Leads are attached to the ends of the rods. The advantage of this type is, it produce high resistance under moderate power.

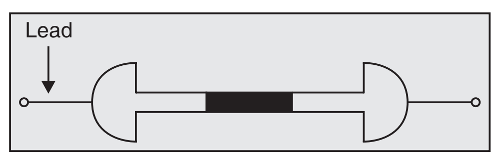


Fig. 15.22.

Advantages

Some of the main advantages of thermister are given below:

1. Low cost
2. Sensitivity is high
3. Small in size.
4. Good stability.
5. High output signal.

Disadvantages

Some of the disadvantages of thermister are given below:

1. Not suitable for high temperature measurement.
2. Requires external power supply.

Appilications

Main applications of thermister are given below:

1. Used for measurement and control of temperature.
2. Used for providing time delay.
3. Used as temperature compensation element in electronic equipments.
4. Used for measuring thermal conductivity of a medium

Example 15.1. *At R_o = 1050 Ω at 27°C, the corresponding β = 3140. What is the temperature when the thermistor resistance is 2330 Ω.*

Solution: Given: R_o = 1050 Ω; T_o = 27°C; β = 3140 and R_T = 2330 Ω.

We know that,

$$R_T = R_o e^{\beta\left(\frac{1}{T}-\frac{1}{T_o}\right)}$$

$$2330 = 1050\,e^{3140\left(\frac{1}{T}-\frac{1}{300}\right)}$$

$$3140\left(\frac{1}{T}-\frac{1}{300}\right) = \log_e 2219 = 0.797$$

$$T = \frac{1}{35.87\times 10^{-4}} = 278.77\ K\ \textbf{Ans.}$$

Example 15.2. *Find the sensitivity $S = \frac{\delta R}{\delta T}$ of the transducer at the given operating point in the example.*

Solution: Given: R_T = 2.330 Ω; β = 3140 and T = 278.77 K

We know that, $R = R_o e^{\beta\left(\frac{1}{T}-\frac{1}{T_o}\right)}$

and sensitivity is given by,

$$\frac{\delta R}{\delta T} = R\left(\frac{-\beta}{T^2}\right)$$

$$= \frac{(-2330)\times(3140)}{(278.77)^2} = -\,94.14\ \Omega/K\ \textbf{Ans.}$$

15.12 Difference between RTD, Thermocouple and Thermistors

Three difference types of devices are available to measure temperature: the resistance temperature detector(RTD), thermocouple, and the thermistor. The main difference and characteristics curve shown in Fig. 15.23 are given below.

1. **Resistance Temperature Detector.** Its constructed similar to an accurate wire wound resistor. It is most accurate of the three types of temperature sensing devices because it has the best stability and the best linear response. Its main disadvantages are a slow response time, small resistance change, and it is sensitive to self-heating effects.
2. **Thermocouple.** Its constructed with two dissimilar metals joined together and takes advantage of the thermoelectric potential property of dissimilar metal junctions. The main advantages of a thermocouple are that a current source is not necessary and it has the largest temperature range of the three types of temperature sensors. The primary

disadvantages are a low voltage (mV) output, a reference (cold junction) temperature is needed, and it has the lowest sensitivity of the three types.

3. **Thermistor.** The thermistor has much higher resistance values and exhibits a larger change in resistance with respect to temperature, but its temperature range is very limited in comparison to the other two types of temperature sensors.

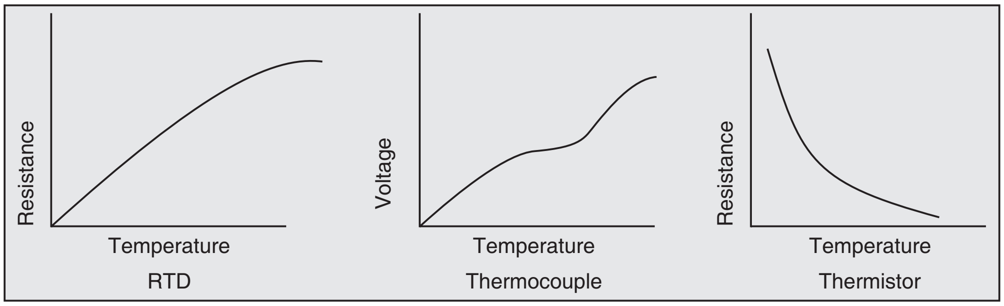


Fig. 15.23.

15.13 Basic concepts of Radiation

Fig. 15.24 shows the electromagnetic spectrum. What we see with our eyes is only the small part (visible region) of a broad spectrum of electromagnetic radiation. On the immediate high energy side of the visible spectrum lies the ultraviolet, and on the low energy side is the infrared (IR). This invisible portion of light carries various supplementary information.

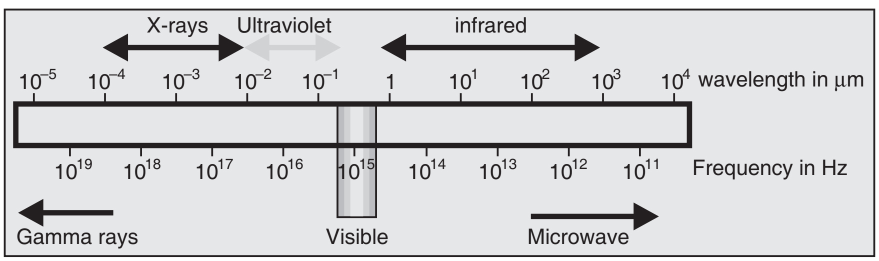


Fig. 15.24.

15.14 Planck's law

Planck's law states that the intensity of electromagnetic radiation emitted by a blackbody is a function of frequency (or wavelength). Black body will radiate energy at all frequencies. The Planck's law gives a distribution that peaks at a certain wavelength, the peak shifts to shorter wavelengths for higher temperatures, and the area under the curve raise rapidly with increasing temperature as shown in Fig. 15.25.

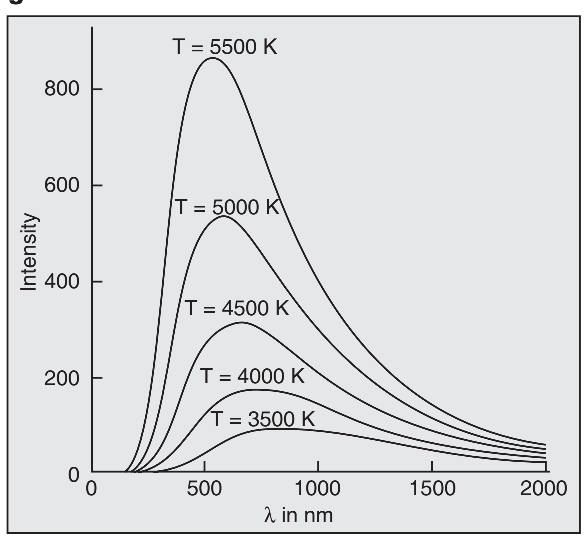


Fig. 15.25.

15.15 Wien's displacement and Stefan' Boltzmann law

Wien's displacement law states that the wavelength at which the blackbody emission spectrum varies inversely with the blackbody temperature or we can say hotter an object is, the shorter the wavelength at which it will emit most of the radiation. Stefan' Boltzmann law states that the total energy radiated per unit surface area of a black body per unit time is inversely proportional to the fourth power of the temperature of the black body.

The Wien's law provides the wavelength of the peak of the radiation distribution, whereas the Stefan-Boltzmann law gives the total energy emitted by the blackbody at all wavelengths. The operation of radiation pyrometer is based on the blackbody concepts. A black body is a hypothetical object that absorbs the entire radiation incident upon it. Such body does not reflect any radiation and appears perfectly black. It is a surface that absorbs all the radiant energy that falls on it and radiates the maximum thermal energy possible for a particular temperature. The total radiation emitted per unit surface area of the black body is according Stefan-Boltzmann law:

$$H_o = \sigma T^4 \text{ W/m}^2$$

Where σ = Stefan Boltzman constant = $57.2 \times 10^{-9} \dfrac{W}{m^2K^4}$

T = absolute temperature

The perfect black body is the most efficient thermal absorber and emitter because any object at thermal equilibrium will emit the same amount of light as it absorbs at every wavelength. The radiation spectrum of a black body is determined only by the temperature and not by the properties, material and structure. These features, as an ideal source to emit or absorb radiation make the black body valuable for many applications. For an ideal black body absorbtivity and emissivity is one. The concept of a blackbody is an idealization, since real surface do not absorb all the radiant energy that falls on them, they reflect radiation to some extent, and do not radiate all thermal energy theoretically possible.

In practical applications for thermal pyrometers, the transfer of thermal energy takes place at temperatures above absolute zero. Ptevost's theory of exchanges states that for two black bodies in sight, each will radiate energy to the other, and hence the net energy transfer is,

$$\Delta H = \sigma (T_1^4 - T_2^4) \text{W/m}^2$$

T_1 and T_2 are the absolute temperature with $T_1 > T_2$

The ratio of the thermal energy radiated by a real surface to the energy that would be radiated by a perfect black body at the same temperature is known as the real surface's emissivity. Emissivity is defined as the ratio of the energy radiated by an object at a given temperature to the energy emitted by a perfect radiator, or blackbody, at the same temperature. The emissivity of a blackbody is 1.0. All values of emissivity fall between 0.0 and 1.0.

$$H_\lambda = \varepsilon_\lambda H_{0\lambda}$$

Where ε_λ = emissivity for the wavelength

A blackbody is an idealized physical body that absorbs all incident electromagnetic radiation. A blackbody in thermal equilibrium, at a constant temperature emits electromagnetic radiation called blackbody radiation. A blackbody in thermal equilibrium,

1. It is an ideal emitter if it emits as much or more energy at every frequency than any other body at the same temperature.
2. It is a diffuse emitter if the energy is radiated isotropically, independent of direction.

15.16 Gray Body

The body which emits less thermal radiation than a perfect blackbody or its surface emissivity (ε) is less than one but is constant over all frequencies. It is useful approximation to some real world materials over some frequency ranges. The spectral emission of gray body is shown in Fig. 14.26.

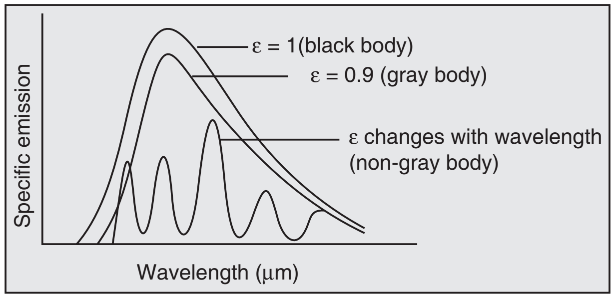


Fig. 15.26.

15.17 Black Body to Real Objects

A perfect blackbody is only a physical abstraction which does not exist in real world. Each body radiates electromagnetic radiation at a temperature above zero (–273.15°C = 0K). This radiation is nothing but the body thermal energy which is being converted into electromagnetic energy and therefore termed as thermal radiation. Real materials show slightly different behavior as compared to an ideal black body. The properties of the real objects always deviate from those of an ideal blackbody. The radiation incident on the real body may undergo following physical phenomenon like reflection, absorption and transmission each term are explain below:

1. **Absorptivity.** The fraction of the irradiation absorbed by a surface is called the absorptivity of a material. It can be characterized by both a directional and spectral distribution. It is understood that surfaces may exhibit selective absorption with respect to wavelength and direction of the incident radiation. However, for most engineering applications, it is desirable to work with surface properties that represent directional averages.
2. **Reflectivity.** The reflectivity of a surface describes the fraction of incident radiation reflected by a surface. If the intensity of the reflected radiation is independent of the direction of the incident radiation and the direction of the reflected radiation.
3. **Transmissivity.** The remaining part of the radiation is transmitted out and the amount of radiation transmitted through a surface is transmissivity. This process too may be selective depending on the nature of the material and the incident radiation.
4. **Emissivity.** The emissivity varies with the surface condition of the object and also with temperature variation and wavelength. If this value is not accurate, then the true temperature cannot be measured. In other words, a variation or change in emissivity will cause a change in the indications.

15.18 Pyrometer

A pyrometer is a non-contacting device that intercepts and measures thermal radiation, a process known as pyrometry. This device can be used to determine the temperature of an object surface. Although the term pyrometer is generally considered to apply to instruments that measure high temperatures only, some pyrometers are designed to measure low temperatures. A heated object gives off electromagnetic radiation. If the object is sufficiently hot, it will give off visible light, ranging from dull red to blue-white. Even if the object is not hot enough to glow, however, it gives off infrared radiation.

Fig. 15.27 shows the basic radiation pyrometers. The energy radiated from a hot body is a function of its temperature. The heat radiated by the hot body is focused on a radiation detector. The radiation detector is blackend and it absorbs all or almost all radiation falling on it.

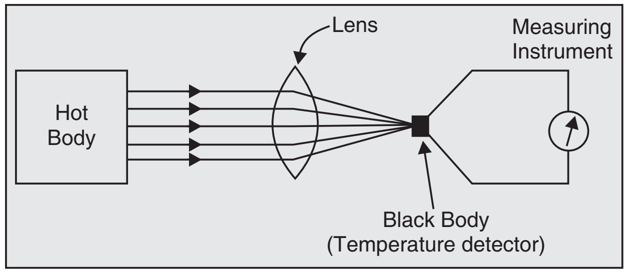


Fig. 15.27.

Radiation pyrometer is used when temperature to be measured is very high and physical contact with the heat body is impossible. Radiation pyrometers are used under conditions where corrosive vapours or liquid would destroy thermocouples, resistance thermometer and Thermistor. These pyrometers also find applications where the temperatures are above the range of thermocouple. Radiation pyrometer measures the radiant heat emitted or reflected by a hot object. Thermal radiations are electromagnetic radiation lies in the wavelength region from about 0.1 to 100 micrometer.

The classified of pyrometer according to the wavelength bands are Broadband pyrometer and Narrow band pyrometers. We will discussed each pyrometer one by one in the following pages.

1. **Broadband pyrometers.** Broadband pyrometers are simplest and less expensive device which have the response from 0.3 microns wavelength to an upper limit of 2.5 to 20 microns. The name itself indicates that these pyrometers measure a significant fraction of the thermal radiation emitted by the object. They greatly rely on the emissivity of the surface being measured. The path to the target must be clear from water vapor, dust, smoke, steam and radiation absorptive gases present in the atmosphere, as these can attenuate emitted radiation from the target resulting in inaccurate measurements. Also, the optical system and sighting window should be clean. High and constant emissivity at longer wavelengths makes these pyrometers suitable for measuring temperature of organic materials.
2. **Narrow band pyrometers.** Optical pyrometers can be considered a subset of narrow band devices. There are several other categories in narrow band pyrometers single color pyrometer and ratio type pyrometer each are given below:
   - **(a) Single color pyrometers.** These pyrometers operate over a narrow range of wavelengths. They are also called as single color pyrometers. The spectral response of these pyrometers is usually less than 1 micron. They are normally used for measuring glass at 5.14 μm. Metals can also be measured as their rate of emissivity is high only in a narrow band. The spectral response of the particular device depends on the type of the detector used. For an instance, the response of a pyrometer with a silicon cell detector is around 0.9 – 1.1 microns. These pyrometers are can work on selected wavelength range with the help of filters. But for this more sensitive detectors and advances in signal amplifiers are required.
   - **(b) Ratio radiation pyrometers (two colour pyrometers).** This pyrometer measures the radiated energy of an object between two narrow wavelength bands and then calculates the ratio of the two energies. This ratio is the function of the temperature of the object. This is also called as two colour pyrometer because the two wavelengths corresponded to different colors in the visible spectrum.

The optical pyrometers can be considered a subset of narrow band devices. Fiber optic pyrometers can be classified as wide band, narrow band, or ratio devices. The detail explanation of various types of pyrometer instrument are given in following pages.

15.19 Total Radiation Pyrometer

The total radiation pyrometer receives a sample of the total radiation of a hot body and focuses it on to a temperature sensitive transducer. It includes both visible and invisible (infrared) radiations. The wavelength of the light in visible range is from 0.3 to 0.72 μm, whereas the infrared radiations are associated with relatively large wavelength of 0.72 to 1000 μm. Infrared radiation required special optical materials for focusing. Ordinary glass is unsatisfactory as it absorbs infrared radiations.

Fig. 15.28 shows a diagram of the Fery's total radiation pyrometer. It consists of blackened tube open at one end to receive the radiations from the object whose temperature is to be measured. The other end of the tube has a radiation from the target falls on the concave mirror, which can be moved back and forth to focus radiation on the surface of the radiation receiver. Normally platinum black surface is used because its absorptive is around 0.98. The hot junction of a thermocouple is attached to the radiation receiver. A shielding element is provided between the target and thermocouple to protect the thermocouple junction from receiving direct radiation. The developed emf is read on a millivoltmeter which may be calibrated to a temperature scale.

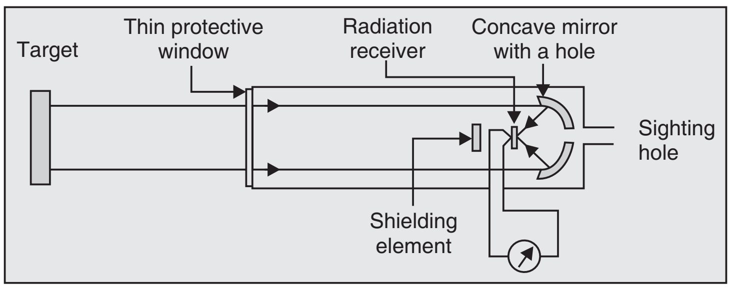


Fig. 15.28.

The focusing is done by convex lens systems through with the possibility of selective absorption by the lens system, while a concave mirror is free from such source of error. The presence of absorption media, such as smoke, dust etc., in the intervening space as well as the change in emissivity of the radiation receiver by oxidation or by any other cause may upset the calibration of the instrument. Due to the fourth power law ($H \propto T^4$) the characteristics of total radiation pyrometer are non-linear and the device exhibit poor sensitivity in the lower temperature ranges. Total radiation pyrometer cannot be used for temperature lower that 600°C since at lower temperature error may be introduced by the fact that the temperature of the pyrometer itself may not be negligible as compared with that of hot body. The total radiation pyrometer is used for a temperature range of 1200°C to 3500°C.

15.20 Infrared Radiation Pyrometer

This is also known as Selective Radiation Pyrometer. Above temperature of 550°C surface starts to radiate visible light energy. There is a proportional increase in infrared energy as the temperature of the surface radiating body increase. The energy level in the radiations from a hot body is distributed in the different wavelengths. As the temperature increase the emissive power shifts to shorter wavelength.

Fig. 15.29 shows the infrared radiation pyrometer. Various types of photo-electric transducers are commonly used for infrared transducers. For industrials application photo-voltaic cells are used. These cells respond to the wavelength in infrared region and may be used to measure temperature down to 400 °C.

The infrared radiation is focused on a photo-voltaic cell, ensure that the cells does not become overheated. The core of radiation passing to the cell is defined by the area of the first diaphragm. The protective windows is used to protect the cell and filter from physical damages, it's made up of thin glass. The filter is used on the range of 100 °C to 1200 °C. This filter help in preventing the photo cell form being overheated.

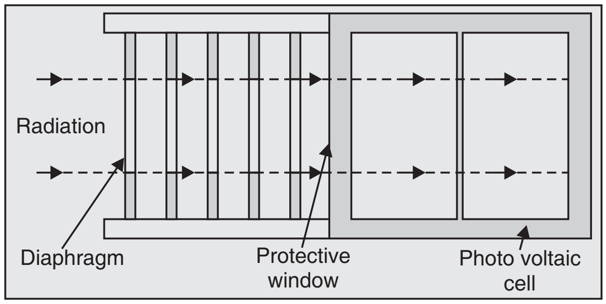


Fig. 15.29.

Infrared systems depend on the transmission of the infrared radiant emery being emitted by a heated body to a detector in the measuring system. The sensor head is focused on the object whose temperature is being measured and controlled.

The infrared energy falling on the detector either changes the detector resistance in proportion to the temperature as in the case of thermistor or generates an emf in the detector such as a thermopile. The change in resistance or generated emf in then indicated on a meter.

Infrared pyrometer are commonly used in the plastic industries especially in thermoforming and blow molding applications to measure the temperature of the heated polymer as it is being formed.

15.21 Optical Pyrometer

An optical pyrometer determines the temperature of a very hot object by the color of the visible light it gives off. The color of the light can be determined by comparing it with the color of an electrically heated metal wire. In one type of pyrometer, the temperature of the wire is varied by varying the strength of the current until the operator of the instrument determines that the color of the wire matches the color of the object. A dial, operated by the current that heats the wire, indicates the temperature. The Optical Pyrometer is a highly-developed and well accepted noncontact temperature measurement device. Optical Pyrometers work on the basic principle of using the human eye to match the brightness of the hot object to the brightness of a calibrated lamp filament inside the instrument.

Any metallic surface when heated emits radiation of difference wavelengths which are not visible at low temperature but about 550°C, radiations is shorter wavelength are visible to eye and from the color approximate temperature is measured. The approximate values of temperature for color us given in Table 15.2.

Table 15.2. Color Scale

Color	Temperature in °C
Dark Red	540
Medium Cherry Red	900
Orange	900
Yellow	1010
White	1205

The principle of temperature measurement by brightness comparison is used in optical pyrometer. A color variation with the growth in temperature is taken as an index of temperature. This optical pyrometer compares the brightness of image produced by temperature source with that of reference temperature lamp. The current in the lamp is adjusted until the brightness of the lamp is equal to the brightness of the image produced by the temperature source. Since the intensity of light of any wave length depends on the temperature of the radiating object, the current passing through the lamp becomes a measure of the temperature of the temperature source when calibrated.

Fig. 15.30 shows the optical pyrometer. An eye piece is at one end and an objective lens at the other end. A power source, rheostat and ammeter connected to a reference temperature bulb. The lamp is powered through a battery and variable resistor connected in series with it. An ammeter is inserted in series with the filament so as to measure intensity of light in terms of current flowing through the filament. The brightness of the filament can be adjusted by varying variable resistor. An absorption screen is placed in between the objective lens and reference temperature lamp. The absorption screen is used to increase the range of the temperature which can be measured by the instrument.

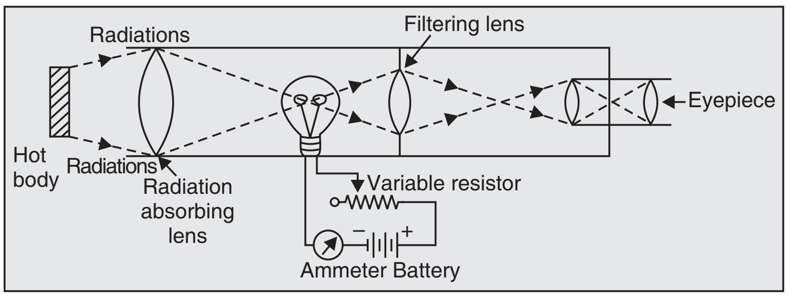


Fig. 15.30.

When a temperature source is to be measured, the radiation from the source is focused onto the filament of the reference temperature lamp using the objective lens. Now the eye piece is adjusted so that the filament of the reference temperature lamp is in sharp focus and the filament is seen super imposed on the image of the temperature source. The radiation from the source is emitted and the optical objective lens captures it. The lens helps in focusing the thermal radiation on to the reference bulb. The observer watches the process through the eye piece and corrects it in such a manner that the reference lamp filament has a sharp focus and the filament is superimposed on the temperature source image. The observer starts changing the rheostat values and the current in the reference lamp changes. This in turn, changes its intensity. This change in current can be observed in three different ways.

1. Fig. 15.31 shows the condition when the filament is dark. That is filament is cooler than the temperature source.

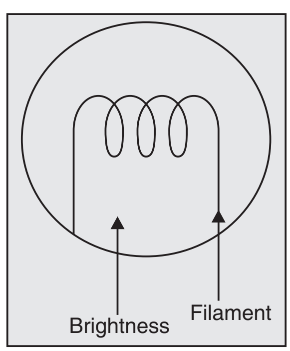


Fig. 15.31.

2. Fig. 15.32 shows the condition when filament is bright. That is the filament is more hotter than the temperature source.

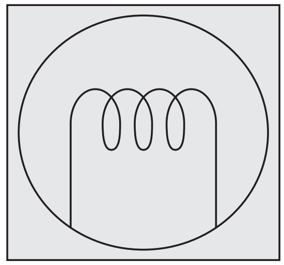


Fig. 15.32.

3. Fig. 15.33 shows the condition when filament disappears. Thus, there is equal brightness between the filament and temperature source. At this time the current that flows in the reference lamp is measured, as its value is a measure of the temperature of the radiated light in the temperature source.

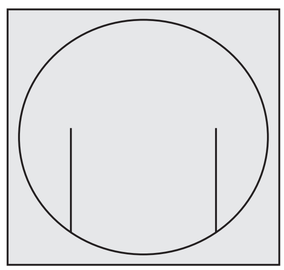


Fig. 15.33.

There are some limitation of optical temperature of more than 700°C can only be measured since illumination of the temperature source is a must for measurement. It cannot be used for the continuous monitoring and controlling purpose.

Advantages

Some of the advantages of optical pyrometer are given below:

1. Simple assembling of the device enables easy use of it.
2. There is no need of any direct body contact between the optical pyrometer and the object.
3. This device can not only be used to measure the temperature, but can also be used to see the heat produced by the object.

Disadvantages

Some of the disadvantages of optical pyrometer are given below:

1. As the measurement is based on the light intensity, the device can be used only in applications with a minimum temperature of 700°C.
2. The device is not useful for obtaining continuous values of temperatures at small intervals.

Applications

Some of the application of optical pyrometer are given below:

1. Used to measure temperatures of liquid metals or highly heated materials.
2. Can be used to measure furnace temperatures.

15.22 Fiber Optic Radiation Pyrometers

Pyrometers with fiber optics are used for applications involving strong electrical or magnetic interference fields. This makes it possible to place the sensitive electronic system outside the danger zone. Fig. 15.34 shows the Fiber optic pyrometers. It can be classified as wide band, narrow band, or ratio devices. These devices use an optical fiber to direct the radiation to the detector. The spectral response of these fibers is extended to about 2 microns so it is useful in measuring object temperatures to as low 100°C. An optical head, a glass fiber and a signal processing unit together forms a fiber optic pyrometer. The optical head does not contain any electronics. It is basically used where the sighting path to the target is not clear. In an optical fiber the captured radiation is transmitted by total internal reflection. Therefore signal can be transmitted without any loss. Optical fiber consists either of a single fiber (mono-fiber) or multi-fiber.

Fig. 15.34.

Advantages of Fiber optics over other pyrometer

Some of the main advantages of fiber optics over other pyrometers are:

1. They are unaffected by strong electromagnetic fields therefore can be easily used where such type of interference fields are present.
2. It can be placed in hard-to-reach fields.
3. As it does not carry any electrical current, so it is ideal for explosive and hazardous locations.
4. Optical head and the fiber are free from any electronic components so cooling is not required and hence can be used to measure high temperatures (near about 250 °C).
5. The diameter of a optical fiber is small therefore the small spot size can be obtained.

15.23 Radiation Receiving Elements

The main purpose of a radiation temperature measuring device is to convert the radiant energy into a suitable from for indication of temperature. There are the following types of radiation receiving elements, they are given below:

1. Vacuum Thermocouple

A vacuum thermocouple is a device in which a very sensitive thermocouple strip but no filament is bonded to it is enclosed in an evacuated tube or bulb with a suitable window to admit the radiant energy. The heat loss from the thermocouple due to conduction and convention is greatly reduced because of the evacuated envelope. This result in appreciable temperature rise of the detecting junction and therefore a measurable emf can be obtained even for a small radiant energy received at the detecting junction. Since the thermocouple has a low mass and is placed in vacuum, it can respond to rapid changes in radiant energy.

2. Thermopile

Thermopile detector output is proportional to incident radiation. A thermopile is made of thermocouple junction pairs connected electrically in series. The absorption of thermal radiation by one of the thermocouple junctions, called the active junction, increases its temperature. The differential temperature between the active junction and a reference junction kept at a fixed temperature produces an electromotive force directly proportional to the differential temperature created.

Fig. 15.35 the thermopile elements of a series of thermocouples of alternate material A and B are placed between a heat source and a heat sink. The hot junction comes into thermal equilibrium with the high temperature surroundings producing an emf at the leads. If a current flow then the thermal energy is converted into electrical energy. The remaining energy absorbed at the hot junction is rejected to the heat sink at the cold junction.

The two most important parts of all thermal radiation detectors are the absorber and the temperature transducer. When a thermopile is used, the radiant energy is absorbed into a layer coated on the active junction which acts as the heat source, and the difference of temperature between the active and the reference junctions is translated into an output voltage through the Seebeck effect.

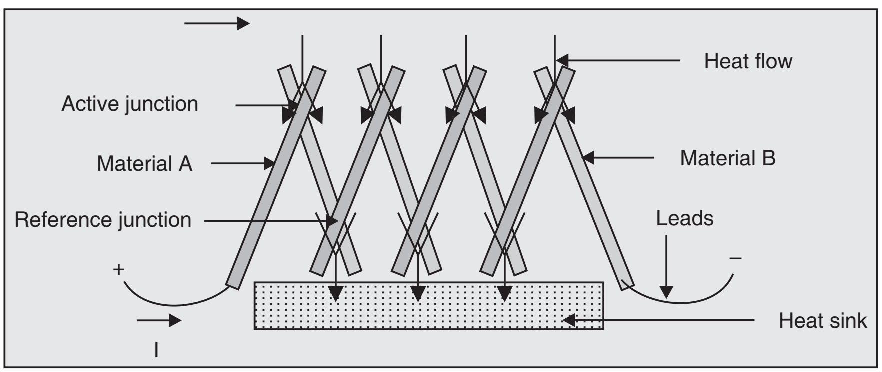


Fig. 15.35.

3. Bolometer

A bolometer or calorimeter is a detector for radiation. It is a thermal device that changes its electrical resistance with temperatures. The resistance of the bolometer changes in response to the thermal radiation focused on it.

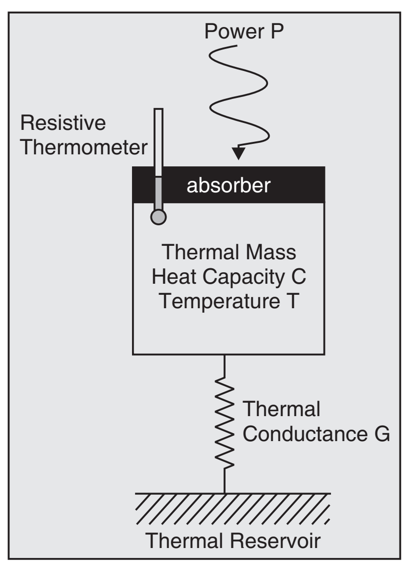


Fig. 15.36.

Fig. 15.36 shows a bolometer consists of an absorptive element, such as a thin layer of metal, connected to a thermal reservoir through a thermal link. A bolometer consists of an absorptive element, such as a thin layer of metal, connected to a thermal reservoir through a thermal link. The result is that any radiation impinging on the absorptive element raises its temperature above that of the reservoir the greater the absorbed power, the higher the temperature. The temperature change can be measured directly with an attached resistive thermometer, or the resistance of the absorptive element itself can be used as a thermometer. The Bolometers are directly sensitive to the energy left inside the absorber. The most sensitive bolometers are very slow to reset. On the other hand, compared to more conventional particle detectors, they are extremely efficient in energy resolution and in sensitivity. They are also known as thermal detectors. They are produced from thin foils or metal films. Today, most bolometers use semiconductor or superconductor absorptive elements rather than metals. These devices can be operated at cryogenic temperatures, enabling significantly greater sensitivity.

4. Photo-electric Transducers

Photo-electric transducers used for detection of radiation energy are photo-emissive cells, photo-conductive cells and photovoltaic cells. The output of these cells varies with the amount if radiant energy incident on them. In general the photo-electric transducers are sensitive to given portions of the spectrum and therefore they are used with partial and optial radiation pyrometers.

15.24 Temperature Measurement of Flowing Liquids

Temperature of a fluid is measurement by immersing the thermometer elements or probe into the fluid which is held steady and at rest. There is no relative motion between the fluid and the thermometer. The thermometer should be moving with the fluid with the same velocity. As this is impossible, the fluid in motion is brought almost the rest in the vicinity of the temperature probe kept inside an enclosure known as stagnation chamber. Due to the velocity suddenly becoming zero, the kinetic energy of the flowing mass is converted to thermal energy, resulting in an temperature of the fluid trapped in the stagnation chamber. Assuming that there is no heat transfer of any other kind of chamber, and treating the fluid to have been brought to rest adiabatically, it can be shown that the increase in the temperature of the fluid around the thermometer is given by,

$$\Delta T = (T_1 - T_2) = \frac{V^2}{2C_P}$$

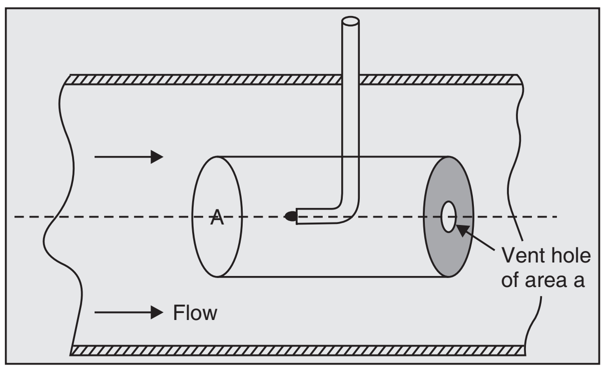


Fig. 15.37.

Where T_1 = stagnation temperature of the fluid in the stagnation chamber
T_2 = free-stream or static temperature
V = free-stream velocity
C_P = specific heat of the fluid at constant pressure

Fig. 15.38 shows stagnation chamber with a ventilating hole. The probe design varies with the application and no probe is really free from the errors due to the small heat losses from the conduction and radiation. Even through the conduction and radiation losses are zero the temperature indication will still be lower than the stagnation temperature. Each probe is tested for its deviation in its performance and is expressed in terms of a recovery factor R, defined by,

$$R = \frac{T_{th} - T_2}{T_1 - T_2}$$

Where T_{th} is the stagnation temperature indicated by thermometer. R is generally determined by experiment and usually between 0.75 and 0.99. Fig. 15.38 shows a probe that has a recovery factor of 0.99 to 1. The thermometer element may be kept open and bare for fast response.

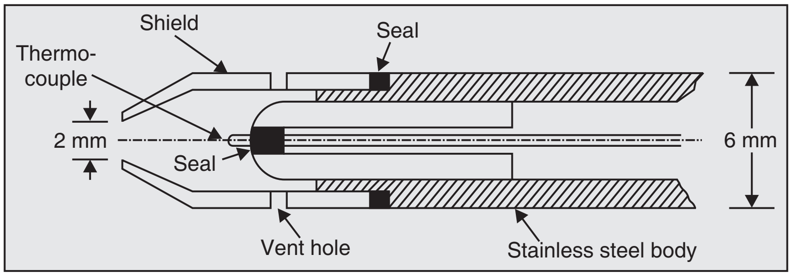


Fig. 15.38.

15.25 Temperature Compensation

It is obvious that the temperature of the strain gauge and the body on which it is cemented should remain at the same temperature at which they are cemented together, throughout the period of strain measurement. Then any increase in resistance of the gauge can be considered to be due to strain of the structure transmitted to the strain gauge. In practice, however, it is difficult to hold the entire system under, which may be large or small in size, at one temperature, throughout the period of measurement. Wheatstone bridge as shown in Fig. 15.39 in having two identical gauges, one a dummy gauge and the other an active gauge, in a unit ratio. The dummy gauge is cemented to the surface of an identical structure, kept free from any mechanical stress. When both structures are under stress-free conditions and at the same temperature, the bridge is balanced. An equal rise in temperatures of both the structures raises equally the resistances value of both the active and dummy gauge, and the bridge still remains balanced. When the test structure is strained, the resistance of the active gauge only goes up and the unbalance voltage is proportional to the strain.

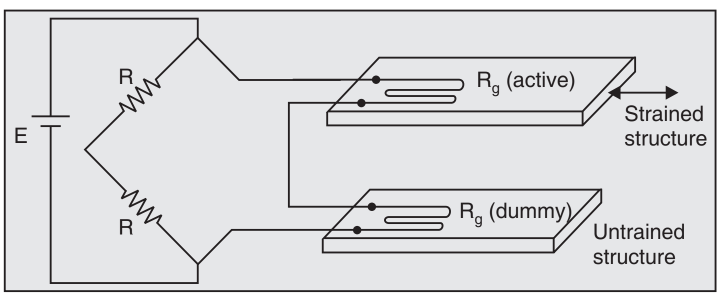


Fig. 15.39.

If the strain in the transverse direction is zero, the second gauge has its resistance effected by temperature only and the effect of temperature is the same for both gauges, as they are proximate to each other as shown in Fig. 15.40.

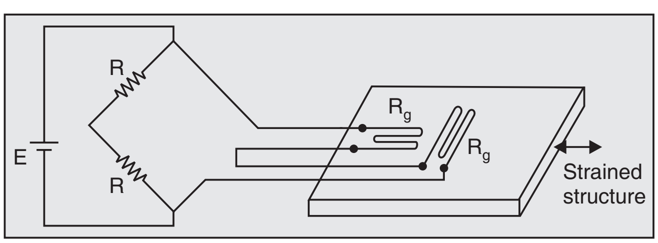


Fig. 15.40.

Fig. 15.41 shows the two gauges are strained equally but in opposite sense. Such an arrangement is possible only with basic structures such as a cantilever which may have that strain gauges mounted on opposite sides of cantilever. It is essential that both the top and bottom surfaces of the cantilever are always at the same temperature and such a condition is possible only with cantilevers and other are physically small in size.

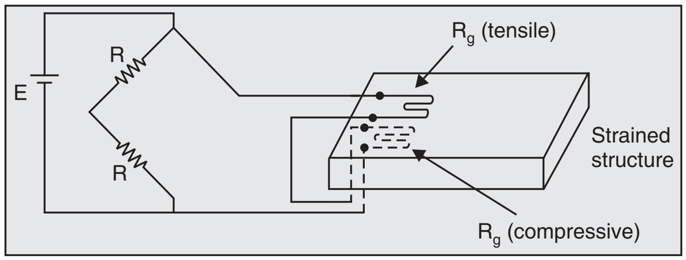


Fig. 15.41.

Fig. 15.42 shows for temperature compensation while doubling the value of unbalanced obtained. Two active gauges mounted side by side on the top surface are under tensile strain, and occupy the diagonally opposite arms of the Wheatstone bridge, while the other two compressive strains occupy the remaining two arms.

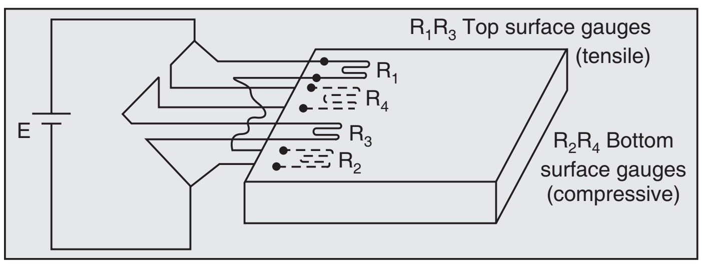


Fig. 15.42

15.26 Measurement of Torque

Torque measurement is based upon the angular displacement or twist in the shaft in a calibrated length of torque tube attached to the shaft. The strain is sensed by transducers and is measured. The strain measurements are then interpreted in terms of torque by proper calibration. These measurements can be used for measurement of proper if combined with proper speed measuring devices. The measurement of torque required in many engineering fields specially in rotating machines. There are various methods for measuring torque, they are given below:

15.27 Strain Gauge Type Torque Measurement

In strain gauge type torque meter, the strain gauge elements are mounted in pairs each subtending an angle 45° to the shaft axis, on one side of the shaft. One gauge measured the increase in length (in the direction in which the surface is under tension) and the other measures the decrease in the length in the other direction. Another similar pair is mounted on the opposite side of the shaft. In Fig. 15.43 strain gauges 3 and 4 are mounted on the opposite side of the shaft. The cross-section view of the arrangement is shown in Fig. 15.43.

The torque sensor can be connected to its power source and signal conditioning electronics circuit. The excitation voltage for the strain gauge is inductively coupled, and the strain gauge output is converter to a modulated pulse frequency. This arrangement has the following advantages, they are given below:

1. It is fully temperature compensated.
2. It provides automatic compensation for bending and axis loads.
3. It gives the maximum sensitivity for a given temperature.

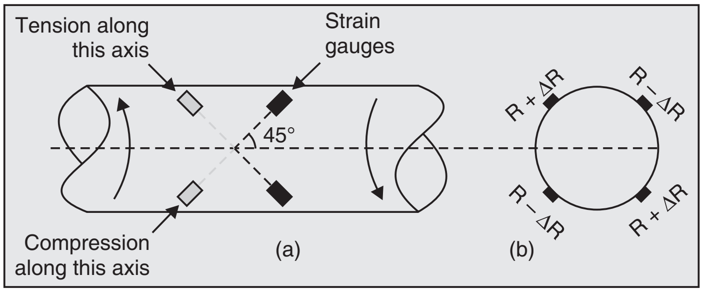


Fig. 15.43.

Fig. 15.44 shows the inductive coupling of the rotating Wheatstone bridge of strain gauges to power and output electronics. Instead of rotating transducer, the infrared torque sensor is often used as a contactless method of getting the torque signal from the rotating sensor back to the stationary world. The IR beam is used to power circuit on the rotating sensor. The circuit provides excitation voltage to the strain gauge bridge, and digitizes the output signal. The digital output signal is then transmitted via infrared light to stationary receiver diodes, where another circuit checks the digital signal for errors and converts it back to an analogue voltage.

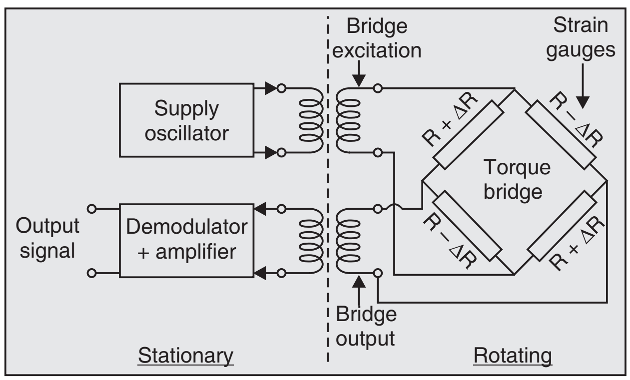


Fig. 15.44.

15.28 Magnetostrictive Torque Transducer

Fig. 15.45 shows the magnetostrictive torque transducer. A coating of magnetostrictive material is rigidly attached to the shaft and an easy axis of magnetization is created in the tangential direction by mechanical stresses. The coating is then magnetized by passing a pulsed current through the shaft (A). A newer design replaces the single circularly polarized coating with one divided into two oppositely polarized circumferential regions. The coating is magnetized by means of two identical permanent magnets brought close to the shaft while the shaft is rotating slowly (B).

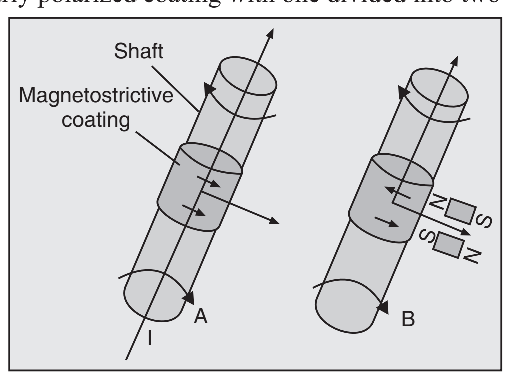


Fig. 15.45.

An axis of magnetization is created in the tangential direction by mechanical stresses. The coating is then magnetized by passing a pulsed current through the shaft. Transducer operation is based on the reorientation of the circumferentially directed remanent magnetization in the coating.

The remanent magnetization, the amount of magnetization that remains in a material after an externally applied field has been removed, is initially oriented in the tangential direction, and the magnetic field created by the shaft is zero. When torque is applied to the shaft, the remanent magnetization reorients and becomes increasingly helical as the torque value increases. This reorientation produces a magnetic field, proportional to the torque, to be detected by a nearby magnetic-field sensing device. The output signal from this device is conditioned in associated electronic circuitry to provide a signal that can be used in a control unit. The drawback is that the generated magnetic fields are weak and the orientation of the magnetization in the coating can be affected by an external axial magnetic field-Earth's, for instance.

15.29 Measurement of Vibration and Acceleration

Vibration is oscillating motion of a particle or body about a fixed reference point. Such motion may be simple harmonic (sinusoidal) or complex (non-sinusoidal). It can also occur in various modes - such as bending or translational modes - and, since the vibration can occur in more than one mode simultaneously

The quantities which are required to be measurement of vibration are displacement, velocity and acceleration. Displacement, velocity and acceleration are related to each other and if any one of three variable concerned is measured the other two can be determined by integration or differentiation employing electronics device.

Acceleration, a vector quantity, is the time rate of change of velocity with respect to a reference system. When the term acceleration is used alone, it usually refers to linear acceleration a, which is then related to linear velocity u, and time t by $a = du/dt$. Angular acceleration is related to angular velocity ω and time t by $a = d\omega/dt$. Mechanical vibration is an oscillation wherein the quantity, varying in magnitude with time so that this variation is characterized by a number of reversals of direction, is mechanical in nature.

This quantity can be stress, force, displacement, or acceleration; however, in measurement technology the term vibration is usually applied to vibratory acceleration and sometimes to vibratory velocity. Mechanical shock is a sudden nonperiodic or transient excitation of a mechanical system.

Seismic Transducers

Fig. 15.46 shows a seismic mass it consists of a mass m suspended from the transducer case a by a spring of stiffness k. The motion of the mass within the case may be damped by a viscous fluid or electric current with damping coefficient c. It is desired to measure the motion of the moving part whose displacement with respect to fixed space is indicated by u. When the transducer case is attached to the moving part, the transducer may be used to measure displacement, velocity, or acceleration, depending on the portion of the frequency range which is utilized and whether the relative displacement or relative velocity $d\delta/dt$ is sensed by the transducing element. The typical response of the mass-spring system is analyzed and applied to the interpretation of transducer output.

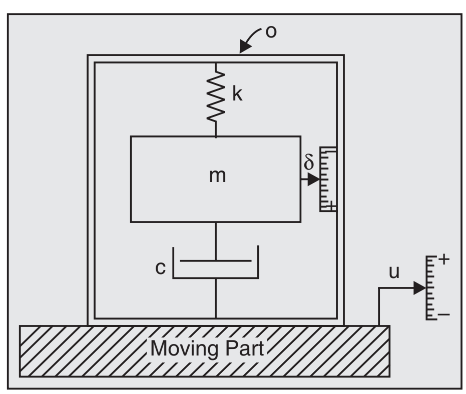


Fig. 15.46.

Consider a transducer whose case experiences a displacement motion u, and let the relative displacement between the mass and the case be δ. Then the motion of the mass with respect to a reference fixed in space is $\delta + u$, and the force causing its acceleration,

$$= -m\frac{d^2u}{dt^2} = -m\frac{d^2(\delta + u)}{d^2t}$$

The force applied by the spring is $-k\delta$ and the force applied by the damper is $-c(d\delta/dt)$, where c is the damping coefficient. Adding all force terms and equating the sum to zero we get,

$$= -m\frac{d^2(\delta+u)}{d^2t} - c\left(\frac{d\delta}{dt}\right) - k\delta = 0$$

$$m\frac{d^2\delta}{d^2t} + c\left(\frac{d\delta}{dt}\right) + k\,\delta = -m\frac{d^2u}{d^2t}$$

Assume that the motion u is sinusoidal $u = u_o \cos \omega t$, where $\omega = 2\pi f$ is the angular frequency in rasdians per second and f is expressed in cycles per second. Neglecting transient terms, the response is define by $\delta = \delta_o \cos(\omega t - \theta)$, then

$$\frac{\delta_o}{u_o} = \frac{\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\omega\frac{c}{m}\right)^2}}$$

$$\theta = \tan^{-1}\left(\frac{\omega\frac{c}{m}}{\frac{k}{m} - \omega^2}\right)$$

The undamped natural frequency f_n of the instrument is the frequency at which,

$$\frac{\delta_o}{u_o} = \infty$$

When the damping is zero ($c = 0$) of the frequency at which $\theta = 90°$, then

$$\omega_n = 2\pi f_n = \sqrt{\frac{k}{m}}$$

Thus, a stiff spring or a light mass produces an instrument with a high natural frequency. A heavy mass or compliant spring produces an instrument with a low natural frequency. The damping in a transducer is specified as a fraction of critical damping. Critical damping c is the minimum level of damping that prevents a mass-spring transducer from oscillating when excited by a step function or other transient. It is defined by,

$$C_c = 2\sqrt{km}$$

Thus, the fraction of critical damping ζ,

$$\zeta = \frac{c}{C_c} = \frac{c}{2\sqrt{km}}$$

The maximum acceleration is given by, $\omega^2 \times$ maximum displacement of mass

Acceleration transducers (accelerometers) are used to measure acceleration as well as shock and vibration. Their sensing element is the seismic mass, restrained by a spring. The motion of the seismic mass in this acceleration-sensing arrangement is usually damped. Acceleration transducers (accelerometers) are used to measure acceleration as well as shock and vibration. Their sensing element is the seismic mass, restrained by a spring. The acceleration is applied to the transducer case causes motion of the mass relative to the case. When the acceleration stops, the mass is returned to its original position by the spring. This displacement of the mass is then converted into an electrical output by various types of transduction elements in steady-state acceleration transducers whose frequency response extends down to essentially 0 Hz. In piezoelectric accelerometers the mass is restrained from motion by the crystal transduction element, which is thereby mechanically stressed when acceleration is applied to the transducer. Such dynamic acceleration transducers do not respond appreciably to acceleration fluctuating at a rate of less than 5 Hz. They are normally used for vibration and shock measurements.

15.30 Potentiometric Accelerometer

Fig. 15.47 shows the potemtiometric accelerometer. This is used for slowly varying acceleration and vibration. The seismic mass is connected between the spring and dashpot. The wiper of the potentiometer is connected to the seismic mass. The motion of the seimic mass relative to the support of the transducer is sensed by the potentiometer and a proportional voltage output is obtained. In the presence of vibration or acceleration, vibration displacement of seismic mass takes place with respect to the housing of the device. The displacement of mass is transferred to the potentiometers through the wiper. Therefore the resistance of the potentiometer changes. This change in resistance gives the value of displacement and hence the acceleration.

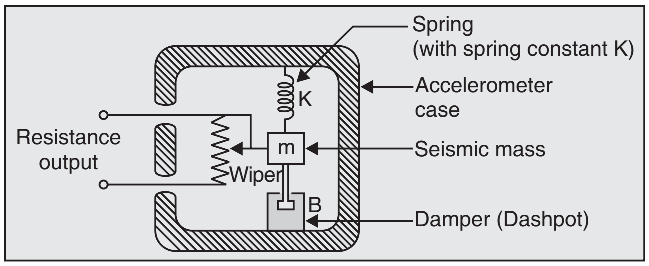


Fig. 15.47.

The main advantage of this system is that is the simplicity in construction. The main disadvantage of this system is very low natural frequency.

15.31 LVDT Accelerometer

A second type of accelerometer takes advantage of the natural linear displacement measurement of the LVDT to measure mass displacement. In these instruments the LVDT core itself is the seismic mass. Displacements of the core are converted directly into a linearly proportional ac voltage.

Fig. 15.48 shows the LVDT accelerometer, the core is attached to two spring steel one at top and other at bottom with the help of rod. When the instrument is subjected to vibrations the sensor core moves up and down the LVDT secondaries give and ac output voltages first of one phase and then, alternately of the opposite phase. The magnitude of this output voltage depends upon the amplitude of the variations. Peak-to-peak magnitude of this output voltage is measured by peak measuring voltmeter.

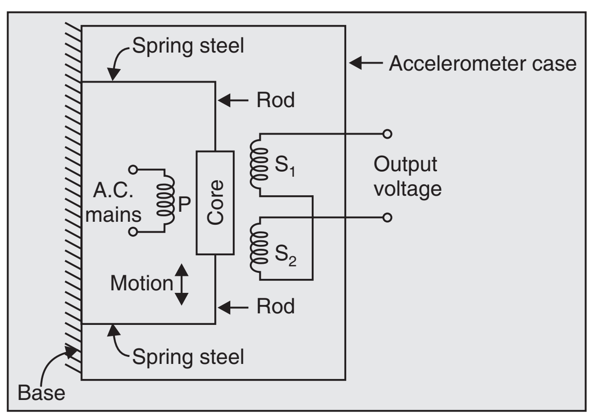


Fig. 15.48.

This instrument has a high natural frequency because of smaller mass of the core and therefore they can be used for measurement of vibration of high frequencies. They offer low resistance to motion than the potentiometers and are capable of much better performance.

15.32 Piezoelectric Accelerometer

The active element of a piezoelectric accelerometer is a piezoelectric material. It based on a property of certain crystal that when it is subjected to stress, a voltage is generated across the crystal. The sensing element of a piezoelectric accelerometer consists of two major parts piezoelectric crystal and seismic mass. With acceleration acting perpendicular to the base, an output is generated by the crystal due to compression force.

Fig. 15.49 shows the piezolelectric accelerometer, the piezoelectric crystal is spring loaded with seismic mass M in contact with the crystal. When the mass crystal is subject to an acceleration the crystal is stressed and force experienced F = M.a. It generates an output voltage across the crystal proportional to the acceleration. With acceleration acting perpendicular to the base, an output is generated by the crystal due to compression. Crystal materials include quartz and several ceramic mixtures such as titanates, niobates, and zirconates.

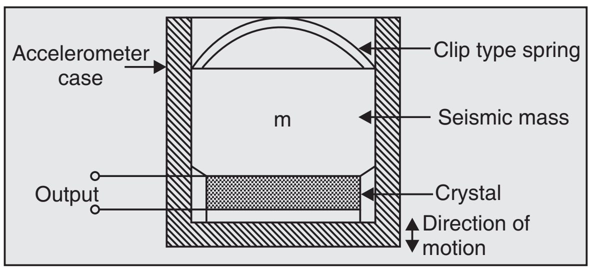


Fig. 15.49.

The main advantage of the piezoelectric accelerometer is that the crystal acts as a spring and damper in the instrument. The natural frequency of the crystal is very high, hence it can be used for very high frequency vibration measurements.

The disadvantage of such accelerometer is that the output voltage must be measured with a instrument having very high impedance to avoid loading effects as the electrical impedance of the piezoelectric crystal is very high.

It does not give an oputput voltage for constant acceleration. It based on the characteristics of piezoelectric motion transducers. It widely used for shock and vibration measurement.

15.33 Strain Guage Accelerometer

Strain-guage accelerometers are very popular and exist in several design versions. Some use unbonded metal wire stretched between the seismic mass and a stationary frame or between posts on a cross-shaped spring to whose center the seismic mass is attached and whose four tips are attached to a stationary frame. Other designs use bonded-metal wire, metal foil, or semiconductor guages bonded to one or two elastic members deflected by the displacement of the seismic mass. The recently developed micromachined accelerometers also employ strain-guage transductions.

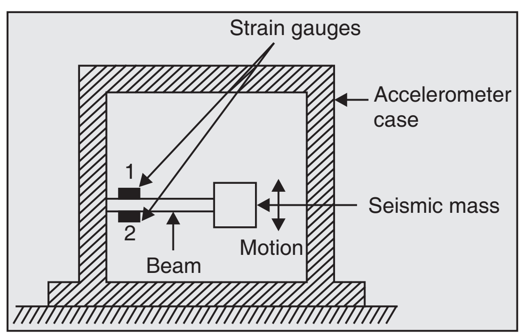


Fig. 15.50.

Fig. 15.50 shows the strain guage type accelerometer. The seismic mass is attached to the accelerometer frame through a low-deflection elastic beam. The strain guages are mounted on this beam. The seismic mass is constrained in the up and down and in and out directions by guides. But the guides permit free movement only in left and right direction.

Application of Accelerometer

Some of the main application accelerometer are given below:

1. Accelerometers can be used to measure vehicle acceleration. They allow for performance evaluation of both the engine/drive train and the breaking systems
2. Accelerometers can be used to measure vibration on cars, machines, buildings, process control systems and safety installations.
3. Modern electronic accelerometers are used in remote sensing devices intended for the monitoring of active volcanos to detect the motion of magma.
4. The PlayStation uses the Dual Shock 3 remote which uses a three axis accelerometer that can be used to make steering more realistic in racing games, such as Motorstorm and Burnout Paradise.
5. Camcorders use accelerometers for image stabilization.

15.34 Calibration of Accelerometers

Accelerometers for the measurement of steady or slowly varying accelerations may be calibrated up to an acceleration of +1*g* (the standard value of *g* is 9.80665 m/s^2) by using the earth's gravitational attraction. The accelerometer is mounted on a tilting table from which the angle θ between the sensing axis and the vertical can be measured. At $\theta = 0$ the force of gravity on the seismic mass is the same as the inertia force due to an acceleration of 9.8 cos θ m/s^2. At any other angle of θ the corresponding acceleration is 9.8 cos θ m/s^2. For accurate calibration the true value of *g* at the location where the calibration is taking place should be used. The standard value, given above, is approximately correct for temperature latitudes, but *g* varies from 9.832 m/s^2 at the poles to 9.780 m/s^2 at the equator.

Some steady-state accelerometers have provision for applying known forces to the seismic mass along the sensing axis, by means of weights, so that if the value of the seismic mass is known, the accelerometer can be calibrated for accelerations greater than *g* by applying the equivalent of the inertia force. If the construction of the accelerometer does not permit this it may be mounted on a turntable so that its sensing axis is radial; the turntable is then run at known angular velocities of ω rad/s, so that known centripetal accelerations of $\omega^2 r$ m/s^2 are applied, where *r* is the radius is meters to the center of the seismic mass.

Piezoelectric accelerometers cannot usually be calibrated by means of static loadings because their charge leaks away, although if the piezoelectric material is quartz the time constant of the leakage may be several days due to its high electrical insulation. It is usual, however, to calibrate piezoelectric accelerometers by shaking them with simple harmonic motion along the sensing axis, by means of an electro-mechanical exciter. For a primary calibration the amplitude of the motion is measured by means of an interferometer, using a laser as the light source and a phototransistor to convert the interference fringes into electrical pulses. By this means both the amplitude, *x*, and the angular frequency, ω, of the motion may be accurately measured; the amplitude of the acceleration is then $\omega^2 x$.

For a secondary calibration, the accelerometer to be calibrated is mounted 'back-to-back' with one which has already been calibrated to act as a transfer standard, and the same simple harmonic motion is applied by the exciter to both. The acceleration applied to the accelerometer to be calibrated is then read from the one which has been previously calibrated.

Example 15.3. *An accelerometer has a seismic mass of 0.06 kg and a spring constant of 4500 N/m maximum mass displacement is ± 0.025 m. Determine maximum measurable acceleration and natural frequency.*

Solution: Given: $m = 0.06$ kg; $k = 4500$ N/m and $d = \pm 0.05$ m

We know that the natural frequency,

$$\omega_o = \sqrt{\frac{k}{m}}$$

$$= \sqrt{\frac{4500}{0.06}} = 273.86 \text{ rad/s}$$

We also know that the maximum acceleration,

$$= \omega_o^2 \times d$$

$$= (273.86)^2 \times 0.025 = 1875 \text{ m/s } \textbf{Ans.}$$

and the natural frequency,

$$f_o = \frac{\omega_o}{2\pi}$$

$$= \frac{273.86}{2\pi}$$

$$= 44 \text{ Hz } \textbf{Ans.}$$

Example 15.4. *In an LVDT accelerometer the outputs are 0.4 mV/mm with a ± 25 mm core displacement. The spring constant is 300 N/m and the mass of the core is 50 g. Determine the maximum measurable acceleration, natural frequency and sensitivity of the accelerometer*.

Solution: Given: m = 50 g = 0.05 kg; k = 300 N/m maximum measure acceleration = 25 mm = 0.025 m.

We know that the natural angular frequency is given by,

$$\omega_o = \sqrt{\frac{k}{m}} = \sqrt{\frac{300}{0.05}}$$

$$= 77.46 \text{ rad/s}$$

Maximum measurable acceleration is given by,

$$= \omega^2 \times \text{Maximum measurable acceleration}$$

$$= (77.46)^2 \times 0.025$$

$$= 150 \text{ m/s}^2 \textbf{ Ans.}$$

and the natural frequency,

$$f_o = \frac{\omega_o}{2\pi}$$

$$= \frac{77.46}{2\pi} = 12.33 \text{ Hz } \textbf{Ans.}$$

and sensitivity,

$$S = \frac{\text{Maximum measurable acceleration}}{\text{Maximum core displacement} \times \text{Output}}$$

$$= \frac{150}{25 \times 0.4} = 15 \text{ ms}^{-2}/\text{mV } \textbf{Ans.}$$

15.35 Measurement of Liquid Level

The direct conversion to liquid level position to electrical signal is used in many applications. There are several instances where we need to monitor the liquid level in vessels. In some cases the problem is simple, we need to monitor the water level of a tank. But in some cases, the vessel may be sealed and the liquid a combustible one as a result, the monitoring process becomes more complex.

The various methods of the liquid level measurement are resistive method, inductive method, capacitive methods, gamma rays, ultrasonic method and float method. Resistive method is the simplest electrical method of measuring liquid level and also known as the contact point type. The unit is simple and is capable of indicating liquid level directly. The main drawback of this measuring system is that any change in the conductivity of the liquid may lead to serious error. Float method is another simplest method of measurement of liquid level and makes use of a simple float or displacer as the primary sensing element. This method operates on the basis of buoyancy effect. Liquid level, interface level, and the level of granular solids can be measured using the electrical capacitance effect. There are different methods for measuring the liquid level they are given below:

15.36 Ultrasonic Liquid Level Measurement System

Ultrasonic method can be effectively used for measurement of liquid level in a sealed tank. An ultrasonic transmitter and receiver pair is mounted at the bottom of the tank. Ultrasonic wave can pass through the liquid, but gets reflected at the liquid-air interface, as shown in Fig. 15.51. The time taken to receive the pulse is measured, that can be related with the liquid level. For accurate measurement, variation of speed of sound with the liquid density (and temperature) should be properly compensated.

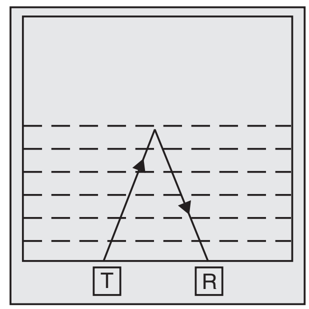


Fig. 15.51.

15.37 Hydrostatic Differential Pressure Type

In this method, the level of liquid is calculated with the help of hydrostatic pressure. The hydrostatic pressure developed at the bottom of a tank is given by,

$$P = h\rho g$$

where h = is the height of the liquid level

ρ = density of the liquid

g = gravitational force

Fig. 15.52 shows the arrangement for measuring the level of liquid. Here we put two pressure tapings, one at the bottom and the other at the top of the tank, we can measure the pressure difference between the top and bottom of the tank. We can measure the differential pressure, which can be calibrated in terms of the liquid level. The drum level of a boiler is normally measured using this basic principle. However proper care should be taken in the measurement compensate for variation of density of water with temperature and pressure.

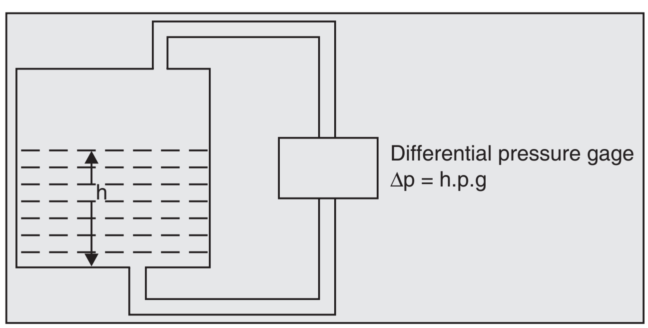


Fig. 15.52.

15.38 Humidity Measurement

Humidity measurement finds wide applications in different process industries. Moisture in the atmosphere must be controlled below a certain level in many manufacturing processes, e.g., semiconductor devices, optical fibers etc. Humidity inside an incubator must be controlled at a very precision level. Textiles, papers and cereals must be dried to a standard storage condition in order to prevent the quality deterioration.

A hygrometer measures the value of humidity in term of relative humidity. Many hygroscopic materials, such as wood, hair, paper, etc. are sensitive to humidity. Their dimensions change with humidity. The transducers used for measurement of humidity use materials which change their electrical properties due to humidity. The change in dimension can be measured and calibrated in terms of humidity.

The humidity can be expressed in different ways: (*a*) absolute humidity, (*b*) relative humidity and (*c*) dew point. Humidity can be measured in different ways. Some of the processes are explain in the following pages.

15.39 Resistive Hygrometer

The resistive hygrometer based on the property that the resistance of material changes with humidity in presence of hygroscopic materials. Some hygroscopic materials like lithium chloride is coated on a resistive electrode. When such electrode is placed to humidity variation then the resistance of electrode also varies. Several electrodes are used which operate for narrow range of relative humidity. In the most commonly used hygrometer 100 to 0 percent humidity change, the resulting resistance change covers wide range $10^4\Omega$ to $10^9\Omega$. But using only single electrodes for 0–100 % relative humidity is not practical. Several electrodes operate for narrow range of relative humidity say 0–5 %, 5–10 % and so on.

Fig. 15.53 shows the resistive hygrometer. It uses a conducting film mixture of hygroscopic material like lithium chloride and carbon. The film bonded on an insulating substrate and kept between the main electrodes. When the electrodes are placed in humidity variations, the resistance changes in electrode take place. In lower relative humidity the resistance is higher as lower lithium chloride us absorbed. But as relative humidity increases, the lithium chloride absorbed is also more thus the resistance is lower.

At the extreme condition high condensation resulted which damages the electrodes. It incorporates temperature correction circuit arrangement to protect electrodes from damages due to high condensation. In some hygrometers the electrodes are operated under constant temperature conditions to protect electrodes against condensation. The response time of the resistive hygrometers is very less which is of the order of few seconds. The accuracy of such electronic resistive hygrometer is within $\pm$ 1.5 % to $\pm$ 2.5 %.

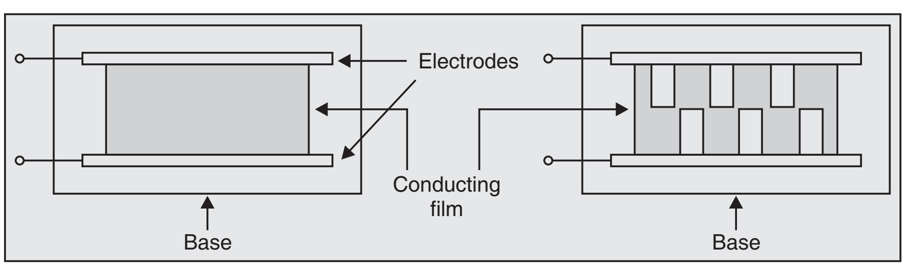


Fig. 15.53.

15.40 Capacitive Hygrometer

The capacitance of the material changes with changes in dielectric constant of the material between two parallel plates. Many solids absorb moisture and their values of the conductance or capacitance change with the degree of moisture absorption. Moisture content changes the capacitance between two electrodes placed inside. By measuring the capacitance variation, the moisture content can be measured.

The main limitation is that changes in dielectric constant due to humidity are very small to measure with standard measuring equipment. Generally transducers are used is oscillator as frequency determining element. The change in the capacitance due to humidity is heterodyned with beat frequency oscillator. It gives the output as frequency change. Such changes in frequency are calibrated in terms of changes in capacitance due to changes in dielectric constant and hence it gives relative humidity.

15.41 Crystal Hygrometer

This method is based on the principle that the humidity change of hygroscopic material is calibrated in terms of the frequency changes of an oscillator.

Fig. 15.54 show the crystal hygrometer. In this we used the crystal of hygroscopic materials. It is coated with hygroscopic polymers. The crystals are used as frequency determining elements in an electronic oscillator. When the humidity changes its changes the mass of the crystal coated with hygroscopic polymers due to water absorb by the crystal. The frequency is also changes which are calibrated in terms of humidity.

This hygrometer is mostly used in telemetry systems as the frequency range is adjustable according to the standard frequency of telemetry.

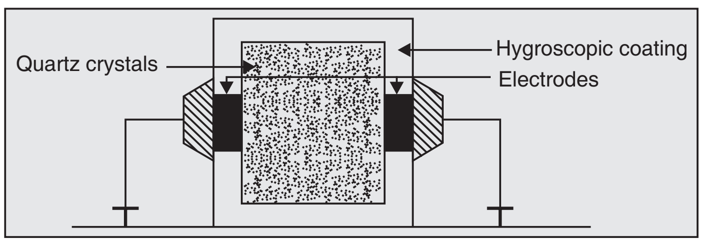


Fig. 15.54.

15.42 Infrared Technique for Humidity Measurement

Water molecule present in any material absorb infrared wave at wavelengths 1.94 μm, 2.95 μm and 6.2 μm. The degree of absorption of infrared light at any of these wavelengths may provide a measure of moisture content in the material.

15.43 Psychrometer Method for Humidity Measurement

Psychrometric method for measurement of relative humidity is a popular method. In this method two bulbs dry bulb and wet bulb are used. The wet bulb is soaked in saturated water vapour and the dry bulb is kept in the ambient condition. The temperature difference between the dry bulb and wet bulb is used to obtain the relative humidity through a psychrometric chart. The whole process can also be automated.

15.44 Dew point measurement

If a gas is cooled at constant pressure to the dew point, condensation of vapour will start. The dew point can be measured by placing a clean glass mirror in the atmosphere. The temperature of the mirror surface is controlled and reduced slowly, vapour starts condensation over the mirror. Optical method is used to detect the condensation phenomena, and the temperature of the mirror surface is measured.

15.45 Measurement of Flow

Measuring the flow of liquids or gases is a critical need in many industrial plants. In some operations, the ability to conduct accurate flow measurements is so important that it can make the difference between making a profit or a loss (e.g. oil and gas industry). In other cases, inaccurate flow measurements or failure to take measurements can cause serious results. There are number of transducers used for sensing flow of liquid. They mainly operate on the principle of placing an obstruction in the path of liquid causing a change in fluid pressure which is dependent upon the rate of flow. By measuring the difference in pressure before and after the obstruction by means of differential pressure sensor, the rate of flow may be determined. Some of the method for determining the flow of liquid is explain in the following pages.

15.46 Turbine Flow Meter

Turbine meters widely use for accurate liquid measurement applications. The turbine flow meter translates the mechanical action of the turbine rotating in the liquid flow around an axis into a user-readable rate of flow. The turbine tends to have all the flow traveling around it. The turbine wheel is set in the path of a fluid stream. The flowing fluid impinges on the turbine blades, imparting a force to the blade surface and setting the rotor in motion. When a steady rotation speed has been reached, the speed is proportional to fluid velocity. Turbine flow meters are used for the measurement of natural gas and liquid flow.

Fig. 15.55 shows the magnetic pickup type turbine meter. It consists of a multiple-bladed rotor mounted with a pipe, perpendicular to the liquid flow. The rotor spins as the liquid passes through the blades. The rotational speed is a direct function of flow rate and can be sensed by magnetic pick-up, photoelectric cell, or gears. As the rotator rotate so does the magnet and therefore a rotating magnetic field is produced. This produces an a.c voltage pulse in the pick-up coil located external to the meter housing. Electrical pulses can be counted and totalized by a counter to give the value of total flow over a particular interval of time.

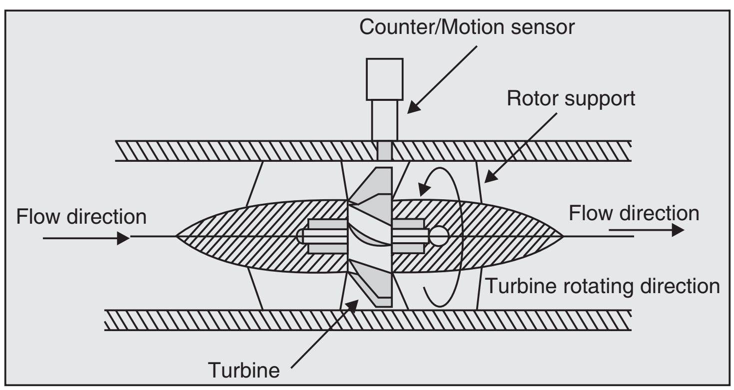


Fig. 15.55.

There are some limitations of turbine flow meter. It is used only in straight pipe line and requires the clean liquids and gases for measurement..

Advantages

The output is in electrical digital form which lends itself admirably to line or radio telemetry for recording or control at a distance point.

15.47 Electromagnetic Flow Meters

The electromagnetic flowmeter or simply the magnetic flow meters use a magnetic field applied to the metering tube, which results in a potential difference proportional to the flow velocity perpendicular to the flux lines. The potential difference is sensed by electrodes aligned perpendicular to the flow and the applied magnetic field.

The physical principle at work is Faraday's law of electromagnetic induction. The magnetic flow meter requires a conducting fluid and a non-conducting pipe line. The field coils through which current flows generate a magnetic field with induction B perpendicular to the longitudinal axis of the tube. The operation of a magnetic flow meter is based upon Faraday's Law, which states that the voltage induced across any conductor as it moves at right angles through a magnetic field is proportional to the velocity of that conductor.

Where $E = vBl$

E = The voltage generated in a conductor

v = velocity of flow

B = magnetic field strength

l = diameter of pipe (distance between two electrode)

The flow measurement with a magnetic flow meter requires that the fluid being measured must be electrically conductive for the Faraday principle to apply. As from the Faraday's Law its indicates that signal voltage (E) is dependent on the average liquid velocity (V) the magnetic field strength (B) and the length of the conductor (D). A magnetic field is established throughout the entire cross-section of the flow tube.

Fig. 15.56 shows the electromagnetic flow meter. The emf consists of a non-ferromagnetic measuring tube with an electrically insulating inner surface, and magnetic coils and electrodes that are arranged diametrically on the tube and are in contact with the process liquid through the tube wall.

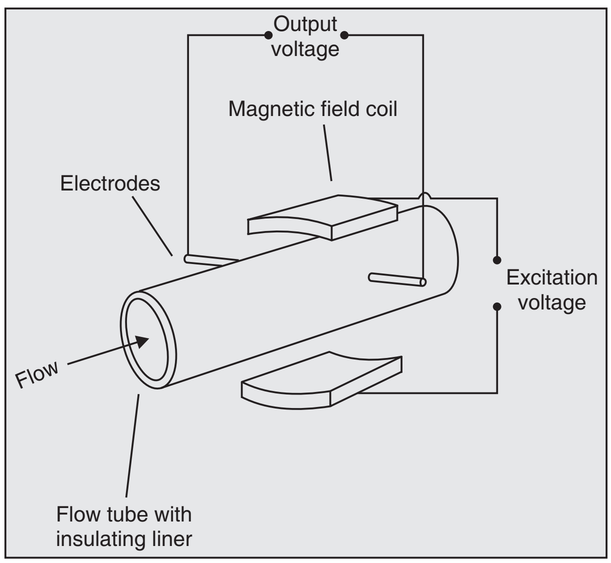


Fig. 15.56.

A magnetic flow meter is a volumetric flow meter which does not have any moving parts and is ideal for wastewater applications or any dirty liquid which is conductive or water based. Magnetic flow meters will generally not work with hydrocarbons, distilled water and many non-aqueous solutions. Magnetic flow meters are also ideal for applications where low pressure drop and low maintenance are required.

Advantages

Some of the main advantages of magnetic flowmeter are:

1. There is no obstruction to flow that may cause pressure drops.
2. The output voltage is linear to the flow rate.

3. The electromagnetic flow meter is manufactured to measure flow in pipes of any size provided powerful magnetic field can be produced.
4. The output is unaffected by changes in characteristics of liquid such as viscosity, pressure and temperature.

Disadvantages

Fluids with low conductivity, such as de-ionized water, boiler feed water, or hydrocarbons, can cause the flow meter to turn off and measure zero flow.

Applications

Magnetic flow meters measure the velocity of conductive liquids in pipes, such as water, acids, caustic, and slurries. Magnetic flow meters can measure properly when the electrical conductivity of the liquid.

15.48 Hot Wire Anemometers

It was introduced in the 1950s and commonly use in fluid research facilities and laboratories. It utilizes a thermal effect to measure flow velocity. Thermal anemometers have extremely small sensors and thus they can be used to measure the instantaneous velocity at any point in the flow without appreciable disturbing the flow.

Fig. 15.57 shows a thermal anemometer. It is called a hot-wire anemometer if the sensing elements is a wire and a hot-film anemometer if the sensor is a thin metallic film less than 0.1 μm. It makes use of the principle of heat transfer from a heated surface being dependent upon the flow conditions passing over it.

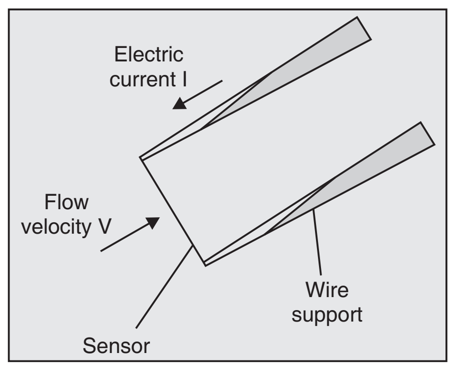


Fig. 15.57.

The hot-wire anemometer is used in gas flow measurement. It consists of an electrically heated fine platinum wire which is immersed into the flow. When the velocity of fluid increases, the rate of heat transfer from the heated wire to the flow stream also increases. Thus a cooling effect on the wire electrode occurs. This causes its electrical resistance to change.

In a constant-current anemometer, the fluid velocity is determined from a measurement of the resulting change in wire resistance. In a constant-resistance anemometer, fluid velocity is determined from the current needed to maintain a constant wire temperature and thus, the resistance constant.

Both the constant-current and constant-resistance anemometers are explained below in more detail.

Constant-Current Anemometer

Fig. 15.58 shows the arrangement of constant-current anemometer. The anemometer is kept in the gas stream to measure flow rate. A constant current is passed through the sensing wire. The voltage across the bridge circuit is kept constant. Due to the gas flow, heat transfer takes place from the sensing wire to the gas flow and hence the temperature of the sensing wire reduces causing a change in the resistance of the sensing wire. The change in resistance becomes a measure of flow rate. The galvanometer which was initially at zero position deflects and this deflection of the galvanometer becomes a measure of flow rate of the gas when calibrated.

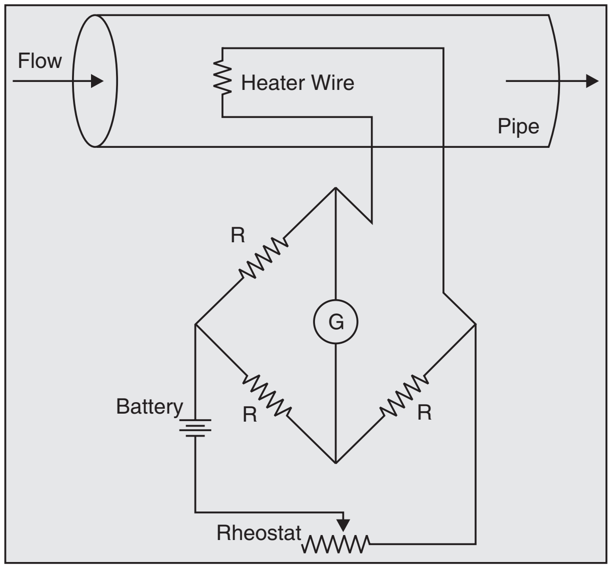


Fig. 15.58. Constant-Current Anemometer

Constant-Resistance Anemometer

Fig. 15.59 shows the arrangement of constant-resistance anemometer. The anemometer is kept in the flowing gas stream to measure flow rate. The current is initially passed through the wire. Due to the gas flow, heat transfer takes place from the sensing wire to the gas flow and this changes the temperature and hence the resistance of the wire. In this method we have to maintain the temperature and resistance of the sensing wire at a constant level. The current through the sensing wire is increased to bring the sensing wire to have its initial resistance and temperature. The electrical current required in bringing back the resistance and hence the temperature of the wire to its initial condition becomes a measure of flow rate of the gas when calibrated.

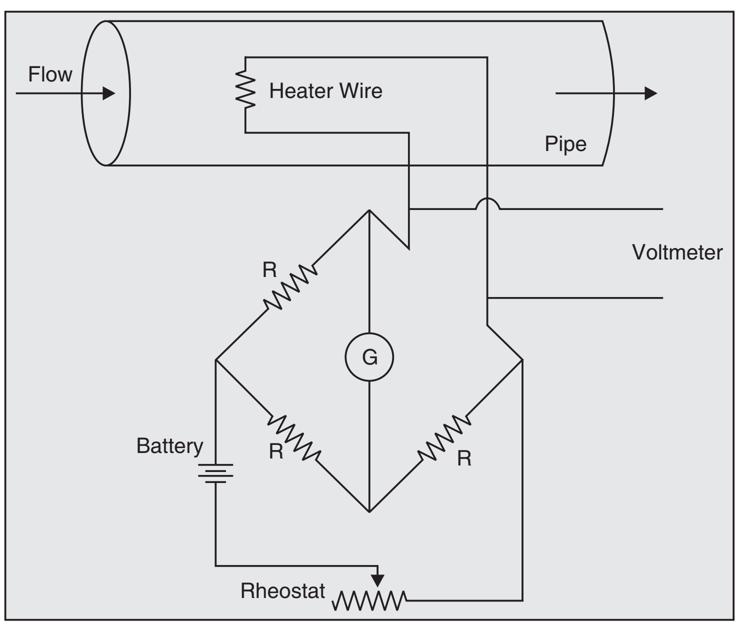


Fig. 15.59. Constant-Resistance Anemometer

Applications

1. Aerospace
2. Automotive
3. Bio-medical & bio-technology
4. Combustion diagnostics
5. Earth science & environmental
6. Fundamental fluid dynamics
7. Hydraulics & hydrodynamics
8. Mixing processes
9. Process & chemical engineering
10. Wind engineering

15.49 Ultrasonic Flow Transducer

An ultrasonic flow meter measures the velocity of a liquid or gas (fluid) by using the principle of ultrasound. Fig. 15.60 shows using an ultrasonic transducers, the flow meter can measure the average velocity along the path of an emitted beam of ultrasound, by averaging the difference in measured transit time between the pulses of ultrasound propagating into and against the direction of the flow.

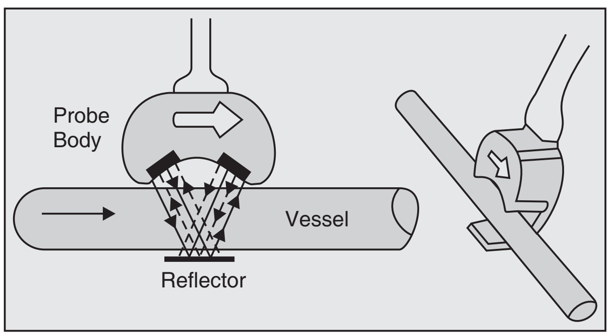


Fig. 15.60.

The ultrasonic flow transducer based on the property of sound. The sound travel in the different velocity depending on the medium it uses to travel. The sound travels faster in water than through the air and these is medium depending on its physical characteristics. When these media are also in motion with respect to an observer, the velocity of sound relative to that observer changes as well.

Fig. 15.61 shows an ultrasonic flow meter using two piezoelectric transducers that can work both as emitters and receivers of sound waves. As an emitters transducers they are excited by series of electric pulses that are converted to acoustic signals. When acting as receivers the pressure waves are converted into electric pulses.

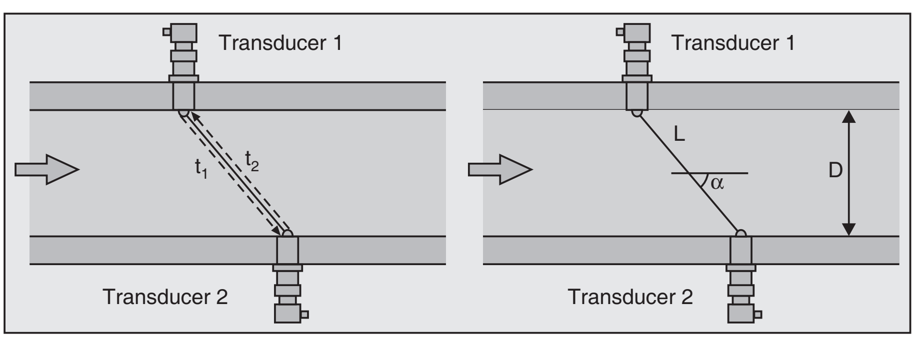


Fig. 15.61.

Transducers are placed "separated by a distance L" and in opposite diameters. The upstream transducer emits a sound signal which is picked up by the downstream receiver after a time t_1. Then the process is reversed and the downstream transducer acts as the emitter where t_2 is the time the sound takes to travel from the downstream to the upstream transducer. The time difference between t_2 and t_1 is used to calculate the average flow velocity of the flow,

$$t_1 = \frac{L}{c + V \cdot \cos\alpha}$$

$$t_2 = \frac{L}{c - V \cdot \cos\alpha}$$

$$t_2 - t_1 = \Delta t = \frac{2L \cdot V \cdot \cos\alpha}{c^2 - V^2 \cdot \cos^2\alpha}$$

Where c is the speed of sound in medium, L is the distance between the transducer and α is the angle. The speed of sound in the medium is considerably higher that the velocity of the flow, $V^2 \cdot \cos^2\alpha$ is always less than 1, term $V^2 \cdot \cos^2\alpha$ is neglected with respect to c^2, then

$$t_2 - t_1 = \Delta t = \frac{2L \cdot V \cdot \cos\alpha}{c^2}$$

The average velocity of the fluid at the cord between the transducers is than,

$$V = \frac{\Delta t \cdot c^2}{2 \cdot L \cdot \cos\alpha} \qquad \text{... }(i)$$

The distance between the transducers L, is related to the diameter D by the following expression,

$$L = \frac{D}{\sin\alpha}$$

Substituting the value of L in the equation (i) we get,

$$V = \frac{\Delta t \cdot c^2}{2 \times \left(\dfrac{D}{\sin\alpha}\right) \times \cos\alpha} = \frac{\Delta t \cdot c^2 \cdot \sin\alpha}{2 \cdot D \cdot \cos\alpha}$$

The speed of sound in the medium can be obtained from the total time that the wave spend in travelling both ways,

$$c = \frac{2 \cdot L}{t_1 + t_2}$$

Substituting the value of $L = \dfrac{D}{\sin\alpha}$ we get,

$$c = \frac{2 \cdot D}{\sin\alpha \cdot (t_1 + t_2)}$$

Ultrasonic flow meters are affected by the temperature, density and viscosity of the flowing medium. They are inexpensive to use and maintain because they do not use moving parts, unlike mechanical flow meters.

Advantages

1. There is no obstruction to flow.
2. It can be clamped on the pipe.

3. It can be portable.
4. There is no moving part in instrument.
5. Bidirectional flow measurement.

Disadvantages

1. It is sensitive to solid or bubble contents.
2. It can interface with the sound pulses.
3. It is sensitive to flow disturbances.

15.50 Measurement of pH Value

The pH value is a measure of the acidity or basicity of an aqueous solution or we say that it is a measure of the hydrogen ion concentration in aqueous solution. pH measurements are important in medicine, biology, chemistry, agriculture, forestry, food science, environmental science, oceanography, civil engineering and many other applications. It is an important parameter to determine the quality of water.

When the hydrogen (H^+) ion predominate the solution is acidic and where the hydroxyl (OH^-) ions are in the majority the solution is alkaline. The product of the hydrogen ion and hydroxyl ion concentration in any solution has a constant value and it is always equal to 10^{-14}. The pH value of the solution is defined as the negative logarithm of the hydrogen ion concentration. Mathematically,

$$pH = -\log_{10} (H^+)$$

The hydrogen ion concentration can be measured on a pH scale which varies from 0 to 14. In a neutral solution the concentration of both hydrogen and hydroxyl ions are equal i.e., both are 10^{-7}. For neutral solution,

$$pH = -\log_{10}(10^{-7}) = 7$$

The pure water is neutral, with a pH close to 7.0 at 25 °C.. Solutions with a pH less than 7 are said to be acidic and solutions with a pH greater than 7 are basic or alkaline. The pH measurement circuit consists of measuring electrode(or glass electrode) and a reference electrode (eg calomel electrode).Both the electrodes are described below:

1. Measuring Electrode

Fig. 15.62 show the measuring electrode or glass electrode. When a pH glass electrode comes into contact with an aqueous measuring solution a 'gel layer' develops on the pH sensitive glass membrane. Such a 'gel layer' arises also on the inside of the glass membrane which is in contact with a defined inner buffer solution. The hydrogen ions either diffuse out of the gel layer, or into the gel layer, depending on the pH value of the measured solution. In the case of an alkaline solution the hydrogen ions diffuse out and a negative charge is established on the outer side of the gel layer. For acidic solution a positive charge is established on the outside of gel layer. The glass electrode has an internal buffer with a constant pH value the potential at the inner surface of the membrane is also constant during the measurement.

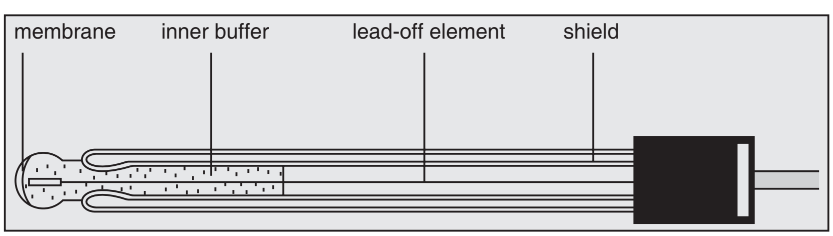


Fig. 15.62.

2. Reference Electrode

Fig. 15.63 show the reference electrode. It consists of a reference element which is immersed in a defined electrolyte. This electrolyte must be in contact with the measured solution. This contact most commonly occurs through a porous ceramic junction. The potential of the reference electrode system is defined by the reference electrolyte and the reference element (e.g. silver/silver chloride). Here it is important that the reference electrolyte has a high ion concentration which results in a low electrical resistance.

Fig. 15.64 shows the arrangement for measuring the pH value. The whole pH measuring circuit consists of a measuring electrode and a reference electrode, which are both immersed in the same solution. The reference electrode is a constant potential regardless of the pH value of solution under test. The potential of the measuring electrode is determined by the pH value of solution. Thus the potential difference between two electrodes depends upon the pH values of solution.

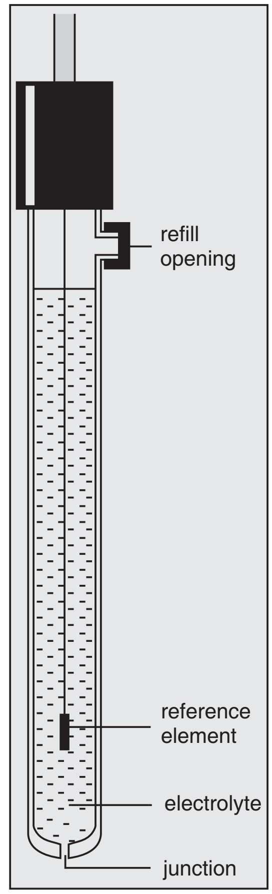


Fig. 15.63.

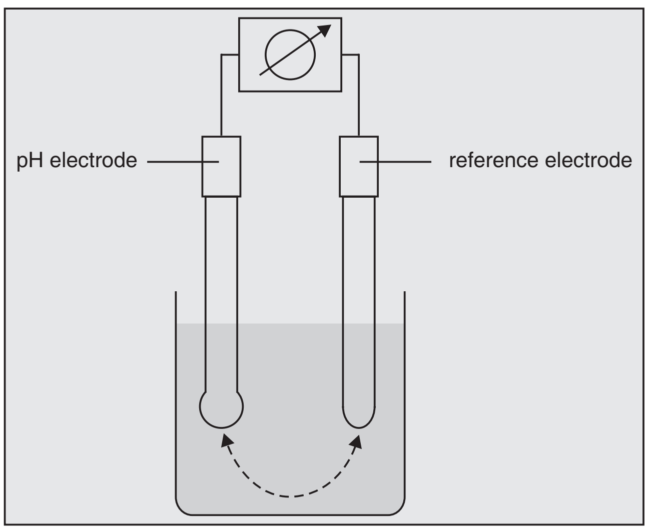


Fig. 15.64.

Applications of pH measurement

pH measurements are of great importance in all branches of the chemical industry, in research and quality-control laboratories, as well as in biology, animal and plant physiology, agriculture and horticulture. Some of the applications are given below:

1. Agriculture
2. Corrosion Prevention
3. Dairy Industry

15.52 Case Study of Temperature Measurement

Case Study: Temperature measurement is crucial in many process monitoring and control applications. The thermocouple is said to be one of the most widely used temperature sensors largely due to its rugged construction and low cost.

An application example is for commercial HTST (High Temperature, Short Time) pasteurization processing for milk. The processing is temperature critical. If the temperature is too low, there are public safety and product quality concerns. If the temperature is too high, energy is wasted and the product can be damaged.

Design a temperature monitoring system as shown in the Fig. 15.65 below.

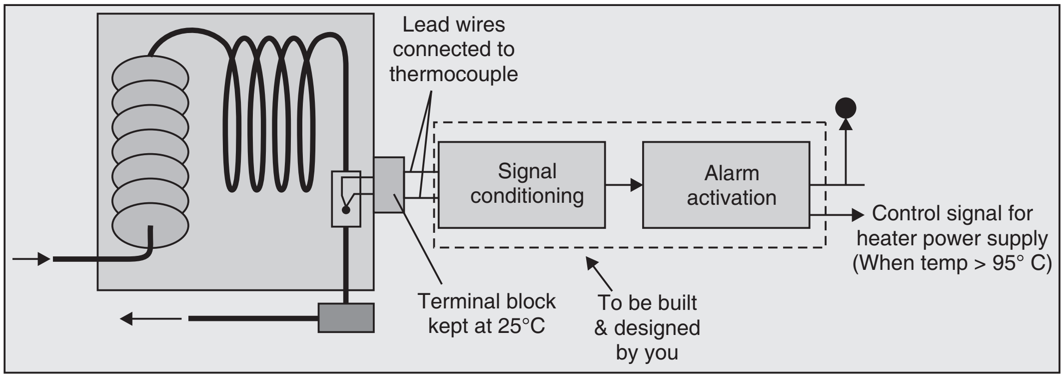


Fig. 15.65. Milk temperature monitoring system

Details of this application are given below:

Type of thermocouple to be used; *K* type (compliant to ITS-90)

Temperature of terminal block (where thermocouple is connected to lead wire): 25°C

Temperature of terminal block of uniform across all surfaces.

Acceptable temperature range of milk: 55°C ~ 95°C.

Alarm type:

- Red LED (when temperature below 55°C)
- Power off heater (when temperature exceed 95°C)

Available power supply: - 10V and 10V

Solution: As seen in the diagram below, the output voltage V_o can be determined either by using the Seebeck coefficient or the temperature conversion table. The red LED must be turned on when $T_j < 55°C$, the reference temperature T_b is kept at 25°C at all times. The heater power supply must be cut off when $T_j > 95°C$, the reference temperature T_b is kept at 25°C at all times. Notice that the reference temperature is also the temperature at the point where the thermocouple is connected to a lead wire or to a measuring instrument.

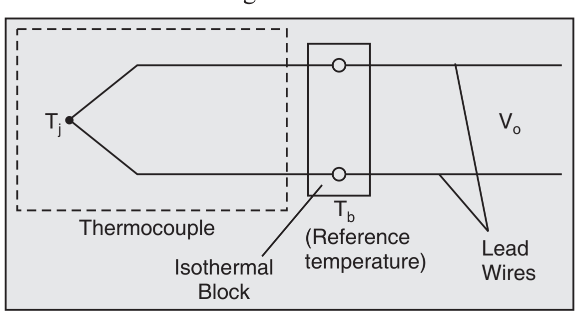


Fig. 15.66.

T_j - Junction temperature

T_b - Isothermal block temperature (also known as reference temperature)

Temperature measured by thermocouple = $(T_j - T_b)$

There are 2 methods to calculate the output voltage V_o for any given measured temperature $(T_j - T_b)$.

Method 1

$V_o = \beta\,(T_j - T_b)$ where β is the Seebeck coefficient

Method 2

Use the appropriate thermocouple voltage conversion chart

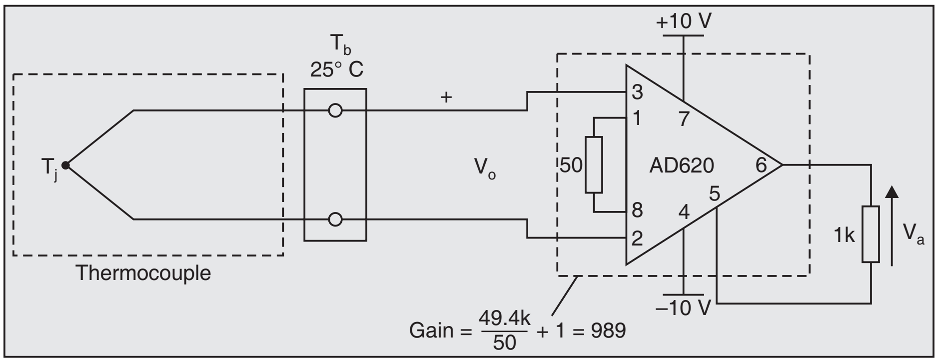


Fig. 15.67.

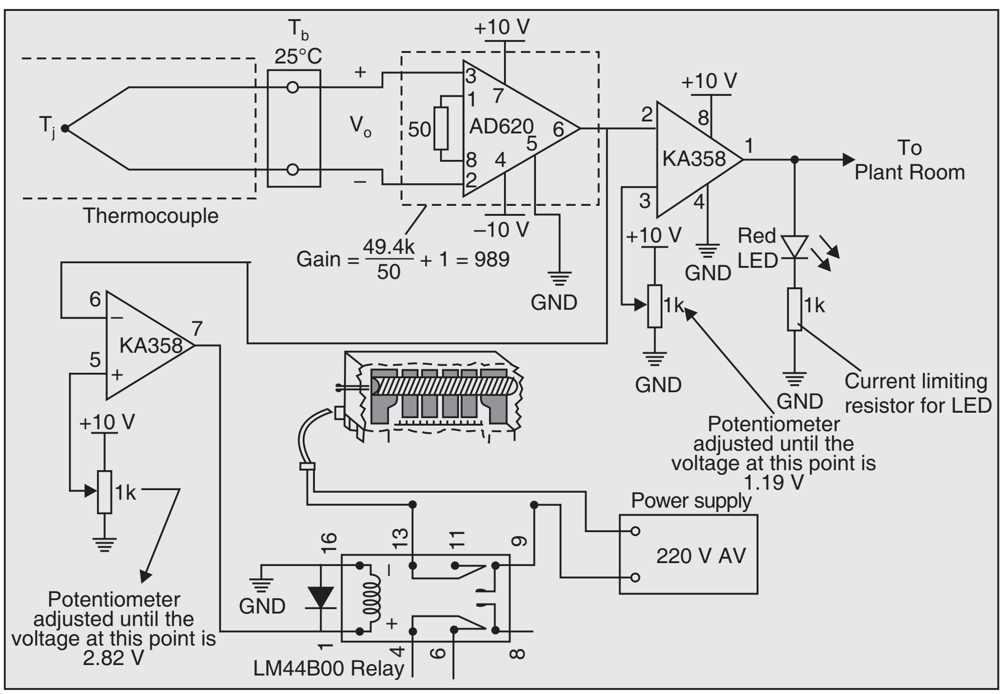


Fig. 15.68.

When milk temperature T_j is at 55°C:

Measured temperature = (55°C – 25°C) = 30°C

V_o = 1.203 mV (for a type *K* thermocouple compliant to ITS-90)

Output voltage of AD620, V_a = gain of amplifier × V_o = 989 × 1.203 mV = **1.19 V**

When milk temperature T_j is at 95°C:

Measured temperature = (95°C – 25°C) = 70°C

V_o = 2.851 mV (for a type K thermocouple complaint to ITS-90)

Output voltage of AD620, V_a = gain of amplifier × V_o = 989 × 2.851 mV = **2.82 V**

As seen above the thermocouple measures relative temperature instead of absolute temperature. In this case the effective temperature measured by the thermocouple is (T_j – T_b).

SUMMARY

In this chapter you have learned that:

1. The thermistor has much higher resistance values and exhibits a larger change in resistance with respect to temperature.
2. Thermocouple is constructed with two dissimilar metals joined together and takes advantage of the thermoelectric potential property of dissimilar metal junctions.
3. Thermopile detector output is proportional to incident radiation.
4. The principle of temperature measurement by brightness comparison is used in optical pyrometer.
5. Total radiation pyrometer includes both visible and invisible (infrared) radiations.
6. Pyrometer device is used to determine the temperature of an object surface.
7. The photoelectric transducers are sensitive to give portions of the spectrum and therefore they are used with partial and optical radiation pyrometers.
8. Resistance temperature detector constructed similar to an accurate wire wound resistor.
9. A transducer can be defined as a device capable of converting energy from one form into another.
10. Transducers can be found both at the input as well as at the output stage of a measuring system.
11. Torque measurement is based upon the angular displacement or twist in the shaft in a calibrated length of torque tube attached to the shaft.
12. The resistive hygrometer based on the property that the resistance of material changes with humidity in presence of hygroscopic materials.
13. Turbine meters widely use for accurate liquid measurement applications.
14. The turbine flow meter translates the mechanical action of the turbine rotating in the liquid flow around an axis into a user-readable rate of flow.
15. In electromagnetic flow meter the potential difference is sensed by electrodes aligned perpendicular to the flow and the applied magnetic field.
16. A magnetic flow meter is a volumetric flow meter which does not have any moving parts and is ideal for wastewater applications or any dirty liquid which is conductive or eater based.
17. pH value is an important parameter to determine the quality of water.

GLOSSARY

Bolometer. It is a thermal device that changes its electrical resistance with temperatures.

Electromagnetic Flow Meters. The electromagnetic flowmeter or simply the magnetic flow meters use a magnetic field applied to the metering tube, which results in a potential difference proportional to the flow velocity perpendicular to the flux lines.

Fiber Optic Radiation Pyrometers. Pyrometers with fiber optics are used for applications involving strong electrical or magnetic interference fields.

Optical Pyrometer. An optical pyrometer determines the temperature of a very hot object by the color of the visible light it gives off.

pH Value. The pH value is a measure of the acidity or basicity of an aqueous solution or we say that it is a measure of the hydrogen ion concentration in aqueous solution.

Photoelectric Transducers. Photo-electric transducers used for detection of radiation energy are photo-emissive cells, photo-conductive cells and photovoltaic cells.

Pyrometer. A pyrometer si a non-contacting device that intercepts and measures thermal radiation, a process known as pyrometry.

Resistance Temperature Detectors. Resistance Temperature Detectors (RTDs) are used to measure temperature by correlating the resistance of the RTD element with temperature.

Thermistor. Thermistor are the semiconductor type resistance thermometers.

Thermocouple. A thermocouple consists of a pair of dissimilar conductors welded or fused together at one end to form the hot or measuring junction with other end available for connection to the cold or reference junction.

Thermopile. A thermopile is made of thermocouple junction pairs connected electrically in series.

Total Radiation Pyrometer. The total radiation pyrometer receives a sample of the total radiation of a hot body and focuses it on to a temperature sensitive transducer.

NUMERICAL PROBLEMS

1. A strain gauge bridge has two fixed resistors R_3 and R_4 of 120 Ω each and a variable resistor R_2, which is 100 Ω at zero strain and 100.8 Ω under strain condition. The gauge factor is 2.5. Determine the strain where the strain gauge is attached.

(**Ans.** 3.55×10^{-3})

2. An accelerometer has a seismic mass of 0.05 kg and a spring constant of 4800 N/m. Maximum mass displacement is ± 20 mm. Calculate natural frequency and maximum measurable acceleration.

(**Ans.** 49.3 Hz, 1920 m/s)

3. A accelerometer the output are 0.5 mV/m with a ± 20 mm core displacement. The spring constant is 400 N/m and the core mass is 60 *g*. Determine the natural frequency, maximum measurable acceleration and accelerometer sensitivity. (**Ans.** 13 Hz, 133.34 m/s, 13.34 ms^{-2}/mV)

4. A thermocouple is used to detect water temperature in the tank as below picture. Assume the room temperature is 10°C. Find out output voltage from thermocouple when the water temperature is 80°C if a type *K* thermocouple is used.

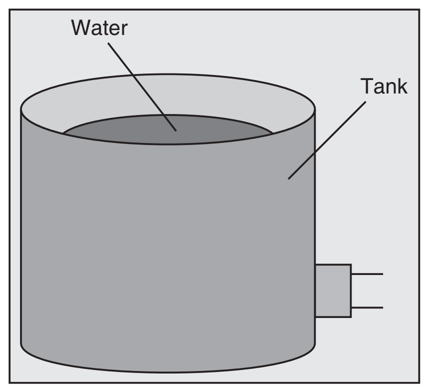


Fig. 15.69.

5. Given a Type "*T*" Thermocouple with a Seebeck coefficient of 41.5 mV/°C (refer to Fig. below). What will be the temperature at the hot junction when the voltmeter reads 4.15 mV? (**Ans.** 2.851 mV)

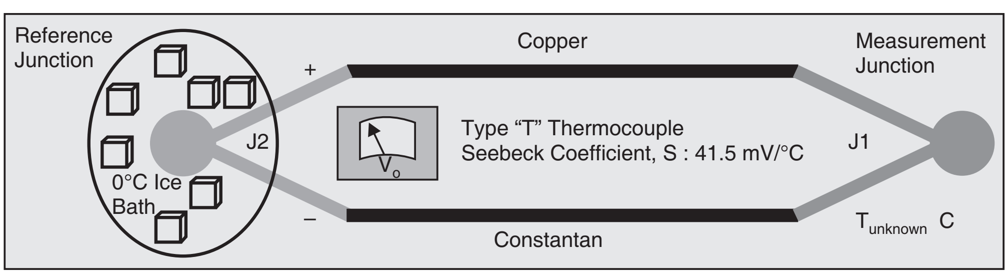


Fig. 15.70.

6. Consider the Figure below.

Let's
$$V_1 = S^* (T_X - T_C) \quad ...(i)$$
$$V_2 = S (T_C) \quad ...(ii)$$

Considering the dotted box have a reference temperature of T_{REF}. When Temperature (T_X and T_C) coming into the dotted box, they will have to take reference to T_{REF}.

To take into account of T_{REF}, T_X will become ($T_X - T_{REF}$) and T_C will become ($T_C - T_{REF}$).

Hence equation (*i*) and (*ii*) will

$$V_1 = S (T_X - T_{REF}) - S (T_C - T_{REF})$$
$$V_2 = S(T_C - T_{REF}).$$

What will happen when $V_1 + V_2$? Assuming the amplifier come with a gain ($G = 1$). What kind of amplifier configuration we have to put in order to yield an final output $V_{out} = S (T_X - T_{REF})$?

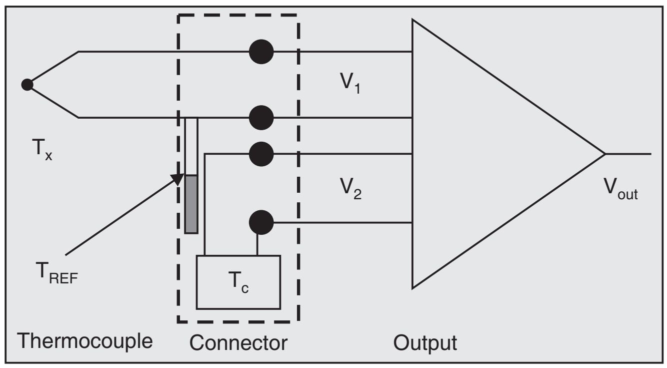


Fig. 15.71.

7. AD620 is used to amplify the signal from thermocouple, calculate the output voltage V_{out} when R_G is 200 Ω. (**Ans.** 0.707 V)

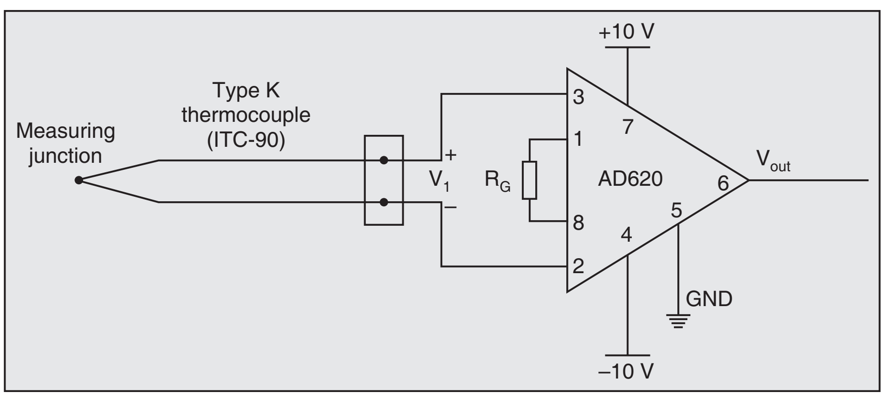


Fig. 15.72.

DESCRIPTIVE QUESTIONS

1. What is a thermocouple?
2. What is thermocouple gauge used for detection of leaks in vacuum systems.
3. Write desired properties of thermocouple metals.
4. What type of scale is used in thermocouple meters?
5. What is the main application of thermocouple meter?
6. What are Pyrometers?

7. Name the types of Pyrometers.
8. What is the principle of operation of a resistance thermometer?
9. Give advantages and disadvantages of resistance thermometers.
10. Give advantages and disadvantages of thermocouples.
11. Describe electromagnetic transducers used for measurement of linear velocity.
(Nagpur University, Summer 2010)
12. Explain any one technique used for measurement of angular displacement.
(Nagpur University, Summer 2010)
13. Define the term "flow". List flowmeters. Explain any two of them with their advantages and limitations.
(Nagpur University, Summer 2010)
14. List various methods of liquid level measurement and explain anyone.
(Nagpur University, Summer 2010)
15. What do you mean by pH value of solution and explain pH electrode.
(Nagpur University, Summer 2010)
16. What are the different types of methods of measurement of liquid level? Explain any two in detail.
(Nagpur University, Summer 2011)
17. Write short note on "Hot wire anemometer". *(Nagpur University, Summer 2011)*
18. What is bourdon tube? Explain its use for measurement of pressure.
(Nagpur University, Summer 2010)
19. List different methods used for measurement of flow of liquids. Explain electromagnetic flowmeter.
(Nagpur University, Summer 2010)
20. Define pH. With the help of neat diagram explain the working of pH meter.
(Nagpur University, Summer 2010)
21. Suggest and explain a suitable instrumentation system to measure the level in petrol tank.
(Nagpur University, Summer 2010)
22. Explain electromagnetic flowmeter with its advantages and disadvantages.
(Nagpur University, Summer 2011)
23. Explain ultrasonic method of level measurement.
(Nagpur University, Summer 2011)
24. Enlist and explain any three transducers used in pressure measurement.
(Nagpur University, Summer 2011)
25. Explain cold junction compensation of thermocouple. *(Nagpur University, Summer 2011)*
26. Describe the operation and construction of optical pyrometer.
(Nagpur University, Summer 2011)
27. Explain construction of thermistor. Give its characteristics and explain the different applications of thermistor.
(Nagpur University, Summer 2011)
28. What is piezoelectric transducer? Derive the expression for output voltage in piezoelectric transducer.
(Nagpur University, Summer 2011)
29. Explain the use of dummy gauge for temperature compensation in strain gauge.
(Nagpur University, Summer 2010)
30. Compare the performance of following devices along with characteristics for the measurement of temperature.
    (*a*) Resistance thermometers
    (*b*) Thermistor

(*c*) Thermocouple *(Nagpur University, Summer 2010)*

31. Write short notes on the following:
(*a*) Seeback effect
(*b*) Piezoelectric transducer
(*c*) Primary transducers
(Nagpur University, Summer 2010)

32. Why is platinum generally used for construction of RTD? Explain the construction of laboratory type platinum RTD.
(Nagpur University, Summer 2010)

33. How are radiation methods used in measurement of temperature? Explain the construction and working of optical pyrometer.
(Nagpur University, Summer 2010)

MULTIPLE CHOICE QUESTIONS

1. Seismic transducer is used for measuring.
(*a*) Linear velocity (*b*) Angular velocity
(*c*) Acceleration (*d*) All of the above

2. The accelerometer using LVDT has advantages of,
(*a*) High natural frequency (*b*) Being-contactless devices
(*c*) Better resolutions (*d*) All of the above

3. Pyrometer is used to measure,
(*a*) Strain (*b*) Pressure
(*c*) Displacement (*d*) Temperature

4. In optical pyrometer temperature is measured by,
(*a*) Thermocouple effect
(*b*) Photocell principle
(*c*) Comparison of brightness of the source with that of a standard source
(*d*) All of the above

5. Hot-wire anemometers are used for measuring,
(*a*) Gas velocities (*b*) Pressure of fluids
(*c*) Liquid discharges (*d*) Very low pressures

6. The main drawback of ultrasonic flow meter are,
(*a*) Low accuracy and slow response
(*b*) Complexity and relatively high cost
(*c*) Affected by pressure and temperature variations
(*d*) None of the above

7. Hydrometer is employed for determination of,
(*a*) Relative humidity (*b*) Specific gravity of liquids
(*c*) Fluid level (*d*) None of these

ANSWERS

1. (*c*) **2.** (*d*) **3.** (*d*) **4.** (*c*) **5.** (*a*) **6.** (*b*)
7. (*b*)

Chapter 16

Data Acquisition System

Outline

Objectives

After completing this chapter, you should be able to:

- Know the data acquisition system
- Understand the IEEE-488 GPIB
- Discuss the various types of data acquisition system.

16.1 Introduction

In most of the real world applications, the analog data must be digitized and transferred into a computer's or microcontroller system's memory. The process by which the microcontroller acquires these digitized analog data is referred to as **data acquisition**. The computer can do several things with the data, depending on the application. In a storage application, such as digital audio recording, video recording, ora digital oscilloscope, the microcontroller will store the data and then transfer them to a D/A converter at a later time to reproduce the original signal. In a process control application, the microcontroller can examine the data or perform computations on them to determine what control outputs to generate.

16.2 Data Acquisition System

Data acquisition (DAQ) is the process of measuring an electrical or physical phenomenon such as

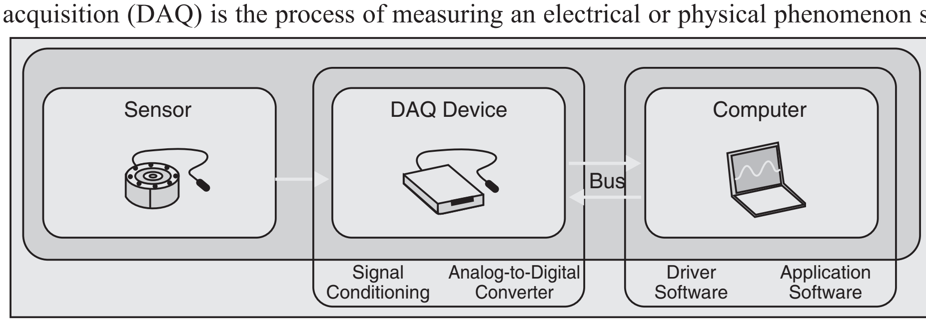


Fig. 16.1

voltage, current, temperature, pressure, or sound with a computer. Fig. 16.1 shows a DAQ system, it consists of sensors, DAQ measurement hardware and a computer with programmable software. Each block of DAQ are explained below:

1. Sensor

It measures a physical phenomenon, such as the temperature of a room, the intensity of a light source, or the force applied to an object etc. A sensor, also called a transducer its converts a physical phenomenon into a measurable electrical signal. Depending on the type of sensor, its electrical output can be a voltage, current, resistance, or another electrical attribute that varies over time. Some sensors may require additional components and circuitry to properly produce a signal that can accurately and safely be read by a DAQ device. Some of the common sensor and their physical phenomenon are given in Table 16.1, below.

Table 16.1.

Sensor	*Phenomenon*
Thermocouple, RTD, Thermistor	Temperature
Photo Sensor	Light
Microphone	Sound
Strain Gage, Piezoelectric Transducer	Force and Pressure
Potentiometer, LVDT, Optical Encoder	Position and Displacement
Accelerometer	Acceleration
pH Electrode	pH

2. DAQ Device

It acts as the interface between a computer and signals from the outside world. It primarily functions as a device that digitizes incoming analog signals so that a computer can interpret them. The three key components of a DAQ device used for measuring a signal are the signal conditioning circuitry, analog-to-digital converter (ADC), and computer bus.

3. Computer

A computer with programmable software controls the operation of the DAQ device and is used for processing, visualizing, and storing measurement data. Different types of computers are used in different types of applications. A desktop may be used in a lab for its processing power, a laptop may be used in the field for its portability, or an industrial computer may be used in a manufacturing plant for its ruggedness. In computer we required the following software to control the operation.

(a) **Driver Software.** The driver software provides application software the ability to interact with a DAQ device. It simplifies communication with the DAQ device by abstracting low-level hardware commands and register-level programming. Typically, DAQ driver software exposes an application programming interface (API) that is used within a programming environment to build application software.

(b) **Application Software.** The application software facilitates the interaction between the computer and user for acquiring, analyzing, and presenting measurement data. It is either a prebuilt application with predefined functionality, or a programming environment for building applications with custom functionality. Custom applications are often used to automate multiple functions of a DAQ device, perform signal-processing algorithms, and display custom user interfaces.

4. Bus

It serves as the communication interface between the DAQ device and computer for passing instructions and measured data. DAQ devices are offered on the most common computer buses including USB, PCI, PCI Express, and Ethernet. More recently, DAQ devices have become available for 802.11 Wi-Fi for wireless communication.

16.3 Data Logging

A data logger is any device that can be used to store data. This includes many data acquisition devices such as plug-in boards or serial communication systems which use a computer as a real time data recording system. Data logging is the measuring and recording of physical or electrical parameters over a period of time. A wide range of devices can measure and log data from basic, single measurement devices to complex systems with built-in analysis functions and displays. Data loggers can measure different types of signals and sensors. Data loggers are used in a variety of applications such as in vehicle data logging, environmental monitoring, structural health monitoring, and machine condition monitoring. Common measurements include temperature, strain, voltage, current, pressure, force, and acceleration.

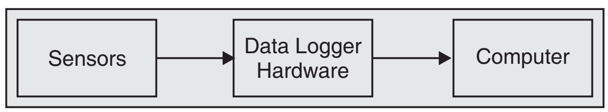


Fig. 16.2.

16.4 IEEE-488 General Purpose Interface Bus (GPIB) Instruments

These days automatic test equipment (*ATE*) is one of the leading methods for testing electronic equipment in factory production and troubleshooting situations. The basic method is to use a programmable digital computer to control a bank of test instruments. The bank of instruments can be configured for a special purpose or for general use. For example, we could select a particular lineup of equipment needed to test a broadcast audio console and provide a computer program to do a variety of measurements such as gain, frequency response, total harmonic distortion etc. The other possibility could be to do a generalized test set. This method is adopted by number of industries who have many electronic devices or systems to test. There is a main bank of electronic test equipment adapters to make the devices (or systems) under test interconnect with the system and a computer program for each type of equipment. Such an approach reduces the test equipment cost drastically.

The Institution of Electrical and Electronic Engineers (*IEEE*) has laid out a specification titled *IEEE* standard Digital Interface for programmable instrumentation or *IEEE*-488. This specification provides details for a standard interface between a computer and instruments. The *IEEE*-488 bus or General purpose interface bus (*GPIB*) is a tool that is based on the *IEEE* specifications. The Hewlett-Packard interface bus (*HPIB*) is a proprietary version of the *IEEE*-488 bus.

The digital signals on the *IEEE*-488 bus are generally similar to *TTL* (transistor-transistor logic), i.e. a logic *LOW* is less than 0.8 V and a logic *HIGH* is greater than 2.0 V. The digital signals can be connected to the instruments through a multiconductor cable up to 20 metres in length provided that an instrument load is placed every 2 metres. Most *IEEE*-488/*GPIB* systems operate unrestricted to 250 kilobytes per second or faster with some restrictions.

There are two basic configurations for the *IEEE*-488/*GPIB* system: (1) linear and (2) star. In the linear configuration shown in Fig. 16.3 (*a*), a tap-off to the next instrument is taken from the previous one in series. On the other hand, in star configuration shown in Fig. 16.3 (*b*), the instruments are connected from a central point.

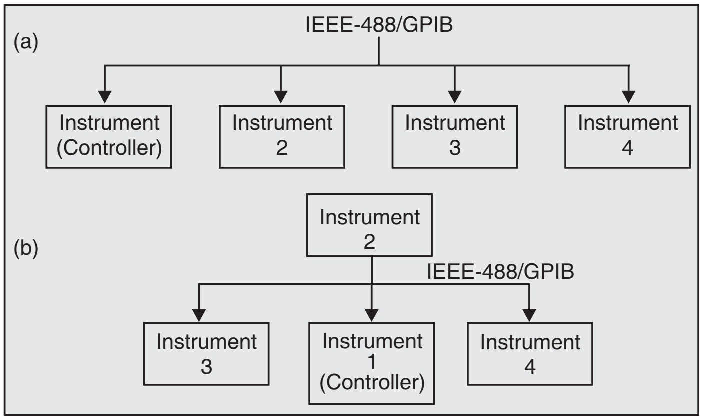


Fig. 16.3.

Figure 16.4 shows the basic structure of *IEEE*-488/*GPIB* system. The figure indicates four different devices (i.e. computer, frequency counter, signal generator and digital multimeter) connected to the bus. The *IEEE*-488/*GPIB* system itself consists of three major buses: (1) general interface management (*GIM*) bus. (2) data *I*/*O* (*DIO*) bus and (3) data byte transfer (*DBT*) bus.

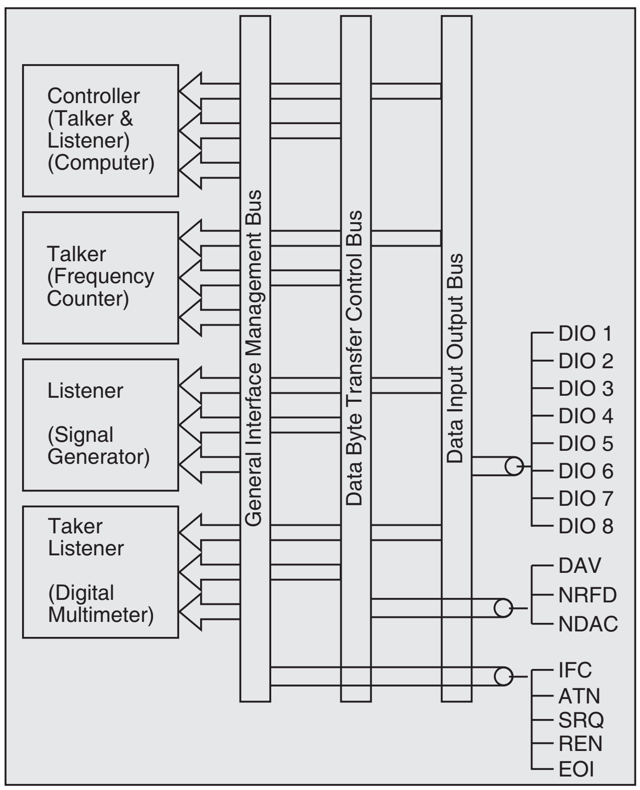


Fig. 16.4.

1. General Interface Management (*GIM*) bus: This bus coordinates the whole system and ensures an ordely flow of data over the data input/output (*DIO*) bus. This bus has a number of signals explained below.

***IFC* (Interface Clear Signal):** This signal is used by the controller to place all devices in a predefined quiescent or standby condition.

***ATN* (Attention Signal):** This signal is used by the computer/controller to let the system know how data on the *DIO* bus lines are to be interpreted and which device is to respond to the data.

***SRQ* (Service Request Signal):** This signal is used by a device on the system to ask the controller for attention. It is basically an interrupt request signal.

***REN* (Remote Enable Signal):** This signal is used by the controller to select between two alternate sources of device programming data.

***EOI* (End or Identify Signal):** This signal is used by talkers for the following two purposes: (1) it will follow the end of a multiple byte sequence of data in order to indicate that the data are now finished. (2) It is also used in conjunction with the *ATN* signal for polling the system.

2. Data *I/O* (*DIO*) bus: This bus is a bidirectional 8-bit data bus that carries data, interface messages and device-dependent messages between the controller, talkers and listeners. This bus sends asynchronously in byte-serial format.

3. Data Byte Transfer (*DBT*) bus: This bus controls the sending of data along the *DIO* bus. There are three signals on this bus as explained below:

***DAV* (Data Valid Signal):** This signal indicates the availability and validity of data on the line. If the measurement is not finished, for example, the *DAV* signal will be false.

***NRFD* (Not Ready for Data Signal):** This signal lets the controller know whether or not the specific device addressed is in a condition to receive data.

***NDAC* (Not Data Accepted Signal):** This signal is used to indicate to the controller whether or not the device accepted the data sent to it over the *DIO* bus.

Each signal line in the bus has a circuit similar to the one shown in Fig. 16.5. As seen from this circuit, each signal line has a pull-up and pull-down resistors, receiver, and driver-circuits. Besides this each signal line has also a shunt protection diode and a stray capacitance.

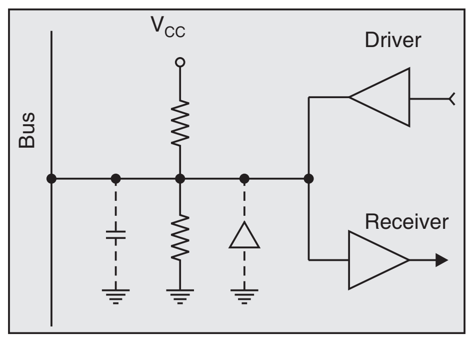


Fig. 16.5.

Figure 16.6 shows the 7-bit binary signals used in the *IEEE*-488/*GPIB* system for *ASCII* and *GPIB* message codes.

The signals defined for the three buses in the *IEEE*-488/*GPIB* systems are implemented as conductors in a system interface cable. Each *IEEE*-488/*GPIB* compatible instrument will have a female 36 pin Amphenol-style connector on the rear panel. The pin-out definitions are given in Table 16.2.

Table 16.2.

Pin No.	*Signal Line*	*Pin No.*	*Signal Line*
1.	*DIO* 1	13.	*DIO* 5
2.	*DIO* 2	14.	*DIO* 6
3.	*DIO* 3	15.	*DIO* 7
4.	*DIO* 4	16.	*DIO* 8
5.	*EOI*	17.	*REN*
6.	*DAV*	18.	Ground (6)
7.	*NRFD*	19.	Ground (7)
8.	*NDAC*	20.	Ground (8)
9.	*IFC*	21.	(Ground 9)
10.	*SRQ*	22.	(Ground 10)
11.	*ATN*	23.	(Ground 11)
12.	Shield	24.	Digital Ground

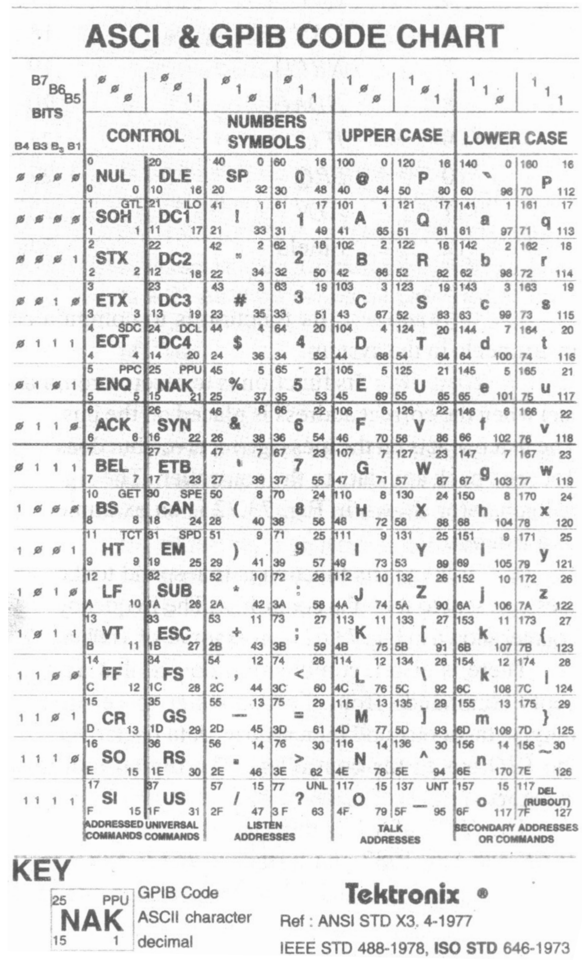
1. Controller: Its function is to communicate device addresses and other inface buses to instruments in the system.

2. Listener: Its function is to receive commands from other instruments (usually the controller) when the correct address is placed on the bus. The listener acts on the message received but does not send back any data to the controller.

3. Talker: Its function is to respond to the message sent to it by the controller. The frequency counter is an example of a talker.

There is also a combination device the accepts commands from the controller to set up ranges, tasks etc. and then returns data back over the *DIO* bus to the controller. The digital multimeter an example of this category.

The *IEEE*-488 was introduced to the electronic industry in 1977. Since then it has evolved to *IEEE*-488.1 in 1987 and further to *IEEE*-488.2 in 1990. At present the system allows the control upto 14 instruments and it has data transfer rate greater than 1 M bytes/s.



ASCI & GPIB CODE CHART

B7 B6 B5 BITS / B4 B3 B2 B1	ø ø ø	ø ø 1	ø 1 ø	ø 1 1	1 ø ø	1 ø 1	1 1 ø	1 1 1
	CONTROL		NUMBERS SYMBOLS		UPPER CASE		LOWER CASE	
ø ø ø ø	0 NUL 0 0	20 DLE 10 16	40 0 SP 20 32	60 16 0 30 48	100 0 @ 40 64	120 16 P 50 80	140 0 ` 60 96	160 16 P 70 112
ø ø ø ø	1 GTL SOH 1 1	21 ILO DC1 11 17	41 1 ! 21 33	61 17 1 31 49	101 1 A 41 65	121 17 Q 51 81	141 1 a 61 97	161 17 q 71 113
ø ø ø 1	2 STX 2 2	22 DC2 12 18	42 2 " 22 34	62 18 2 32 50	102 2 B 42 66	122 18 R 52 82	142 2 b 62 98	162 18 r 72 114
ø ø 1 ø	3 ETX 3 3	23 DC3 13 19	43 3 # 23 35	63 19 3 33 51	103 3 C 43 67	123 19 S 52 83	143 3 c 63 99	163 19 s 73 115
ø 1 1 1	4 SDC EOT 4 4	24 DCL DC4 14 20	44 4 $ 24 36	64 20 4 34 52	104 4 D 44 68	124 20 T 54 84	144 7 d 64 100	164 20 t 74 116
ø 1 ø 1	5 PPC ENQ 5 5	25 PPU NAK 15 21	45 5 % 25 37	65 21 5 35 53	105 5 E 45 69	125 21 U 55 85	145 5 e 65 101	165 21 u 75 117
ø 1 1 ø	6 ACK 6 6	26 SYN 16 22	46 6 & 26 38	66 22 6 36 54	106 6 F 46 70	126 22 V 56 86	146 6 f 66 102	166 22 v 76 118
ø 1 1 1	7 BEL 7 7	27 ETB 17 23	47 7 ' 27 39	67 23 7 37 55	107 7 G 47 71	127 23 W 57 87	147 7 g 67 103	167 23 w 77 119
1 ø ø ø	10 GET BS 8 8	30 SPE CAN 18 24	50 8 (28 40	70 24 8 38 56	110 8 H 48 72	130 24 X 58 88	150 8 h 68 104	170 24 x 78 120
1 ø ø 1	11 TCT HT 9 9	31 SPD EM 19 25	51 9) 29 41	71 25 9 39 57	111 9 I 49 73	131 25 Y 53 89	151 9 i 69 105	171 25 y 79 121
1 ø 1 ø	12 LF A 10	82 SUB 1A 26	52 10 * 2A 42	72 26 : 3A 58	112 10 J 4A 74	132 26 Z 5A 90	152 10 j 6A 106	172 26 z 7A 122
1 ø 1 1	13 VT B 11	33 ESC 1B 27	53 11 + 2B 43	73 27 ; 3B 59	113 11 K 4B 75	133 27 [5B 91	153 11 k 6B 107	173 27 { 7B 123
1 1 ø ø	14 FF C 12	34 FS 1C 28	54 12 , 2C 44	74 28 < 3C 60	114 12 L 4C 76	134 28 \ 5C 92	154 12 k 6C 108	174 28 | 7C 124
1 1 ø 1	15 CR D 13	35 GS 1D 29	55 13 — 2D 45	75 29 = 3D 61	115 13 M 4D 77	135 29] 5D 93	155 13 m 6D 109	175 29 } 7D 125
1 1 1 ø	16 SO E 15	36 RS 1E 30	56 14 . 2E 46	76 30 > 3E 62	116 14 N 4E 78	136 30 ^ 5E 94	156 14 n 6E 170	156 30 ~ 7E 126
1 1 1 1	17 SI F 15	37 US 1F 31	57 15 / 2F 47	77 UNL ? 3 F 63	117 15 O 4F 79	137 UNT _ 5F 95	157 15 o 6F 117	117 DEL (RUBOUT) 7F 127
	ADDRESSED COMMANDS	UNIVERSAL COMMANDS	LISTEN ADDRESSES		TALK ADDRESSES		SECONDARY ADDRESSES OR COMMANDS	

KEY

25 PPU NAK 15 1	GPIB Code / ASCII character / decimal

Tektronix ®

Ref : ANSI STD X3. 4-1977

IEEE STD 488-1978, ISO STD 646-1973

Fig. 16.6.

VXI Bus

The *VXI* bus is another fast growing platform for instrumentation systems. It was introduced in 1987 and since then it has experienced tremendous growth and acceptance around the world. *VXI* uses a mainframe chassis with a maximum of 13 slots to hold modular instrument on plug-in boards.

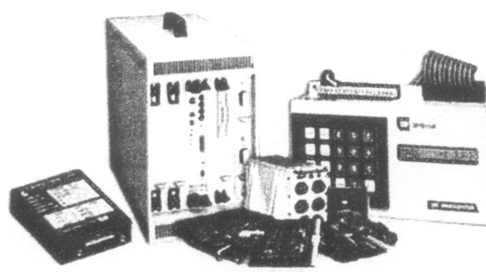


Fig. 16.7.

Figure 16.7 shows an example of system using *VXI* instruments. The *VXI* backplane includes the 32-bit *VME* data bus, high performance instrumentation buses for precision timing and synchronization between instrument components, standard initilization and resource management to ease configuration.

16.5 Sample and Hold Circuits

We have already that analog-to-digital converters are used to convert the electrical signals in analog form to their digital equivalent. In most of the applications in real world, the signals produced by sensors or actuators are continuously changing with time in response to the changing real world variables (e.g. pressure, volume, density, speed, distance etc.) For such situations, when the sensor or actuator output is directly connected as an input to an *A*/*D* converter, the conversion process will be affected due to continuous change in analog inputs. This problem is overcome by placing a sample and hold circuit before the *A*/*D* converter.

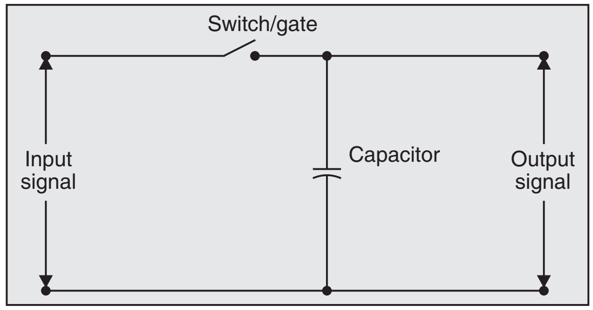


Fig. 16.8.

In most of the circuits, a capacitor is used to store the analog voltage and an electronic switch or logic gate is used to connect or disconnect the capacitor from the analog inputs. The rate at which the switch or logic gate is operated defines the number of samples per second taken from a continuous signal to a discrete signal. It is also called as sampling rate. Figure 16.8 shows the arrangement for the basic sample and hold circuit.

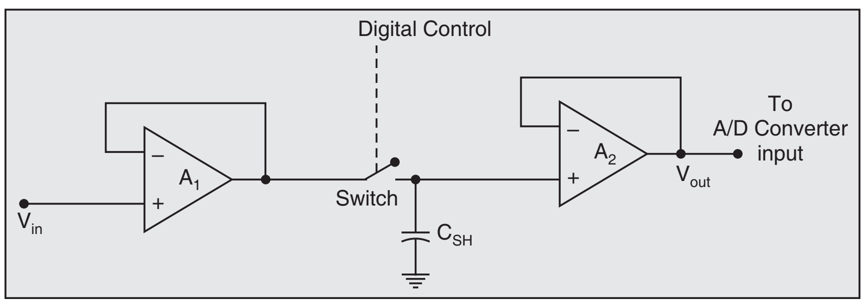


Fig. 16.9.

Figure 16.9 shows a typical circuit diagram of the sample and hold operation. Here analog input is given to the unity gain buffer amplifier A_1 that gives the high impedance to the analog signal and a low output impedance to charge to capacitor C_{SH}. When the switch is closed, the capacitor C_{SH} is connected to the output of amplifier A_1 and will be charged. The switch will be controlled by a digital input. The capacitor gets charged as long as the switch is in closed position. This is called sample operation. When the switch is opened, the capacitor C_{SH} will hold this voltage so that the output of amplifier A_2 will apply the voltage to *A*/*D* converters. The unity gain amplifier A_2 gives high input impedance that will not discharge the capacitor during the conversion time of the *A*/*D* conversion operation. Thus the *A*/*D* converters receive the steady *DC* input voltage. This operation is called as 'hold' operation.

Figure 16.10 (*a*) shows the waveform of an input signal given to the sample and hold circuit while Fig. 16.10 (*b*) the waveform of the circuit output. The vertical lines represent the instances at which the sampling is taking place. In between the two consecutive sampling intervals, the voltage is held constant.

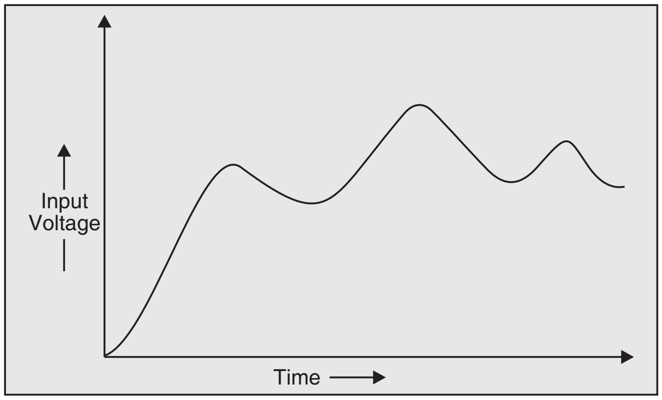


Fig. 16.10 (a).

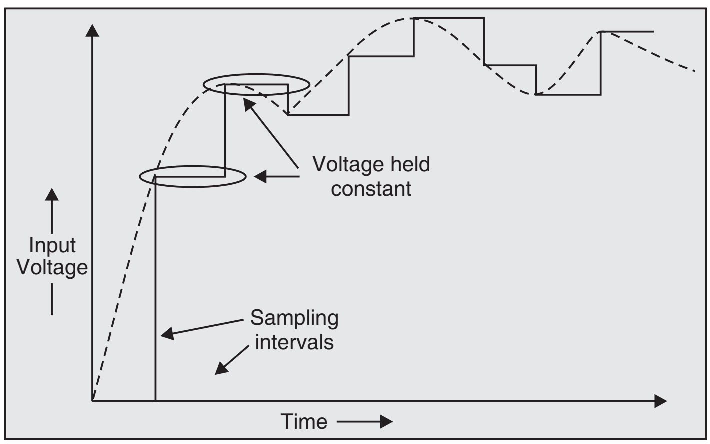


Fig. 16.10 (b). Input signal and sample and hold output.

16.6 Single Channel Data Acquisition System

Figure 16.11 shows the single channel data acquisition system. It consists of a signal conditioner followed by an analog to digital converter. The output are digital code, which is further supplied to a storage or printout device, or to a digital computer for analysis.

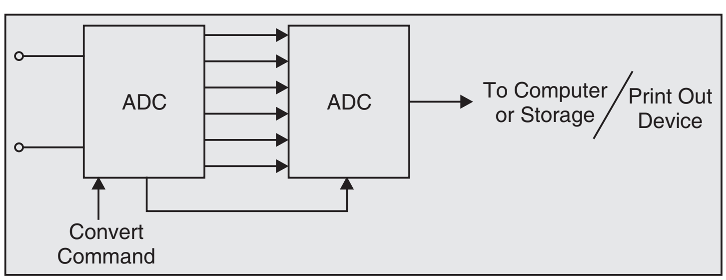


Fig. 16.11. Single Channel Data Acquisition System

16.7 Multichannel Data Acquisition System

Figure 16.12 shows the multichannel data acquisition system. There are several single data acquisition system preceded by a multiplexer. The individual analog signals are applied directly to the multiplexer. These signals are further converted to digital signals by using analog to digital converter. The multiplexer is made to seek the next channel to be converted while the previous data is stored in the sample and hold circuit is converted into digital form. When the conversion is complete, the status line from the converter causes the sample and hold circuit to return to the sample made and acquires the signal of the next channel.

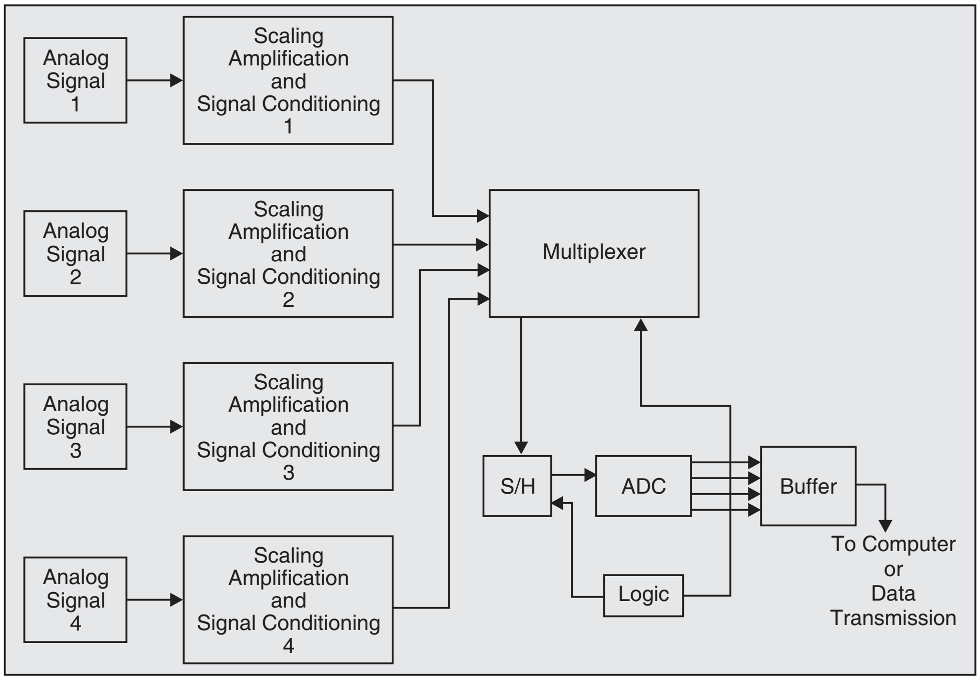


Fig. 16.12. Multi-Channel DAS

After completion of acquisition, the sample and hold is switched the hold mode, a conversion begins again and the multiplexer selects the next channel. This method is relatively slower than systems where the sample and hold outputs or even ADC outputs are multiplexed, but it has the advantage of low cost due to sharing of a majority or subsystems.

16.8 Application of Data Acquisition System

Main application of DAS are given below:

1. In temperature monitoring.
2. Multi-point weight scales.
3. Pressure monitoring.

SUMMARY

In this chapter you have learned that:

1. A data logger is a device to stored data.
2. Data acquisition is the process of measuring physical phenomenon.

GLOSSARY

Single Channel Data Acquisition System. It consists of a signal conditioner followed by A/D converter.

Multichannel Data Acquisition System. Several single DAS is proceeded by a multiplexer.

DESCRIPTIVE QUESTIONS

1. What do you mean by data acquisition system? What are its two major parts? What are its types?
2. What is analog data acquisition system?
3. What is digital data acquisition system?
4. What are the uses of data acquisition systems? *(PTU, Dec., 2005)*
5. What is the function of a data acquisition system? *(PTU, May 2006, 2008)*
6. Enumerate main elements of data acquisition system. *(PTU, Dec. 2008)*
7. What is an instrument system?
8. What are the two ways, that the data acquisition systems are used to measure and record analog signals?
9. Describe the implementation stages in a data acquisition system? *(PTU, May 2005)*
10. What are the two types of instrumentation systems?
11. Explain anyone data acquisition system. *(Nagpur University, Summer 2011)*
12. Explain Modern Digital Data Acquisition System. *(Nagpur University, Summer 2010)*
13. What are the various components of analog and digital Data Acquisition System? *(Nagpur University, Summer 2010)*
14. How are data transmitted on IEEE-488 system? What prevents two units talking simultaneously? *(Nagpur University, Summer 2011)*

MULTIPLE CHOICE QUESTIONS

1. Which of the following is true about data acquisition system (DAS)?
   (*a*) DAS is a group of electronic device that are connected to perform the measurement and quantization of electrical signals for digital processing.
   (*b*) DAS is a group of devices that are connected to store different signals.
   (*c*) DAS is a system to control a process.
   (*d*) DAS is a signal conditioner.

ANSWERS

1. (*a*)

Chapter 17

Telemetry

Outline

Objectives

After completing this chapter, you should be able to:

- Know about telemetry
- Understand the various telemetering system, like voltage, current, position and frequency telemetering system.

17.1 Introduction

Telemetry systems were developed to provide long distance communications. Any system telemetry systems consist of three main parts, a telemeter transmitter, a receiving unit and the telemeter channel that's connects the transmitting and receiving devices.

The connecting link between transmitter and the receiver may be direct or indirect link. Base on the link the telemetry system may be classified as given below:

1. **Land Line Telemetry System.** The land line telemetry system transmits data with direct physical link. The link can be wire used for telephone or power carrier line. Classification of land line telemetry system is basis on the character of electrical signal like voltage, current, frequency, position and pulse.
2. **Radio Frequency (R.F) Telemetry System.** In this telemetry system there is no physical link between telemeter transmitter and telemeter receiver. It transmits the data through the radio link.

Telemetry systems can be also classified as analog telemetry and digital telemetry. If the information is in the form of current, voltage, position, frequency then the system is called analog telemetry system and if the information is in the forms of pulse then the system is called digital telemetry system.

The major difference between analog and digital telemetry is that in analog telemetry system the signal is continuous transmitted while in digital system the signal does not have to transmit continuously. The method involved for the telemetry is depends on the type of data to be transmitted and distance between the transmitter and receiver.

17.2 Telemetering

Telemetering is the measuring the quantity that is far away from the origin area. For example by using the telemetering system it is possible to monitor the power used at several different locations. Fig. 17.1 shows the telemetry system. The basic telemetry system has the following units:

1. Telemeter Transmitter
2. Telemeter Receiver
3. Telemeter Channel

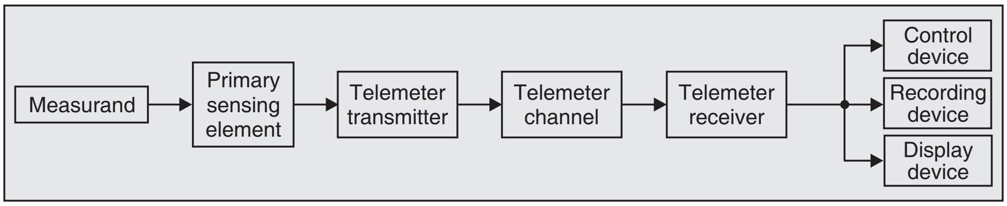


Fig. 17.1.

The measured value is applied to primary sensing element. It measures the physical quantity. Then this physical quantity is converts into an electrical signal by the appropriate electronic circuit known as telemeter transmitter. The output electrical signal of the telemeter transmitter is transmitter to the telemeter receiver through a channel. This channel is known as telemeter channel. It is the link between the sending end and receiving end. At the receiving end the electrical signal is received and converts back into a usable form by the telemeter receiver. The output of the receiver consists device such as recording device, display device, control device etc.

The electrical and electronics methods of data transmission can be used for long distance, these methods are extensively used in instrumentation system. These telemetry systems are of the following types:

1. Voltage Telemetering System
2. Current Telemetering System
3. Position Telemetering System
4. Frequency Telemetering System

All of the above telemetering systems come under the electrical telemetry. We will discuss each telemetering system one by one in the following pages.

17.3 Voltage Telemetering System

Fig. 17.2 shows the circuit of voltage telemetering system. It consists of a slide wire potentiometer, pressure sensitive bourdon tube, pair of wire for telemeter channel and a null balance dc potentiometer or a recorder. The slide wire potentiometer is connected across the constant battery supply with a sliding wire contact positioned by a pressure sensitive bourdon tube. The slide wire of the potentiometer meter is moved by the pressure sensitive bourdon tube.

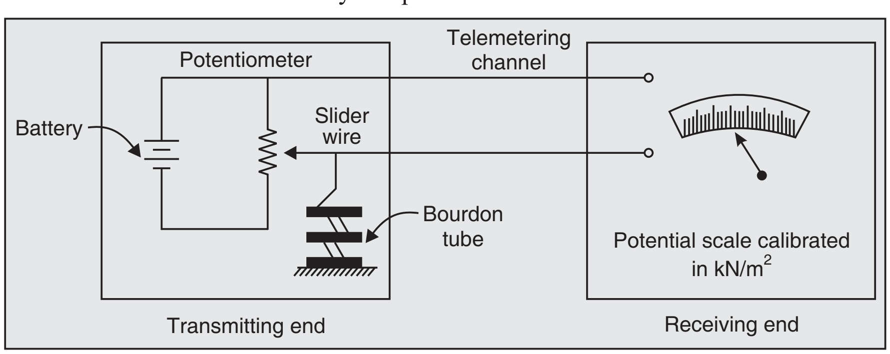


Fig. 17.2.

The telemetering channel consists of a pair of wires connected to the display device. The change in pressure in the system moves the bourdon tube and the sliding contact of the potentiometer. It changes voltage in the telemetry channel. At the receiving end, the voltage is measured with the help of null balance dc potentiometer or recorder.

This telemetering system is mostly used in industry; the distance limit is 300 meters. It main disadvantage is that it requires high quality circuits. The main advantage is that several output voltage can be added in series under linear measurement conditions.

17.4 Current Telemetering System

Fig. 17.3 shows the basic current telemetering system. It is similar to the voltage telemetering system, except that the slide wire potentiometer is connected in series with the battery.

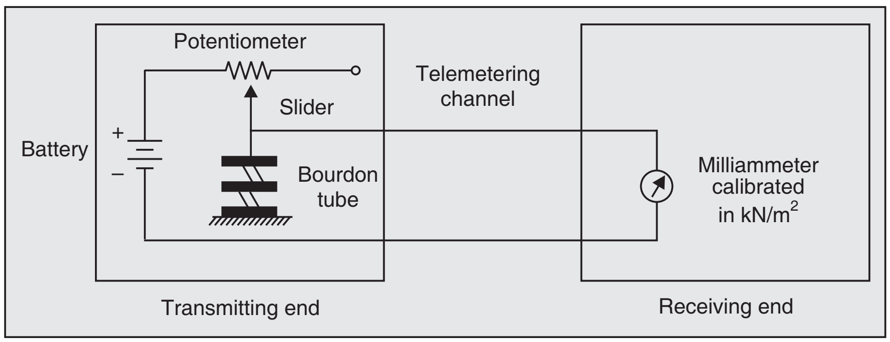


Fig. 17.3.

The sliding wire contact positioned by a pressure sensitive bourdon tube. The slide wire of the potentiometer meter is moved by the pressure sensitive bourdon tube. The telemetering channel consists of a pair of wires, which are connected to a current measuring device.

The change in pressure changes the bourdon tube, which is turn changes the position of the sliding contacts on the potentiometer. This changes the current flow in the circuit. There are two types of current telemetering system. They are given below:

(*a*) Motion Balance Current Telemetering System

(*b*) Forced balance Current Telemetering System

We will discuss one by one each current telemetering system.

(*a*) Motion Balance Current Telemetering System. Fig. 17.4 shows the motion balance current telemetering system. In this system the slide wire is replaced by a position detector such as linear variable differential transformer (LVDT), now the bourdon tube is connected to the core of the LVDT. When the pressure is applied to the bourdon tube, it moves the core of the LVDT. An output voltage is produced which is amplified and rectified. This voltage produces a dc current in the telemetering channel and is measured by millimeter.

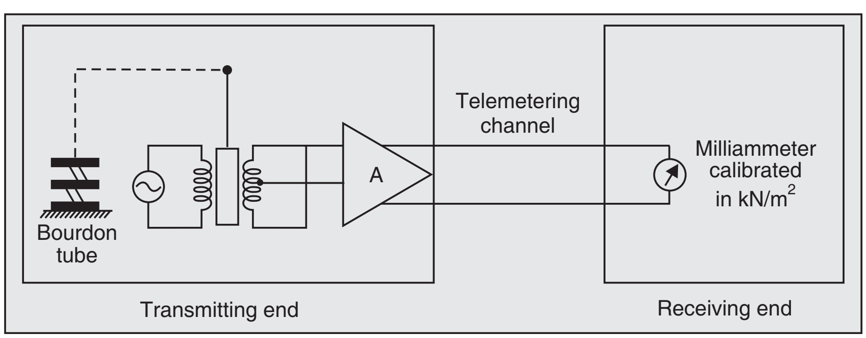


Fig. 17.4.

(*b*) Forced Balanced Current Telemetering System. Fig. 17.5 shows the forced balance current telemetering system. In this the output current is feedback to the input to oppose the motion of the input variable being measured. The bourdon tube after sensing the change in pressure its rotate the feedback coil. As the coil rotates, it changes the flux linkage between the primary and secondary winding. This change in flux linkages varies the amplitude of the amplifier. The output signal is then feedback to the feedback force coil, which produces a force opposing the bourdon input. This system increases the accuracy as smaller motions are required resulting in better linearity.

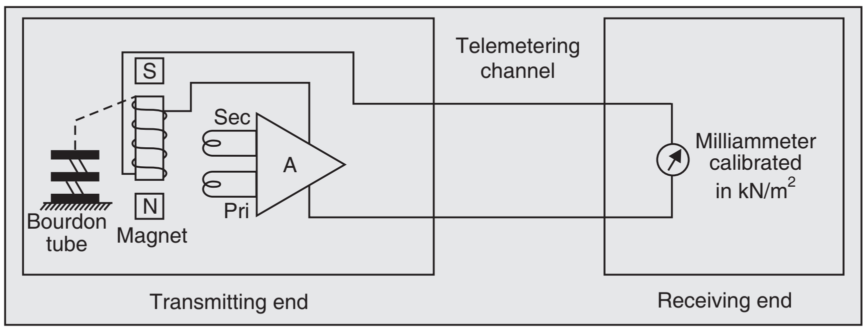


Fig. 17.5.

17.5 Position Telemetering System

Fig. 17.6 shows the position telemetering system. In this system, the relative magnitude of two or more quantities is varied in accordance with the measured variable. This system consists of two potentiometers, one placed at a transmitting end and other is at receiving end. Both potentiometers are connected by a common power supply.

According to the pressure in the bourdon tube the sliding contact of the transmitted potentiometer is placed. The sliding contact of the receiving end is positioned with the help of centre zero galvanometer. The position of the receiving galvanometer is achieved by moving the sliding contact of the potentiometer at the receiving end till the centre zero galvanometer indicates zero.

Whenever the pressure in the bourdon tube changes, it changes the position of slider contact of the transmitted potentiometer. The change in position of the transmitter potentiometer changes the position of the slider contact of the receiving potentiometer, This in turn moves the pointer along the scale calibrated in terms of the pressure scale (kN/m^2). This system is also known as ratio telemetering system.

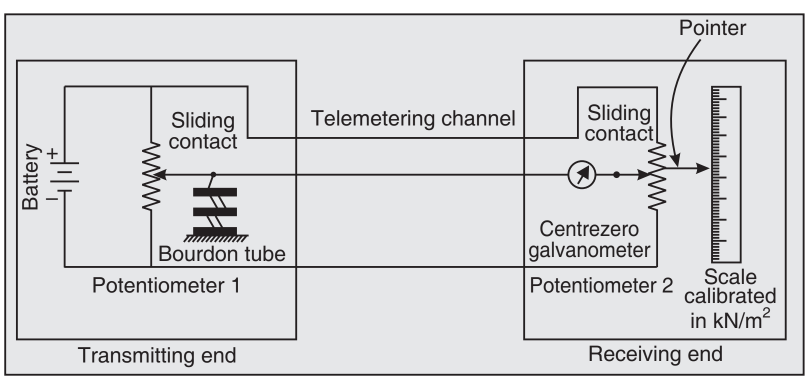


Fig. 17.6.

17.6 Frequency Telemetering System

In frequency telemetering system the link between the transmitting end and the receiving end is established through the radio links. The most common example of this system is controlling of aircraft, rockets and space-crafts. It is more suitable for the transmission of data over distance more than 1 km. A certain band of the radio frequency spectrum a microwave link above 4 MHz is also allocated.

In this system a transmitter is used in which a small variable capacitor is mechanically attached to the shaft of the instrument whose reading is to be telemetered. This capacitor is connected in the circuit of an oscillator so that the output frequency varies according to the instrument reading.

The output of this oscillator is coupled with a second oscillator operating at a fixed frequency. The resultant output is the beat frequency which is very low and detected by the circuit. This beat frequency is transmitted over the connection link between transmitter and receiver.

SUMMARY

In this chapter you have learned that:

1. Telemetry systems were developed to provide long distance communications.
2. Telemetry systems can be also classified as analog telemetry and digital telemetry.
3. Base on the link the telemetry system may be classified as land line telemetry system and frequency telemetry system.

GLOSSARY

Frequency Telemetering System. In frequency telemetering system the link between the transmitting end and the receiving end is established through the radio links.

Land Line Telemetry System. The land line telemetry system transmits data with direct physical link.

Position Telemetering System. In this system, the relative magnitude of two or more quantities is varied in accordance with the measured variable.

Radio Frequency (R.F.) Telemetry System. It transmits the data through the radio link.

Telemetry Systems. Telemetry systems consist of three main parts, a telemeter transmitter, a receiving unit and the telemeter.

Voltage Telemetry System. The voltage telemetry system transmits the measured variable as a function of ac or dc voltage.

DESCRIPTIVE QUESTIONS

1. What do you know about 'telemetry'?
2. Give types of telemetry.
3. Enlist two major telemetry systems.
4. Write two lines about telemetry.
5. What is voltage telemetry?
6. Give types of dc telemetry.
7. Give types of ac telemetry.
8. Explain the term 'Telemetry'.
9. Briefly classify the Telemetry systems.
10. Enlist two major telemetry methods.
11. Enlist various methods of telemetry.
12. Give complete classification of telemetry systems.
13. What are the two basic requirements of landline telemetry? Give its advantages and disadvantages.

14. The advantages of landline telemetry are
15. The disadvantages of landline telemetry are
16. Write a note on General Telemetry system.
17. Write a note on voltage telemetry system.
18. What is the major difference between current and voltage telemetry?
19. What are DC and AC telemetry?
20. Explain principle of position telemetry.
21. With the help of suitable diagrams, explain the current telemetering systems. *(PTU, Dec. 2010)*
22. What is telemetry and what are basics components? Sketch the block diagram representation of a typical telemetry systems and explain the methods of data transmission. *(PTU, Dec. 2010)*
23. Discuss briefly the working of a general telemetering system, with the help of block diagram. *(PTU, May 2011)*
24. Give the difference between DC and AC telemetering systems. *(PTU, Dec. 2010)*
25. List types of telemetry systems and distinguish between dc and ac telemetry systems. *(PTU, May 2009)*
26. What is telemetry and what are its basic components? Sketch the block diagram representation of a typical telemetry system and explain methods of data transmission. *(PTU, May 2009)*
27. List the various types of telemetry systems. *(PTU, May 2009)*
28. Discuss various types of telemetry systems and explain the method of data transmission over the channel link of the system. *(PTU, Dec. 2008)*
29. Give various types and application of telemetry systems. *(PTU, Dec. 2008)*
30. Draw the block diagram of a typical telemetry system and explain the function of each component. *(PTU, May 2007)*
31. Describe the concept of telemetry. *(PTU, Dec. 2004)*

MULTIPLE CHOICE QUESTIONS

1. Telemetry process the information from location by means of,
   (*a*) Mechanical means
   (*b*) Electrical means
   (*c*) CRO
   (*d*) All of the above
2. The position telemetering system using synchros is,
   (*a*) a pulse telemetering system
   (*b*) a RF telemetering system
   (*c*) a DC telemetering system
   (*d*) an AC telemetering system

ANSWERS

1. (*b*) **2.** (*c*)

Chapter 18

Biomedical Instrumentation

Outline

Objectives

After completing this chapter, you should be able to:

- Know what is the biomedical transducer.
- Describe the Electrocardiograph (ECG).
- Understand the Electroencephalograph (EEG).
- Discuss the Electromyograph (EMG).
- Describe the X- Ray machine.
- Understand the EMI scanner.

18.1 Introduction

Electrical signals produced by various bodily activities are used in monitoring diagnosis. The measured signals are generally compared with normal reference signals. The variations in signals can provide accurate diagnosis like

1. Electrocardiography (ECG) – activity of different sections of the heart
2. Electroencephalography (EEG) – electrical activity of the brain
3. Electromyography (EMG) – electrical activity of the muscles

Biopotential electrodes transduce *ionic* conduction to *electronic* conduction so that bio-potential signals can be viewed or stored. They generally consist of metal contacts packaged so that they can be easily attached to the skin or other body tissues. Different types include surface microelectrodes, indwelling microelectrodes & microelectrodes. Skin and other body tissues act as electrolytic solutions.

18.2 Biomedical Transducer

There are some parameters like temperature, blood flow, blood pressure, respiratory function etc. These are to be routinely monitored. These parameters are basically nonelectrical in nature and need to be converting into corresponding electrical signals with the help of transducers. Display and recording systems are required for processing and presenting the picked up signals of interest from the body in a form most convenient for interpretation.

18.3 Temperature Measurement of Body

The temperature of a body is one of the fundamental parameters by which its degree of hotness or coldness is identified. When a substance acquires or release heat, it is reflected through some changes in its physical dimensions and state, which constitute the primary means by which temperature measurements is carried out.

The most popular method of measuring temperature is by using a mercury-in-glass thermometer. However they are slow and difficult to read also reliable accuracy cannot be attained by these thermometers in wide ranges.

In many of the circumstances of lowered body temperature, continuous or frequent sampling of temperature is desirable, as in the operating theater, post-operative recovery room and intensive care unit, and during forced dieresis, massive blood transfusion, and accidental hypothermia.

The continuous reading facility of electronic thermometers obviously lends itself to such applications. Electronic thermometers are convenient, reliable and generally more accurate.

Electronic Thermometers

It is now common to measure temperature with electronics. The most common sensor is a **thermoresistor** (or thermistor) is used for measuring body temperature. This device changes its **resistance** with changes in temperature. The other circuit measures the resistance and converts it to a temperature.

The electronic thermometer consists of thermometer probes, which are connected externally to the unit. The probes convert temperature to an equivalent voltage. This voltage is calibrated and displayed as temperature on digital volt meter. Normally thermistors or thermocouples are used for sensing voltage. Infrared thermometers are used for measuring human body temperature.

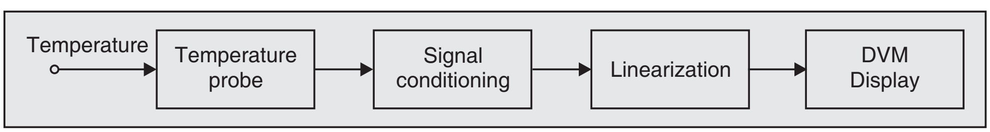


Fig. 18.1. Block Diagram of Electronic Thermometer

Fig. 18.1 shows the block diagram of electronic thermometer. The temperature probe senses the temperature. The probe may be thermocouples, thermistors or infrared probe it depend on the temperature used.

1. Thermocouple probe: Used for sensing high temperature
2. Thermistors Probe: Used for sensing low temperature
3. Infrared probes: Used for sensing human body temperature

The human skin emits infrared energy in proportion to the surface temperature. The infrared probes sense the infrared energy of human skin. The equivalent voltage obtained by the temperature probe is very small and noisy. This voltage is applied to the signal condition unit to amply and filters the voltage signal. The temperature sensors are non linear. Hence linearization is performed on the voltage signal. The digital volt meter calibrates the voltage and displays it on the display. Fig. 18.2 shows the electronic thermometer device.

Fig. 18.2.

18.4 Pulse Sensor

Each time the heart muscle contracts, blood is ejected from the ventricles and a pulse of pressure is transmitted through the circulatory system. This pressure pulse when travelling through the vessels, cause vessel wall displacement which is measurable at various points of the peripheral circulatory system. The pulse can be felt by placing the finger tip over the radial artery in the wrist or some other location where an artery seems just below the skin. The timing and wave-shape of the pressure pulse are diagnostically important as they provide valuable information.

18.5 Photoelectric Pulse Transducers

Photo resistors are normally used for detecting pulsatile blood volume variation by photoelectric method. Most common method is use in photoelectric **plethysmograph** rates are transmittance method and reflectance method. A plethysmograph is an instrument for measuring changes in volume within an organ or whole body. There are two type of method for measuring pulse.

Transmittance Method

Fig. 18.3 shows the arrangement of transmittance method. In this arrangement a miniature lamp and a photo resistor are mounted in an enclosure that fits over the tip of the patient finger. Light is transmitted through the finger tip and the resistor of the photoresistor is determined by the amount of light reaching it. With the pumping of the heart, blood is forced to the extremities and the amount of blood in the finger increase. It changes the optical density with the result that the light transmission through the finger reduces and the resistor of the photo-resistance increase accordingly.

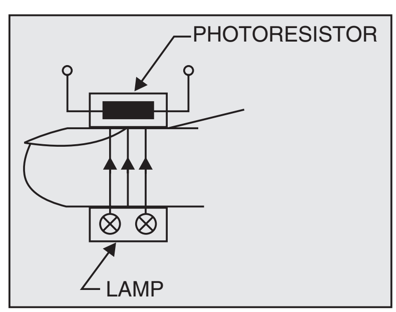


Fig. 18.3.

The photoresistor is connected to the potential driver circuit and produce voltage that varies as the amount of blood in the finger varies. This voltage is displays on an oscilloscope or recorded a strip-chart recorder.

Reflectance Method

Fig. 18.4. shows the reflectance method. In this method the photoresistor is placed adjacent to the lamp. Part of the light emitted by the lamp is reflected and scattered from the skin and the tissues, and falls on the photoresistor. The quantity of light reflected is determined by the blood saturation of the capillaries. The photoresistor vary in proportion to the volume of the blood vessels. The voltage is displays on an oscilloscope or recorded a strip-chart recorder.

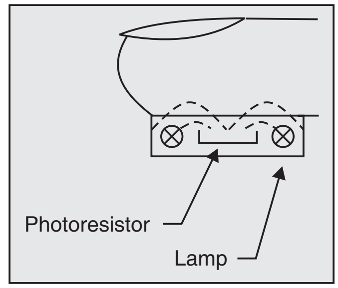


Fig. 18.4.

18.6 Piezoelectric Arterial Pulse Receptor

Piezocrystal may be employed for detection of the pulse waves at certain places of the peripheral systems where considerable displacement of the tissue layer above the artery is involved. The arrangement consists of a piezoelectric crystal clamped in a hermetically sealed capsule subject to the displacement stresses. The displacement can be transmitted to the crystal through a soft rubber diaphragm. The crystal can be connected to an ECG recorder for recording the pulse waveform.

There is another variation of the finger plethysmograph in which an air-coupled piezoelectric transducer is used. With the variation in the blood volume in the finger during the cardiac cycle, slight variations occur in the finger size. These variations can be transmitted as pressure variations in the air column inside the plastic tubing. A piezoelectric transducer at the end of the tube converts the pressure variations to a corresponding electrical signal. This signal can then be amplifier and displayed.

18.7 Strain Gauge Pulse Transducer

In this method, the displacement of the vessel wall is transferred to the semiconductor strain gauge by means of a feeler pin and a leaf spring, as shown in Fig.18.5. The strain gauge is firmly attached to the lead spring on one side and to the feeler pin on the other side. A ring round the feeler pin of the transducer minimizes interference caused by unsteadiness of application of the transducer to the patient's skin. The transducer produces an output of 50 mV for 0.1 mm displacement. The transducer has an internal resistance of 1 kΩ and resonant frequency of the undamped mechanical system as 150 Hz. The transducer yield reliable results.

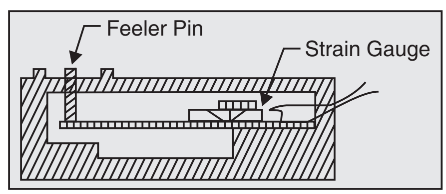


Fig.18.5.

18.8 Respiration Sensors

The primary functions of the respiratory system are to supply oxygen to the tissues and remove carbon dioxide from the tissues. The breathing action is controlled by muscular action causing the volume of the lung to increase and decrease to affect a precise and sensitive control of the tension of CO_2 in the arterial blood. There are several types of transducers have been developed for the measurement of respiration rate. Some of the commonly used transducers for measurement of respiration rate are explain below:

1. Strain Gauge Type Chest Transducer

The respiratory cycle is accompanied by variations in the thoracic volume. Such variation is detected by displacement transducer or a variable resistance element. The transducer is held by an elastic band around the chest. The respiratory movements result in resistance variations of the strain gauge element connected in one arm of a wheatstone bridge circuit. Bridge circuit output varies with chest expansion. The received signal is corresponding to respiratory activity.

2. Thermistors

There is a difference of temperature between inspired and expired air because air is warmed during its passage thought the lungs and respiratory tract. The temperature difference can be sensed by using thermistors placed in front of the nostrils. In case the temperature difference is small, the thermistors can even be initially heated to an appropriate temperature and the variation of its resistance in synchronism with the respiratory rate, as a result of the cooling effect of the air stream can be detected.

The thermistors is placed as a part of a potential dividing circuit or in a bridge circuit whose unbalance signal can be amplified to have the respiratory activity.

18.9 Electrocardiograph (ECG)

The ECG recording instrument is called an electrocardiograph. It records the electrical activity of the heart. Electrical signals from the heart characteristically precede the normally mechanical function and monitoring of these signals has great clinical significance. ECG provides valuable information about a wide range of cardiac disorders such as the presence of an inactive part or an enlargement of the heart muscle.

Although the electric field produced by the heart can be best characterized by vector quantities, it is generally convenient to directly measure only scalar quantities, i.e., a voltage difference of the order of mV between the given points of the body. The diagnostically useful frequency range is usually accepted as 0.05 to 150 Hz. The amplifier and writing part should faithfully reproduce signals in this range. A good low frequency response is essential to ensure stability of the base-line. High frequency response is a compromise of several factors, such as isolation between a useful ECG signal from other signals of biological origin and limitation of direct writing pen recorders due to mass, inertia and friction. The interference of non-biological origin can be handled by using modern differential amplifiers, which provide excellent rejection capabilities.

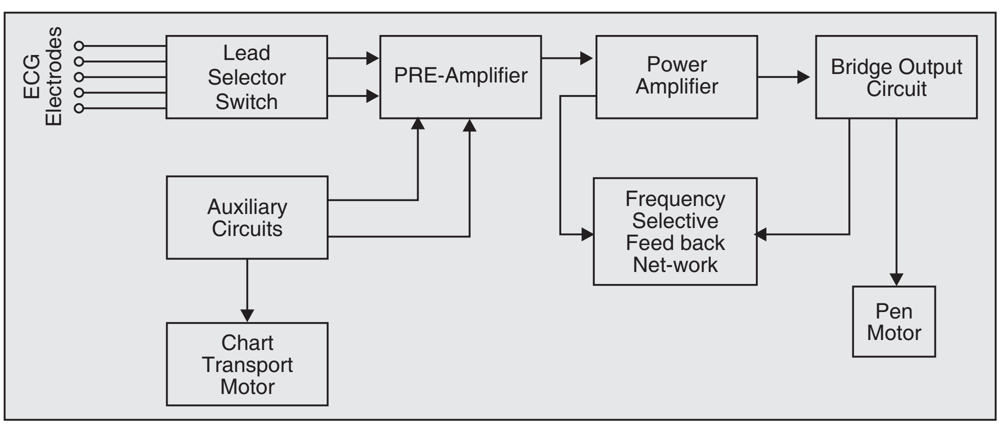


Fig. 18.6. Block Diagram of ECG

Fig. 18.6 shows the block diagram of ECG. The potentials picked up by the patient electrodes are taken to the lead selector switch. In the lead selector, the electrodes are selected two by two according to the lead program. By means of capacitive coupling, the signal is connected symmetrically to the long- tail pair differential preamplifier. The preamplifier is usually a three or four stage differential amplifier having a sufficiently large negative current feed-back, from the last stage to the first stage giving a stabilizing effect. The amplified output signal is picked up single-ended and is supplied to the power amplifier, which is usually of the push-pull differential type. The base of one input transistor of this amplifier is driven by the preamplified unsymmetrical signal whereas the base of the other is driven by the feedback signal resulting from the pen position and connected vie frequency selective network. The output of the power amplifier is single ended and feed to the pen motor which deflects the writing arm on the paper. A direct recorder is usually adequate as the ECG signal of interest has limited bandwidth. Frequency selective network is an R-C network that provides necessary damping of the pen motor and is preset by the manufacturer. The auxiliary circuits provide 1 mV calibration signal and automatic blocking of the amplifier during a change in the position of the lead selector switch. It may include speed control circuit for the chart drive motor.

A stand by operation mode is usually provided on the electro cardio graph. In this mode the stylus moves in response to input signals, but paper is stationary. This mode permits the operator to adjust the gain and base line position controls without wasting paper.

ECG is mostly invariably recorded on graph paper with horizontal and vertical lines at 1 mm intervals with a thicker line at 5 mm intervals. Time measurements and heart rate measurements are made horizontally on the ECG. For routine work, the paper recording speed is 25 mm/s. Amplitude measurements are made vertically in millivolts. The sensitivity of ECG is typically set at 10 mm/mV.

It had been traditional for all ECG to have the right leg electrode connected to the chassis, and from there to ground. This provides a ready path for any ground seeking current through the patient and presented and electric hazard. As the microshok hazard became better understood, particularly when intracardaic catheters are used, the necessity of isolating the patient from the ground was stressed. For this, patient lead would have to be isolated from ground for all line operated units.

The modern ECG machines with their completely patient cable and lead wires and their high, common-mode rejection, are sufficiently resistant to mains interference. However, there could be locations where such interference cannot be eliminated by reapplying the electrodes or moving the cable, instrument or patient. To overcome this problem, some ECG machines have an additional filter to sharply attenuate a narrow band centered up by the substantial reduction of line frequency interference.

18.10 Electroencephalograph (EEG)

EEG is an instrument for recording the electrical activity of the brain, by suitable placing surface electrodes on the scalp. The EEG, describing the general function of the brain activity, is the superimposed wave of neuron potentials operating is non-synchronised manned in physical sense.

If an external stimulus is applied to a sensory area of brain, it responds by producing an electrical potential known as the evoked potential. Evoked potential recorded at the brain surface is the intergraded response of action of many cells. The amplitude of the evoked potential is of the order of 10 μV. The evoked potentials are usually superimposed with electroencephalograms. Therefore, it is essential to remove EEG by averaging technique while making evoked potential measurements.

EEG electrodes are smaller in size and may be applied separately to the scalp or may be mounted in special bands which can be placed on the patient's head/in either case, electrode jelly or paste is used for improving the electrical contact. If the electrodes are intended to be employed under the skin of the scalp, needle electrodes are employed. They offer the advantages of reducing the movement artefacts, EEG electrodes give high skin contact impedance and so preamplifiers are designed to have a very high value of input impedance.

EEG may be recorded by picking up the voltage difference between an active electrode on the scalp with respect to a reference electrode on the ear lobe or other part of the body. Such a recording is known as monopolar recording. However bipolar recording is more popular where in the potential difference between two scalp electrodes is record. Such recording are done with multichannel electro-encephalographs.

EEG signals picked up by the surface electrodes are usually small in compression with ECG signal. They may be several hundred micro-volts, but 50 microvolt peak-to-peak is the most typical. The brain waves, unlike the electrical activity of the heart, do not represent the same pattern over and over again. So brain recording are made over a much longer interval of time in order to be able to detect any kind of abnormalities.

The basic block diagram of an EEG machine is shown in Fig. 18.7. Every channel has an individual, multistage, ac coupled, very sensitive amplifier with differential input and adjustable gain in a wide range. Its frequency response may be selected by single-stage passive filters. A calibrating signal is employed for controlling and documenting the sensitivity of the amplifier channels. This supplies a voltage step of adequate amplitude to the input of the channels. A typical value of calibration signal is 5 μ V/mm.

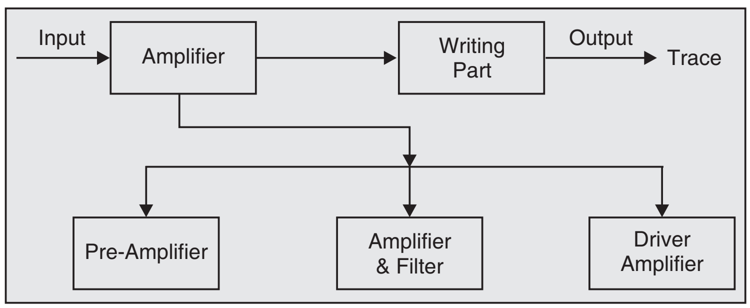


Fig. 18.7. Block Diagram of an EEG

The preamplifier used in EEG must have a high gain and low noise characteristics because the EEG potentials are small in amplitude. In addition, the amplifier must have very high common mode rejection to minimize stray interference signals from power lines and other electrical equipment. Amplifier must be free from drift in order to prevent to slow movement of recording pen from its centre position as a result of vibrations in temperature etc.

The writing part of an EEG machines is usually of the ink writing type direct writing recorder. The best types of pen motors employed in EEG machines have a frequency response of approximately 90 Hz. Most of the machines have response lower than this, and some of them have it as low as 45 Hz. The inkjet recording systems, which gives a response upto 1 kHz is useful for some special applications.

Paper drive is provided by a synchronous motor. An accurate and stable paper drive mechanism is essential and it is normal practice to have several paper speeds available for selection. Speeds of 15, 30 and 60 mm/s are essential.

EEG is recorded simultaneously from an array of many electrodes. The record can be made from bipolar or monopolar lead. The electrodes are connected to separate amplifiers and writing systems. Commercial EEG machines have upto 32 channels, although 8 or 16 channels are more common.

18.11 Electromyograph(EMG)

EMG is an instrument employed for recording the electrical activity of the muscles to determine whether the muscle is contracting or not, or displaying on the CRO and loudspeaker the action potentials spontaneously present in a muscle or induced by voluntary contractions as a means of detecting the nature and location on motor unit or recording the electrical activity evoked in a muscle by simulation of its nerve. The instrument is useful for making a study of several aspects of neuromuscular function, neuromuscular condition, extent of nervelesion, reflex response etc.

EMG is usually recorded by using surface electrodes or more often needle electrodes inserted directly into the muscle. These electrodes pickup the potentials produced by the contracting muscle fibers. The signal can then be amplified and displayed on the CRT screen. It is also applied to an audio-amplifier connected to a loudspeaker. A trained EMG interpreter can diagnose various muscular disorders by listening to the sounds produced when the muscle potentials are feed to the loudspeaker.

The block diagram of a typical setup for EMG recording is shown in Fig. 18.8. The oscilloscope displayed EMG waveforms. The tape recorder is included in the systems to facilitate playback and study of the EMG sound waveforms at a later convenient time. The waveform can also be photographed from the CRT screen by using a synchronised camera.

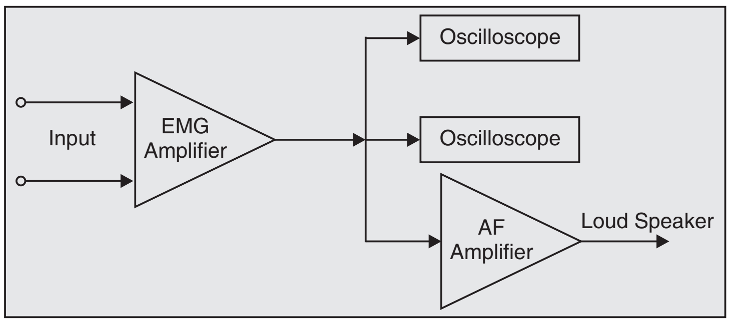


Fig. 18.8. Block Diagram of EMG

The amplitude of the EMG signals depends upon various factors, such as the type and placement of electrodes used and the degree of muscular exertions. The needle electrode in contact with a single muscle fiber will picked spike type voltages whereas a surface electrode picks up many overlapping spikes and therefore, produce an average voltage effect. A typical EMG signal ranges from 0.1 to 0.5 mV. They may contain frequency components extending upto 10 kHz. Such high frequency signals cannot be recorded on the conventional pen recorders and therefore, they are usually displayed on the CRT screen.

The basic system consists of a recording unit and the CRT display, two biological amplifiers with two preamplifiers, a stimulus control unit with constant current or constant voltage stimulator and a digital averaging unit. Special facilities may be added to the basic systems to carry out specific studies. Besides a UV recorder, the data is recorded on a magnetic tape recorder also.

Modern EMGs usually have two CRTs for display and recording purposes. Beam switching provides a four trace display which may be reduced to dual trace or single trace as per needs. One CRT has a normal face plate and is employed for providing a visual display of the acquired signals. For display of action potentials on a CRT screen, a variable persistence storage tube is used. The variable persistence features is especially useful for viewing EMG activity which has a long time period, 200 ms or longer. Displays of single short phenomenon and complex response, such as polyphasic potentials are also enhanced using variable persistence. The other CRT is used for making permanent records.

The recording unit contains a flat-faced fiber optic CRT which duplicates the main CRT display. UL sensitive recording paper is used for making permanent records. The paper is developed directly, as it is advanced by exposure to blue wavelengths of light. Ideally the latent image should be developed is day light but this is frequently impractical. Artificial light, such as that emitted by florescent lamp is suitable. Tungsten filament lamps are not suitable for this type of record development. For producing a trace with a high contrast, the paper should be protected from strong daylight, sunlight or other UV light sources.

Usually a choice is available for selecting any of the paper speeds 1, 2, 5 and 10 mm/s. In certain models lower speeds may also be available and selected from 0.05, 0.1 and 0.0 mm/s.

18.12 X-Ray Machine

X-rays are electromagnetic radiation located at the low-wavelength end of the electromagnetic spectrum. The X-rays in the medical diagnostic region have wavelengths of the order of 0.1 to 1 A. They propagate with speed of 3×10^8 m/s and are unaffected by electric and magnetic fields.

X-ray photons are produced by an electron beam that is accelerated to a very high speed and strikes a target. The electrons that make up the beam are emitted from a heated cathode filament. The electrons are then focused and accelerated by an electrical field towards an angled anode target. The point where the electron beam strikes the target is called the focal spot.

The energy possessed by the electrons appears from the site of collision as a parcel of energy in the form of very penetrating electromagnetic waves (X-rays) of many different wavelengths which together form a continuous spectrum X-rays are produced in a specially constructed glass tube which basically comprise

1. A source for the production of electrons
2. Energy source to accelerate the electrons
3. A free electron path
4. A means of focusing the electron beam
5. A device to stop the electrons

An **X-ray generator** is a device used to generate X-rays. These devices are commonly used by radiographers to acquire an x-ray image of the inside of an object.

Fig. 18.9 shows the block diagram of X-ray machine. There are two part of the circuit, one for producing high voltage which is applied to the anode and cathode of the tube and comprises a high voltage step-up transformer followed by a rectifier. The current through the tube follows the high tension pathway and is measured by a mill-ammeter. A kv selector switch enables to change between exposure. The voltage is measured with a kilo-voltmeter. The exposure switch controls the timer and so the duration of the application of kv. A voltage compensator is included in the circuit in order to compensate for variations in supply voltage.

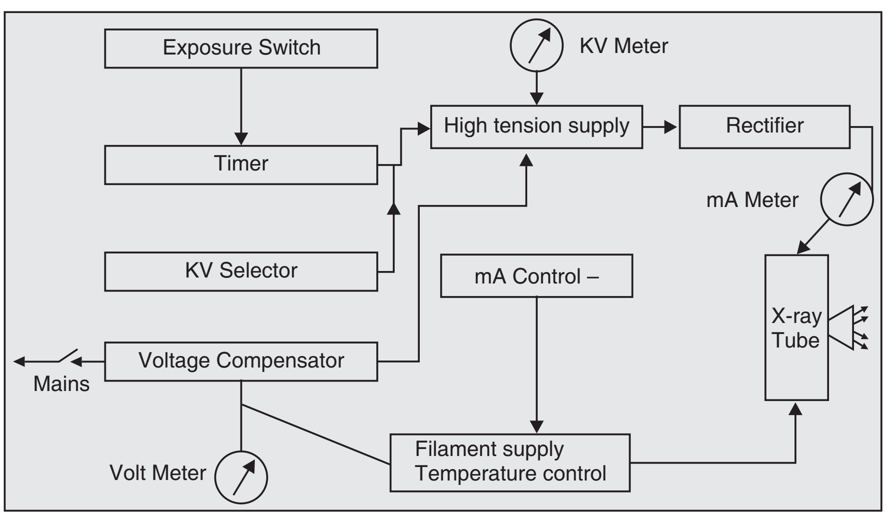


Fig. 18.9. Block Diagram of X-Ray Machine

The second part of the circuit concerns the control of heating of the X-rays tube filament. The filament is heated with 6 to 12 V ac supply at a current of 3 to 5 A. The filament temperature determines the tube current or mA. The filament temperature control is connected with mA selector. The filament current is controlled by using a variable choke or rheostat on the primary side of the filament transformer. The rheostat provides a stepwise, control of the tube current and is most commonly used in modern machines.

A X-ray scan beams X-rays through a part of the body from one source and receives the penetrating rays on a screen on the other side of the body. These rays are absorbed in varying degrees in the body depending on the densities of the organs inside, the screen catches more or less X-rays. This leaves energized particles on the screen that document the tissues inside, with denser tissues showing up whiter, less dense tissues showing up grayer, and the background appearing black. This picture is then run through a computer to create a two-dimensional image of the body.

18.13 EMI Scanner or Computed Axial Tomography (CAT)

The word "tomography" is derived from the Greek *tomos* (slice) and *graphein* (to write). Computed tomography was originally known as the "EMI scan" as it was developed at a research branch of EMI, a company best known today for its music and recording business. It was later known as **computed axial tomography** (CAT or CT scan).

CAT scan is a medical diagnostic technology that makes images of the internal structures of the body. These scans use X-ray technology run through a computer to image a section of the body. X-rays is a type of electromagnetic radiation with short wavelengths, are beamed through the targeted section of the body from several different angles. The focus point comes out as a clear, three-dimensional or cross-sectional image and the other tissues in the area are blurred, making it easier for the physician to differentiate the targeted tissues. Computed axialtomography is commonly used to diagnose conditions or damage in the soft tissues or bones in the head, chest, joints, colon, lungs, and heart.

The CAT scanner is a machine which employs a method of X raying patients whereby the information obtained from the X rays is fully utilized. Before the invention of the CAT scanner it was impossible to produce detailed pictures of patients' brains. With this machine, doctors were first able to show the medical usefulness of scanning. It was the first type of scanner to be adopted in substantial numbers for medicine and set the pattern for other scanning technologies. Present day CAT scanner use X-ray source which provide fan beams and multiple detectors to simultaneously measure the density across a wide position of the slide.

Fig. 18.10 shows the modern CT scanner, which uses a stationary ring of detectors positioned around the patient. Only the x-ray source rotates with wide fan beam geometry, while the detectors are stationary. Hence, the geometry is called rotate-stationary motion.

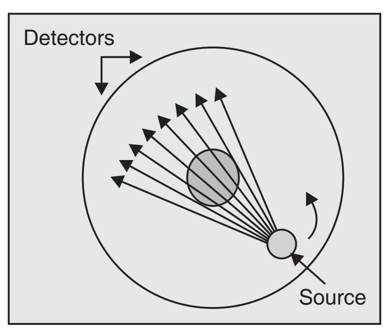


Fig.18.10. Modern CT Scanner

X-rays normally produce much better images of dense bodily structures, such as bones, than of brains or other soft tissues. To produce images of the separate parts of the brain it was necessary to introduce air or special liquids to the area. These were hazardous techniques. In addition, X-ray pictures are often confusing, since they are made up from overlapping shadows from different layers and structures in the body.

The brain scanner overcame this by using computing power to construct a picture from a series of 28,800 measurements made by a paired X-ray source and detector rotating around the patient. It took this first scanner several hours to produce its images.

Fig. 18.11 shows the CAT scan. The X-ray source and detector are mounted opposite to each other. If the patient is placed between source and detector, X-rays from the source are passed through the body. The radiation transmitted from the body is sensed by detector. The source is made moving or detector or both across the section of the body. The measurements are made at regular intervals. The patient moving inside the chamber on a trolley, X-ray and detector can move in clock-wise or one direction, axially. Hence, it is termed as Computer Axial Tomography

A computed axial tomography scan rotates the X-ray source around the targeted tissue to get many cross-sectional X-ray images of the focal point. These images are then compiled to create a 3D picture.

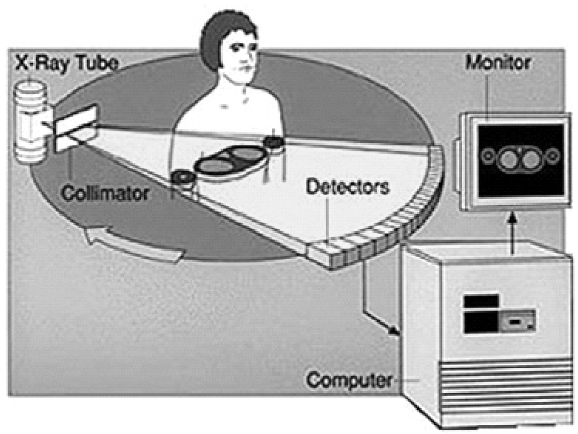


Fig. 18.11. CAT Scan Machine

The reconstruction process involves the collection of X-ray transmission values outside the patient. These transmission values are an index of how much the radiation was attenuated is passage through the patient. The collection of such data from a number of different angles around the patient is used to calculate the attenuation occurring at each picture element within the patient. Various data collection schemes have been employed for the acquisition of X-ray transmission data. All schemes involve some geometrical pattern of scanning around the patient coupled with use of a suitable radiation detector. The signal from the radiation detector is digitized by the use of an analog-to-digital converter and passed on to the completed, the results are displayed on a video monitor. Interim storage of the images is via hard disk. Long-term storage is accomplished either on magnetic tape or on optical disks. Block diagram of Computed Axial Tomography is shown in Fig. 18.12.

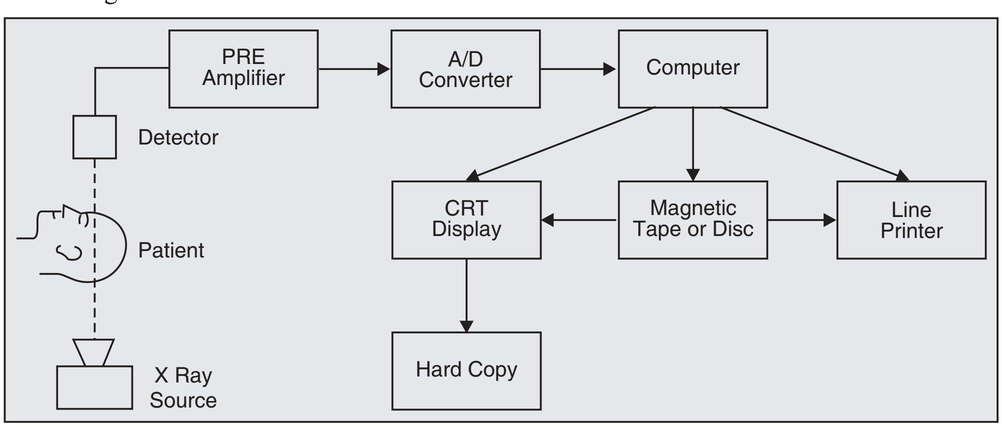


Fig. 18.12. Block Diagram of Computed Axial Tomography

18.14 Magnetic Resonance Imaging (MRI)

Magnetic resonance imaging (MRI), nuclear magnetic resonance imaging (NMRI), or **magnetic resonance tomography (MRT)** is a medical imaging technique that uses magnetism, radio waves, and a computer to produce images of body structures. The good contrast it provides between the different soft tissues of the body make it especially useful in brain, muscles, heart, and cancer compared with other medical imaging techniques such as computed tomography (CT) or X-rays.

Magnetic Imaging is based on the nuclear properties of hydrogen atoms in the body. Elements having odd number of protons in the nucleus have magnetic properties. Such elements are hydrogen -1, carbon -13, oxygen -17, sodium-23, Fluorine-19, Phosphorous -31, etc. Hydrogen atom nucleus has a single proton which being odd number has the property of spin. This works like a magnet when the patient is placed in a strong magnetic field, the magnetic moments of protons align with or against the field lines of the magnet.

A small excess of magnetic moments of protons align with the field so that a net magnetic vector (NMV) is created.

If RF pulses of the same frequency as the processing nuclei are applied at right angles to the main static magnetic field, the hydrogen nuclei tissues get disturbed. They absorb energy and change their orientation with respect to the magnetic field and are lifted to the higher energy state. Now, if the field is put off, the hydrogen nuclei go back to their low energy state after emitting energy they had received. All this process is known as nuclear magnetic resonance. The emitted energy can be detected, digitized, amplified, encoded and transformed by computer into cross-sectional images. The MRI images are accurate for visualization of tumors, inflammatory and vascular abnormalities.

The MRI scanner is a tube surrounded by a giant circular magnet. The patient is placed on a moveable bed that is inserted into the magnet as shown in Fig. 18.13. The magnet creates a strong magnetic field that aligns the protons of hydrogen atoms, which are then exposed to a beam of radio waves. This spins the various protons of the body, and they produce a faint signal that is detected by the receiver portion of the MRI scanner. The receiver information is processed by a computer, and an image is produced.

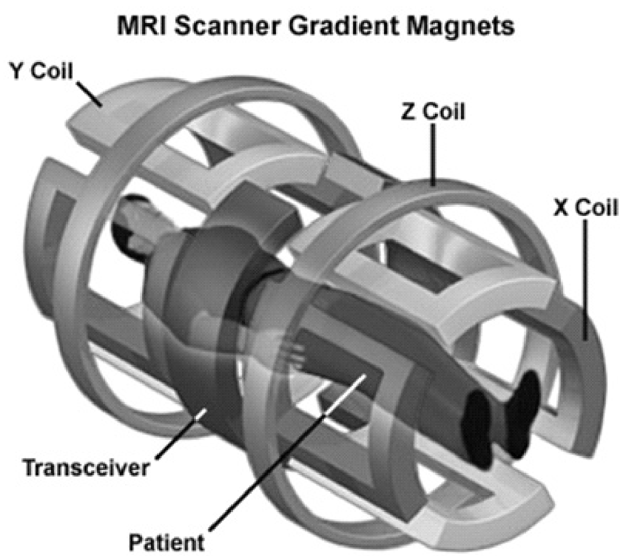


Fig. 18.13.

Fig. 18.14 shows the block diagram of MRI scan. A strong uniform and steady magnetic field is developed by the magnet, which is kept near the patient. In order to produce controlled spatial non-uniform magnetic fields in different directions, to cover the exposed area, different gradient coil systems have been closed. On both sides of the patient, the transmitter and receiver RF coil in placed. The superposition of the uniform magnetic field on the patient and the linear gradient field from the RF coils take place at resonance frequencies. The resonance frequency of the processing nuclei depends on the position of along the direction of the magnetic field gradient. This results in the production of one-dimensional image of the three-dimension object. One can obtain two/three-dimensional images by taking the projection gradient coil along x, y and z directions.

The motion of the gradient magnetic field is controlled by computer. The nuclear magnetic signal is received by the receiver coil and is fed into the computer. The images of the object are constructed on the screen by the computer using Fourier transformation. In recent years, in order to improve the image quality than obtained by conventional magnets in MRI systems, superconducting magnets are used.

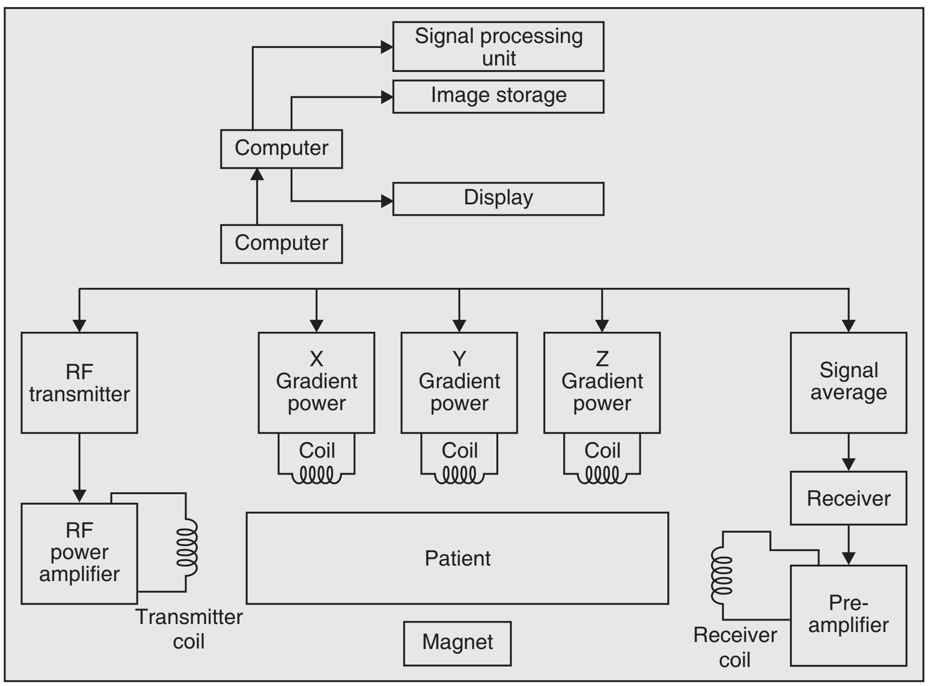


Fig. 18.14. Block Diagram of Magnetic Resonance Imaging

The image and resolution produced by MRI is quite detailed and can detect tiny changes of structures within the body. For some procedures, contrast agents, such as gadolinium, are used to increase the accuracy of the images.

MRI is a non-invasive technique with excellent soft tissue contrast. It is slow process, relatively expensive. It cannot image bones. MRI is used for soft tissues-brain, vessels of brain, eyes, inner ear, heart, abdominal vessels, kidney, etc. Naturally it is able to diagnose related problems of the organs. It is extremely accurate method of disease detection throughout the body. In the head, trauma to the brain can be seen as bleeding or swelling. Other abnormalities often found include brain aneurysms, stroke, tumors of the brain, as well as tumors or inflammation of the spine.

18.15 Emission Computerized Tomography

Radioactive isotopes of certain elements can be used to trace the metabolism, pathways, and concentrations of the body parts. Emission computerized tomography can provides detailed three dimensional distribution map of an isotope which is injected into the body and allowed to distribute itself. The three dimensional image is created by taking scans of several slices. Naturally instrumentation for emission computerized tomography is very sophisticated. Computerized tomography methods are being developed for ultrasonic imaging of the heart and abdominal organs.

SUMMARY

1. The thermoresistor (or thermistor) sensor is used for measuring body temperature.
2. Photo resistors are normally used for detecting pulsatile blood volume variation by photoelectric method.
3. Electrocardiography (ECG) record the activity of different sections of the heart.
4. ECG provides valuable information about a wide range of cardiac disorders such as the presence of an inactive part or an enlargement of the heart muscle.
5. Electroencephalography (EEG) record the electrical activity of the brain.
6. The EEG, describing the general function of the brain activity, is the superimposed wave of neuron potentials operating is non-synchronized manned in physical sense.
7. Electromyography (EMG) record the electrical activity of the muscles.
8. X-rays devices are commonly used by radiographers to acquire an x-ray image of the inside of an object.
9. Magnetic resonance imaging (MRI) is a medical imaging technique used in radiology to visualize detailed internal structures.

GLOSSARY

CAT scan: CAT scan is a medical diagnostic technology that makes images of the internal structures of the body.

Electrocardiograph (ECG): The ECG recording instrument is called an electrocardiograph. It records the electrical activity of the heart.

Electroencephalograph (EEG): EEG is an instrument for recording the electrical activity of the brain, by suitable placing surface electrodes on the scalp.

Electromyograph (EMG): EMG is usually recorded by using surface electrodes or more often needle electrodes inserted directly into the muscle.

Magnetic Resonance Imaging (MRI): A magnetic resonance imaging (MRI) scan is a radiology technique that uses magnetism, radio waves, and a computer to produce images of body structures.

Plethysmograph: A plethysmograph is an instrument for measuring changes in volume within an organ or whole body.

DESCRIPTIVE QUESTIONS

1. Describe biomedical transducers.
2. Write short note on
   (*i*) Transducer for measurement of body temperature
   (*ii*) Pulse sensors
   (*iii*) Respiration sensors
3. Describe with block diagram the working of X-ray machine.
4. Explain the working of ECG.
5. Describe the working of EEG.
6. Explain the working of EMG.
7. Explain and describe CAT scan.
8. Explain the working principle of MRI.
9. Explain the block diagram of CAT scan in detail.

Chapter 19

Virtual Instrumentation

Outline

Objectives

After completing this chapter, you should be able to:

- Understand the Virtual Instrument.
- Know about LabVIEW
- Creating the Virtual Instrument.

19.1 Introduction

Virtual Instrumentation is the use of customizable software and modular measurement hardware to create user-defined measurement systems, called *virtual instruments*.

Traditional hardware instrumentation systems are made up of pre-defined hardware components, such as digital multimeters and oscilloscopes that are completely specific to their stimulus, analysis, or measurement function. Because of their hard-coded function, these systems are more limited in their versatility than virtual instrumentation systems. The primary difference between hardware instrumentation and virtual instrumentation is that software is used to replace a large amount of hardware. The software enables complex and expensive hardware to be replaced by already purchased computer hardware; e.g. analog-to-digital converter can act as a hardware complement of a virtual oscilloscope, a *potentiostat* enables frequency response acquisition and analysis in electrochemical impedance spectroscopy with virtual instrumentation.

The concept of a synthetic instrument is a subset of the virtual instrument concept. A synthetic instrument is a kind of virtual instrument that is purely software defined. A synthetic instrument performs a specific synthesis, analysis, or measurement function on completely generic, measurement agnostic hardware. Virtual instruments can still have measurement specific hardware, and tend to emphasize modular hardware approaches that facilitate this specificity. Hardware supporting synthetic instruments is by definition *not* specific to the measurement, nor is it necessarily (or usually) modular.

Leveraging commercially available technologies, such as the PC and the analog-to-digital converter, virtual instrumentation has grown significantly since its inception in the late 1970s. Additionally, software packages like National Instruments' *LabVIEW* and other graphical programming languages helped grow adoption by making it easier for non-programmers to develop systems.

19.2 Virtual Instrument

A virtual instrument consists of an industry-standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and driver software, which together perform the functions of traditional instruments. Virtual instruments represent a fundamental shift from traditional hardware-centered instrumentation systems to software-centered systems that exploit the computing power, productivity, display, and connectivity capabilities of popular desktop computers and workstations. Although the PC and integrated circuit technology have experienced significant advances in the last two decades, it is software that truly provides the leverage to build on this powerful hardware foundation to create virtual instruments, providing better ways to innovate and significantly reduce cost. With virtual instruments, engineers and scientists build measurement and automation systems that suit their needs exactly (user-defined) instead of being limited by traditional fixed-function instruments (vendor-defined).

Engineers and scientists whose needs, applications, and requirements change very quickly, need flexibility to create their own solutions. You can adapt a virtual instrument to your particular needs without having to replace the entire device because of the application software installed on the PC and the wide range of available plug-in hardware.

A traditional instrument contains an integrated circuit to perform a particular set of data processing functions but in a virtual instrument, these functions would be performed by software running on the PC processor. You can extend the set of functions easily, limited only by the power of the software used.

By employing virtual instrumentation solutions, you can lower capital costs, system development costs, and system maintenance costs, while improving time to market and the quality of your own products.

There is a wide variety of available hardware that you can either plug into the computer or access through a network. These devices offer a wide range of data acquisition capabilities at a significantly lower cost than that of dedicated devices. As integrated circuit technology advances, and off-the-shelf components become cheaper and more powerful, so do the boards that use them. With these advances in technology come an increase in data acquisition rates, measurement accuracy, precision, and better signal isolation.

Depending on the particular application, the hardware you choose might include analog input or output, digital input or output, counters, timers, filters, simultaneous sampling, and waveform generation capabilities. The wide gamut of boards and hardware could include any one of these features or a combination of them.

19.3 Architecture of Virtual Instrument

Fig 19.1 shows the architecture of the virtual instrument. It consists of the following block:

1. Sensor Module
2. Sensor Interface
3. Medical Information Systems Interface
4. Processing Module
5. Database Interface
6. User Interface

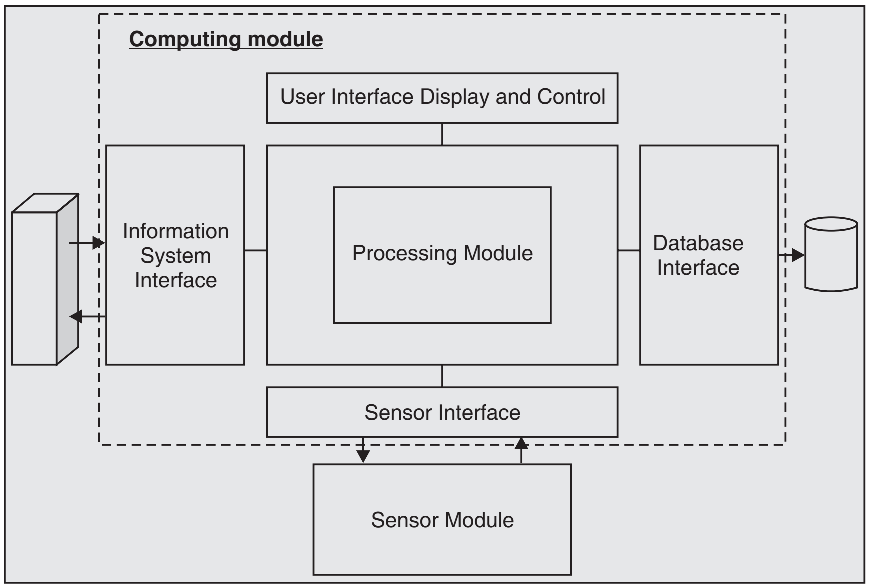


Fig.19.1. General architecture of a virtual instrument

The sensor module transforms the physical signal into electrical form. A sensor interface communicate with the sensor module to a computer. Once the data are in a digital form on a computer, they can be processed, mixed, compared, and otherwise manipulated, or stored in a database. Then, the data may be displayed, or converted back to analog form for further process control. Biomedical virtual instruments are often integrated with some other medical information systems such as hospital information systems. We will discuss each block one by one in the following pages..

1. Sensor Module

A sensor module mainly consists of three parts the sensor, signal conditioning part and ADC converter. The sensor detects physical signals from the environment. If the parameter being measured is not electrical then the sensor must include a transducer to convert the information to an electrical signal.

The signal conditioning module performs signal conditioning prior to ADC conversion, such as. This module usually does the amplification, transducer excitation, linearization, isolation, or filtering of detected signals. We will discuss signal conditioning in detail in Chapter 13.

The ADC converter changes the detected and conditioned voltage into a digital. The converter is defined by its resolution and sampling frequency. The converted data must be precisely time -stamped to allow later sophisticated analyses.

2. Sensor Interface

These days there are many interfaces used for communication between sensors modules and the computer.

According to the type of connection sensor interfaces can *wired* and *wireless*.

Wired Interfaces are usually standard parallel interfaces, such as General Purpose Interface Bus (GPIB), Small Computer Systems Interface (SCSI), system buses (PCI eXtension for Instrumentation PXI or VME Extensions for Instrumentation (VXI), or serial buses (RS232 or USB interfaces).

Wireless Interfaces are increasingly used because of convenience. They are 802.11 family of standards, Bluetooth, or GPRS/GSM interface. Wireless communication is especially important for implanted sensors where cable connection is impractical or not possible.

3. Medical Information Systems Interface

The Virtual instruments are increasingly integrated with other medical information systems, such as hospital information systems. They can be used to create executive dashboards, supporting decision support, realtime alerts and predictive warnings.

4. Processing Module

In this module the integration of the general purpose microprocessors/microcontrollers allowed flexible implementation of sophisticated processing functions. The processing function used in virtual instrumentation may be classified as *analyticprocessing* and *artificial intelligence techniques*.

The Analytic functions define clear functional relations among input parameters. Some of the common analyses used in virtual instrumentation include spectral analysis, filtering, windowing, transforms, peak detection, or curve fitting.

The Artificial intelligence technologies could be used to enhance and improve the efficiency, the capability, and the features of instrumentation in application areas related to measurement, system identification, and control. These techniques exploit the advanced computational capabilities of modern computing systems to manipulate the sampled input signals and extract the desired measurements.

5. Database Interface

Computerized instrumentation allows measured data to be stored for off-line processing, or to keep records. There are several currently available database technologies that can be used for future purpose.

6. User Interface

The user sends requests to the computer typing commands, and receives response in a form of textual messages. Presentation is usually done on a screen with fixed resolution. The communication between a user and a computer is purely textual.

19.4 Virtual Instrumentation in Engineering Process

Virtual instruments provide significant advantages in stage of the engineering process from research and design to manufacturing test. They are given below:

1. Research and Design

In research and design an engineers and scientists demand rapid development and prototyping capabilities. With virtual instruments they can quickly develop a program, take measurements from an instrument to test a prototype, and analyze results, all in a fraction of the time required to build tests with traditional instruments.

The demanding requirements of research and development (R&D) applications require seamless software and hardware integration. Whether you need to interface stand-alone instruments using GPIB or directly acquire signals into the computer with a data acquisition board and signal conditioning hardware, LabVIEW makes integration simple. With virtual instruments we can also automate a testing procedure, eliminating the possibility of human error and ensuring the consistency of the results by not introducing unknown or unexpected variables.

2. Development Test and Validation

With the flexibility and power of virtual instruments, we can easily build complex test procedures. For example in automated design verification testing, we can create test routines in LabVIEW and integrate software such as National Instruments TestStand, which offers powerful test management capabilities. You develop code in the design process, and then plug these same programs into functional tools for validation, test, or manufacturing.

3. Manufacturing

Manufacturing applications require software to be reliable, high in performance, and interoperable. Virtual instruments based on LabVIEW offer all these advantages, by integrating features such as alarm management, historical data trending, security, networking, industrial I/O, and enterprise connectivity. With this functionality, you can easily connect to many types of industrial devices such as PLCs, industrial networks, distributed I/O, and plug-in data acquisition boards. By sharing code across the enterprise, manufacturing can use the same LabVIEW applications developed in R&D or validation, and integrate seamlessly with manufacturing test processes.

19.5 Software in Virtual Instrument

Software is the most important component of a any virtual instrument. With the right software tool an engineers and scientists can efficiently create their own applications, by designing and integrating the routines that a particular process requires. They can also create an appropriate user interface that best suits the purpose of the application and those who will interact with it.

An important advantage that software provides is modularity. When dealing with a large project, engineers and scientists generally approach the task by breaking it down into functional solvable units. These subtasks are more manageable and easier to test, given the reduced dependencies that might cause unexpected behavior. You can design a virtual instrument to solve each of these subtasks, and then join them into a complete system to solve the larger task. The ease with which you can accomplish this division of tasks depends greatly on the underlying architecture of the software.

Distributed Applications

A virtual instrument is not limited or confined to a stand-alone PC. In fact, with recent developments in networking technologies and the Internet, it is more common for instruments to use the power of connectivity for the purpose of task sharing. Typical examples include supercomputers, distributed monitoring and control devices, as well as data or result visualization from multiple locations.

19.6 Instrument Driver

An instrument driver is a set of software routines that control a programmable instrument. Each routine corresponds to a programmatic operation such as configuring, reading from, writing to, and triggering the instrument. Instrument drivers simplify instrument control and reduce test program development time by eliminating the need to learn the programming protocol for each instrument.

For example National Instruments provides instrument drivers for a wide variety of instruments; these instrument drivers are written in LabVIEW and/or LabWindows/CVI and use either the Plug and Play architecture or the Interchangeable Virtual Instrument (IVI) architecture. Both architectures use Virtual Instrumentation Software Architecture (VISA) to provide bus and platform independent instrument communication. There are the following types of instrument driver:

1. Plug and Play

A Plug and Play instrument driver is a set of functions used to control and communicate with a programmable instrument. Each function corresponds to a programmatic operation such as configuring, reading from, writing to, and triggering the instrument. Plug and Play instrument drivers comply with programming guidelines. The Plug and Play drivers maintain a common architecture and interface and include application examples, you can quickly and easily connect to and communicate with your instruments with very little or no code development.

Plug and Play instrument drivers provide source code native to the development environment. With access to source code, you can modify, customize, optimize, debug, and add functionality to the instrument driver. Source code also enables Plug and Play instrument drivers to be cross-platform, so you can use them in any operating system that works with LabVIEW or LabWindows/CVI software.

2. Interchangeable Virtual Instrument (IVI)

VI drivers are more sophisticated instrument drivers that feature increased performance and flexibility. These drivers are designed for more complex test applications that require interchangeability, state caching, or instrument simulation.

IVI drivers implement state-caching to eliminate redundant commands that may be sent to the instruments in your system. This reduction in instrument I/O can provide significant performance improvements. IVI drivers can also be configured to run in simulation mode, where the actual instrument and the signal it acquires or generates is simulated in software.

One of the most important features of IVI drivers is their ability to allow instruments to be interchanged in a system without modifying the test application. The IVI Foundation has defined eight classes of instruments: DC Power Supplies, DMMs, Function Generators, Oscilloscopes/Digitizers, Power Meters, RF Signal Generators, Spectrum Analyzers, and Switches. An instrument that conforms to one of the IVI Class specifications may be substituted with another instrument of the same class, regardless of manufacturer or bus connection (GPIB, USB, LXI, PXI).

19.7 LabVIEW

LabVIEW is the short form of Laboratory Virtual Instrumentation Engineering Workbench. It is a system design platform for visual programming language from National Instruments. LabVIEW is an integral part of virtual instrumentation because it provides an easy-to-use application development environment designed specifically with the needs of engineers and scientists in mind. LabVIEW offers powerful features that make is easy to connect to a wide variety of hardware and other software. Main feature of LabVIEW are given below:

1. Graphical Programming

One of the most powerful features that LabVIEW offers engineers and scientists is its graphical programming environment. With LabVIEW, you can design custom virtual instruments by creating a graphical user interface on the computer screen through which you do the following:

(*a*) Operate the instrumentation program
(*b*) Control selected hardware
(*c*) Analyze acquired data
(*d*) Display results

You can customize front panels with knobs, buttons, dials, and graphs to emulate control panels of traditional instruments, create custom test panels, or visually represent the control and operation of processes. The similarity between standard flow charts and graphical programs shortens the learning curve associated with traditional, text-based languages.

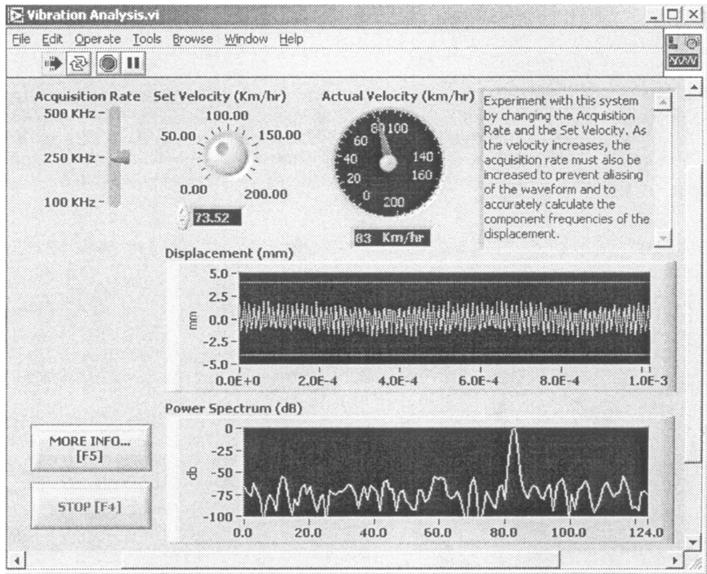


Fig. 19.2. Illustrating LabVIEW Virtual Instrument Front Panel
(Courtesy: National Instruments)

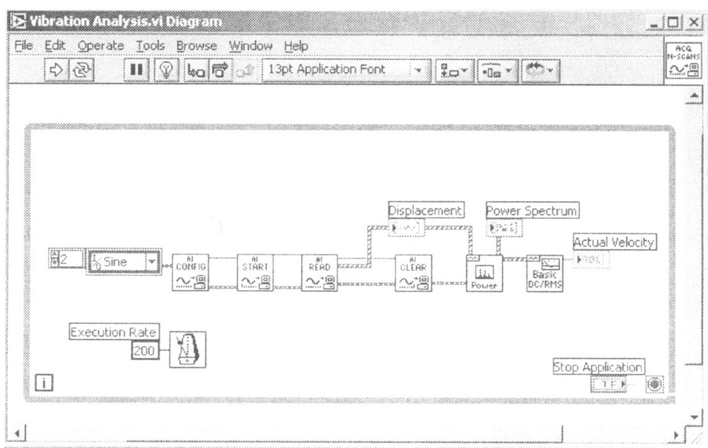


Fig. 19.3. Illustrating LabVIEW Virtual Instrument Block Diagram.
(Courtesy: National Instruments)

You determine the behavior of the virtual instruments by connecting icons together to create block diagrams, which are natural design notations for scientists and engineers. With graphical programming, you can develop systems more rapidly than with conventional programming languages, while retaining the power and flexibility needed to create a variety of applications.

2. Connectivity and Instrument Control

Virtual instrumentation software productivity comes about because the software includes built-in knowledge of hardware integration. Designed to create test, measurement, and control systems, virtual instrumentation software includes extensive functionality for I/O of almost any kind.

3. Open Environment

LabVIEW provides the tools required for most applications, it is an open development environment. LabVIEW also offers a full range of options for communications and data standards, such as

TCP/IP, OPC, SQL database connectivity, and XML data formats.

4. Reduces Cost and Preserves Investment

The use of a single computer equipped with LabVIEW for countless applications and purposes, it is a versatile product. Virtual instrumentation with LabVIEW proves to be economical, not only in the reduced development costs but also in its preservation of capital investment over a long period of time.

5. Multiple Platforms

LabVIEW runs on Windows 2000, NT, XP, Me, 98, 95, and NT embedded, as well as Mac OS, Sun Solaris, and Linux. LabVIEW also compiles code to run on the VenturCom ETS real-time operating system through the LabVIEW Real-Time Module. National Instruments continues to make available older versions of LabVIEW for Windows, Mac OS, and Sun operating systems. LabVIEW is platform independent.

Because LabVIEW applications are portable across platforms, you can be assured that your work today will be applicable in the future. As new computer technologies emerge, you can easily migrate your applications to new platforms and operating systems.

6. Distributed Development

You can easily develop distributed applications with LabVIEW, even across different platforms. With easy-to-use server tools, you can offload processor-intensive routines to other machines for faster execution, or create remote monitoring and control applications. Powerful server technology can simplify the task of developing large, multicomputer applications. LabVIEW includes standard networking technologies such as TCP/IP, and incorporates robust publishing and subscribe protocols.

7. Analysis Capabilities

Virtual instrumentation software requires comprehensive analysis and signal processing tools, because the application does not just stop when the data is collected. High-speed measurement applications in machine monitoring and control systems usually require order analysis for accurate vibration data.

8. Visualization Capabilities

LabVIEW includes a wide array of built-in visualization tools to present data on the user interface of the virtual instrument for charting and graphing as well as 2D and 3D visualization. You can instantly reconfigure attributes of the data presentation, such as colors, font size, graph types, and more, as well as dynamically rotate, zoom, and pan these graphs with the mouse. Rather than programming graphics and all custom attributes from scratch, you can simply drag-and-drop these objects onto the instrument front panels.

9. Flexibility and Scalability–Key Advantages

Engineers and scientists have needs and requirements that can change rapidly. They also need to have maintainable, extensible solutions that can used for a long time. By creating virtual instruments based on powerful development software such as LabVIEW, you inherently design an open framework that seamlessly integrates software and hardware. This ensures that your applications not only work well today but that you can easily integrate new technologies in the future as they become available, or extend your solutions beyond the original scope, as new requirements are identified. Moreover, every application has its own unique requirements that require a broad range of solutions.

19.8 Applications of LabVIEW

LabVIEW is a powerful, industry-standard graphical development environment. Academic campuses worldwide use LabVIEW to deliver project-based learning. LabVIEW offer unrivaled integration with thousands of hardware devices and provides hundreds of built-in libraries for advanced analysis and data visualization. With the intuitive nature of graphical system design, educators and researchers can design, prototype, and deploy their applications. Some of the importants of LabVIEW are given below:

1. **Take measurements in minutes.** With built-in I/O integration and instrument control, you can quickly configure and use almost any measurement device. LabVIEW delivers seamless connectivity with a wide range of measurement hardware and instruments communicating through USB, PXI, Ethernet, GPIB, and many others, helping you get to the data and experimentation faster.
2. **Analyze signals with advanced built-in math and signal processing functions.** Access thousands of built-in functions to perform advanced math and signal processing functions such as filtering, frequency analysis, probability and statistics, curve fitting, interpolation, and more. Unlike software development tools designed only for DAQ or signal processing, LabVIEW is a completely integrated solution so you can simultaneously acquire and analyze data.
3. **Visualize and Interact With Live Data While Your Application Is Running.** Quickly create GUIs to interact with your applications and visualize your data using hundreds of included charts, graphs, thermometers, and 2D and 3D visualization tools.
4. **Access Hundreds of Free LabVIEW Courseware Downloads.** Gain access to free educational resources, labs, exercises, and tutorials that can help you learn how to use LabVIEW and incorporate it into a multitude of engineering and science disciplines.
5. **Prepare Students With Industry-Standard Tools and Skills.** LabVIEW is a development environment that has been built specifically for engineers and scientists and is used by over 90 percent of Fortune 500 manufacturing companies.

19.9 Virtual Instrumentation with LabVIEW

LabVIEW is a graphical development environment with built-in functionality for simulation, data acquisition, instrument control, measurement analysis, and data presentation. LabVIEW gives you the flexibility of a powerful programming language without the complexity of traditional development environments. LabVIEW delivers extensive acquisition, analysis, and presentation capabilities in a single environment, so you can seamlessly develop a complete solution on the platform of your choice.

Note: For more information related to LabVIEW software, visit the National Instruments Website.

LabVIEW programs are called virtual instruments (VIs). Each VI contains three main parts, they are given below:

1. Front Panel
2. Block Diagram
3. Icon/Connector

We will discuss each part one by one in the following pages.

19.10 Front Panel of Virtual Instrument

Figure 19.4 shows the front panel of VI, It is the user interface of the VI. You build the front panel with controls and indicators, which are the interactive input and output terminals of the VI, respectively. Controls are knobs, pushbuttons, dials, and other input devices. Indicators are graphs, LEDs, and other displays. Controls simulate instrument input devices and supply data to the block diagram of the VI. Indicators simulate instrument output devices and display data the block diagram acquires or generates.

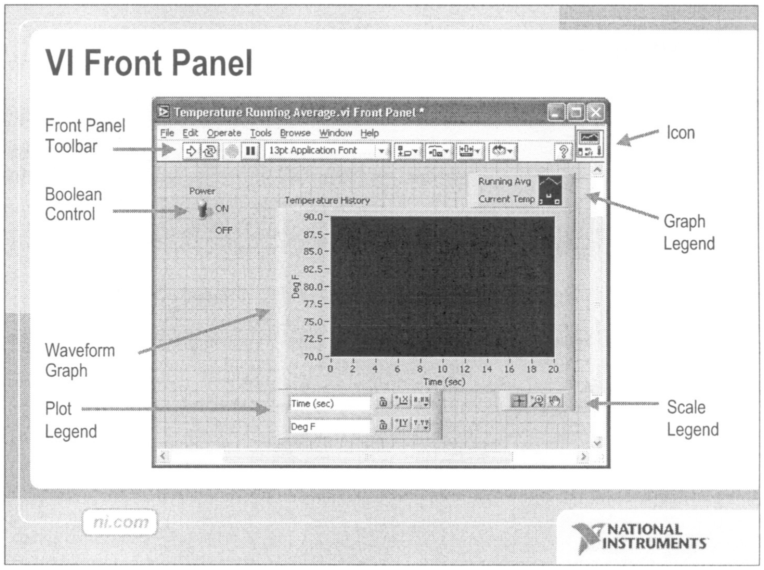


Fig. 19.4. (Courtesy: National Instruments)

In this picture, the **Power switch** is a boolean control. A boolean contains either a true or false value. The value is false until the switch is pressed. When the switch is pressed, the value becomes true. The **temperature history** indicator is a waveform graph. It displays multiple numbers. In this case, the graph will plot Deg F versus Time (sec).

19.11 Block Diagram of Virtual Instrument

Figure 19.5 shows the VI block diagram. The block diagram contains this graphical source code. Front panel objects appear as terminals on the block diagram. Additionally, the block diagram contains functions and structures from built-in LabVIEW VI libraries. Wires connect each of the nodes on the block diagram, including control and indicator terminals, functions, and structures.

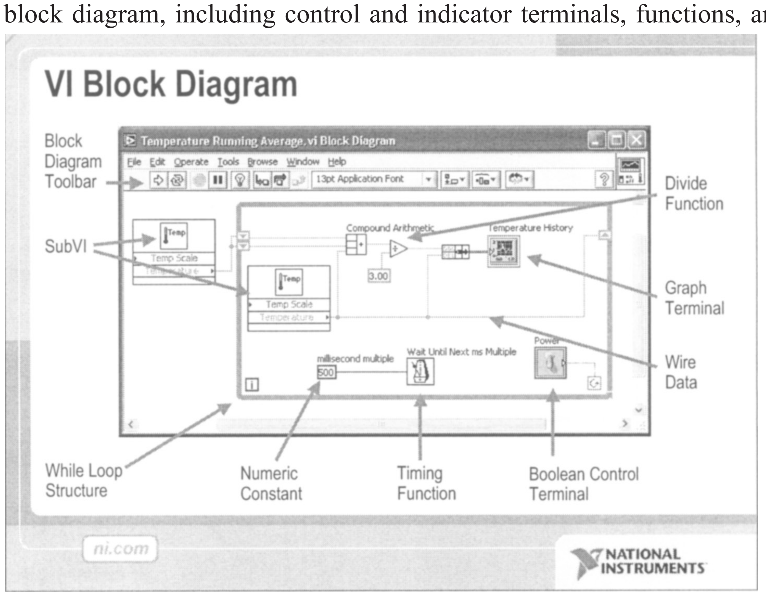


Fig. 19.5. (Courtesy: National Instrument)

In this block diagram, the subVI **Temp** calls the subroutine which retrieves a temperature from a Data Acquisition (DAQ) board. This temperature is plotted along with the running average temperature on the wavefront graph **Temperature History**. The **Power** switch is a boolean control on the Front Panel which will stop execution of the While Loop. The While Loop also contains a Timing Function to control how frequently the loop iterates.

19.12 Controls and Function Palettes of Virtual Instrument

Figure 19.6 shows the control and function palettes of virtual instrument. Use the **Controls** palette to place controls and indicators on the front panel. The **Controls** palette is available only on the front panel. Select **Window>>Show Controls Palette** or right-click the front panel workspace to display the **Controls** palette. You also can display the **Controls** palette by right-clicking an open area on the front panel. Tack down the **Controls** palette by clicking the pushpin on the top left corner of the palette.

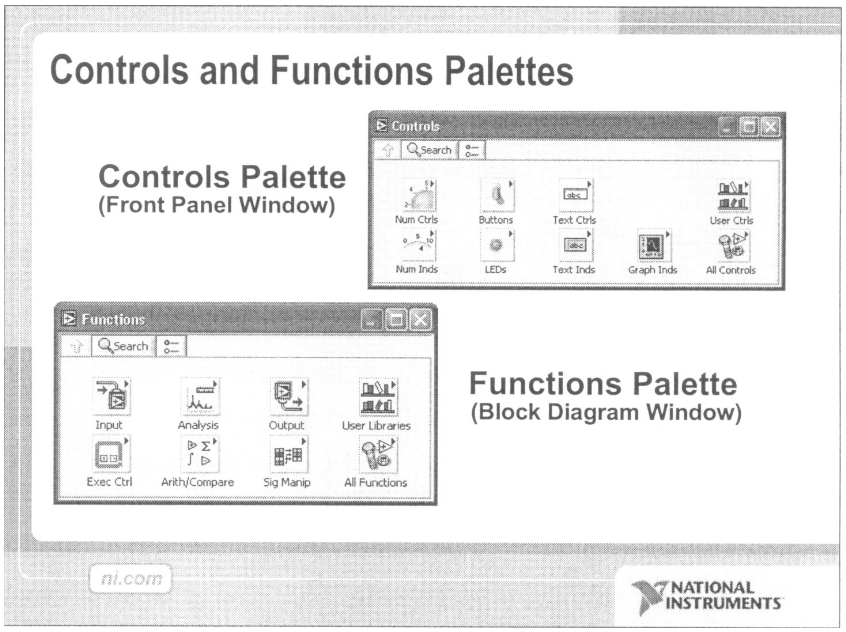


Fig. 19.6. (Courtesy: National Instruments)

Use the **Functions** palette, to build the block diagram. The **Functions** palette is available only on the block diagram. Select **Window>>Show Functions Palette** or right-click the block diagram workspace to display the **Functions** palette. You also can display the **Functions** palette by right-clicking an open area on the block diagram. Tack down the **Functions** palette by clicking the pushpin on the top left corner of the palette.

19.13 Creating Virtual Instrument

When you create an object on the Front Panel, a terminal will be created on the Block Diagram. These terminals give you access to the Front Panel objects from the Block Diagram code as shown in Fig. 19.7.

Each terminal contains useful information about the Front Panel object it corresponds to. For example, the color and symbols provide the data type. Double-precision, floating point numbers are represented with orange terminals and the letters DBL. Boolean terminals are green with TF lettering.

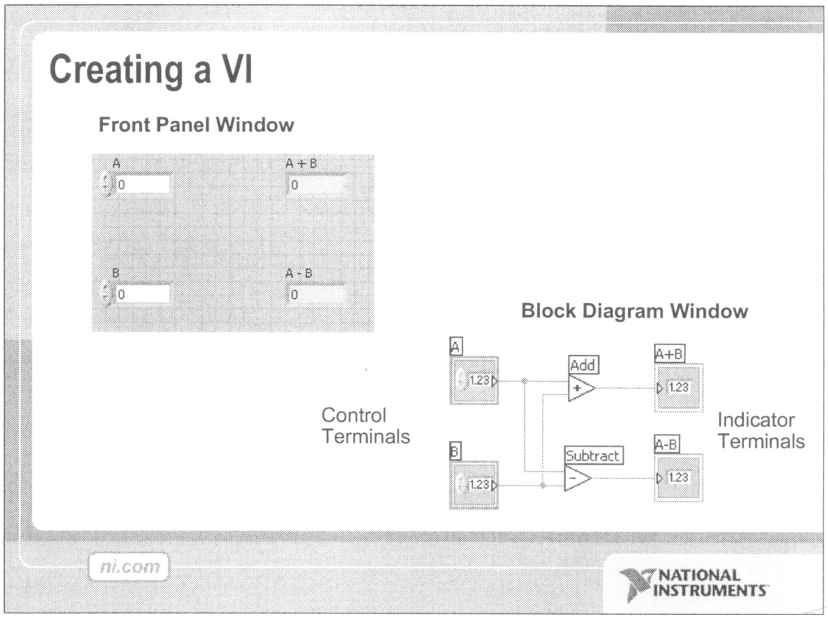


Fig. 19.7. (Courtesy: National Instruments)

In general, orange terminals should wire to orange terminals, green to green, and so on.

Controls have an arrow on the right side and have a thick border. Indicators have an arrow on the left and a thin border. Logic rules apply to wiring in LabVIEW: Each wire must have one (but only one) source (or control), and each wire may have multiple destinations (or indicators).

The program in this slide takes data from A and B and passes the values to both and Add function and a subtract function. The results are displayed on the appropriate indicators.

19.14 Wheatstone Bridge Based Measurements with DAQ and LabVIEW

We use the wheatstone bridge with DAQ with LabVIEW to make a precise measurement for sensor suchas strain gauges and load cells. Certain sensors and gauges, such as a strain gauge, output a very small change in resistance; this makes the task of detecting the changes in the sensor difficult. To measure such small changes in resistance or voltage, these sensors are almost always used in a bridge configuration with a voltage excitation source. The general Wheatstone bridge, as shown in Fig. 19.8, consists of four resistive arms with an excitation voltage, V that is applied across the bridge. We can then calculate the change in resistance of R_3 by comparing V_O to V, provided that the resistance of the other resistors are known,

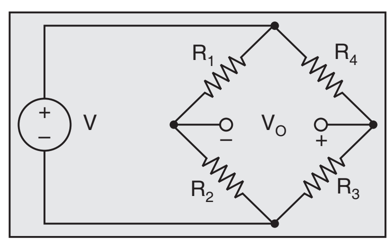


Fig. 19.8.

$$V_O = \left[\frac{R_3}{R_3 + R_1} - \frac{R_2}{R_1 + R_2} \right] V$$

The Wheatstone Bridge is wired to DAQ as 2 analog inputs, one to measure V_O and the other to measure V. We also must connect the +5V output pin of the DAQ to the top of the bridge to serve as the excitation voltage high, and connect the Digital Ground (DGND) to the bottom of the bridge to serve as the excitation voltage low. This will allow us to measure the excitation voltage in case it is not exactly at a constant 5VDC. This will serve as a *Remote Sense* of the excitation voltage.

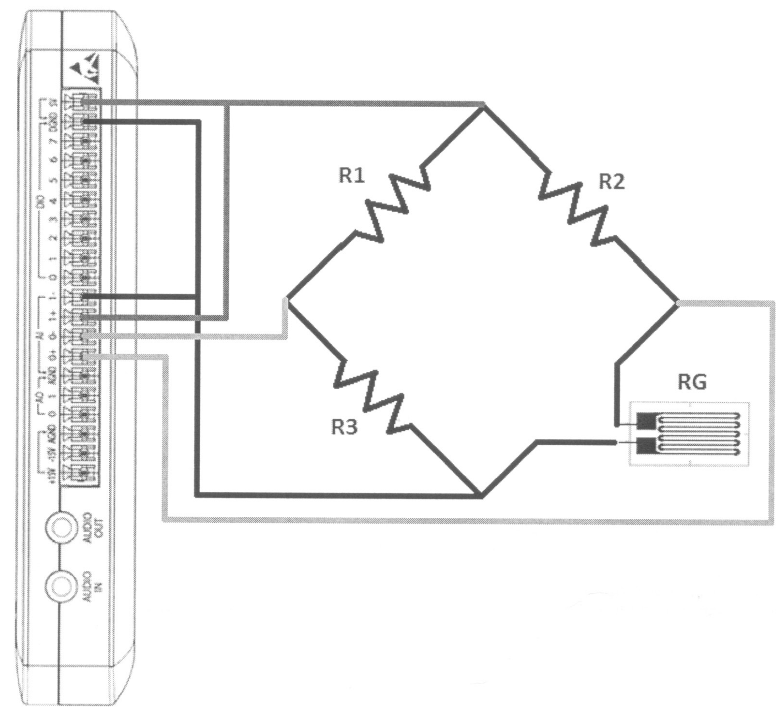


Fig. 19.9. Illustrating Wiring Diagram (Courtesy: National Instruments)

LabVIEW User Interface. The user interface shown in Fig. 19.10 the Voltage Drop, V_O, the measured Excitation Voltage, V and the ratio of the V_O and V.

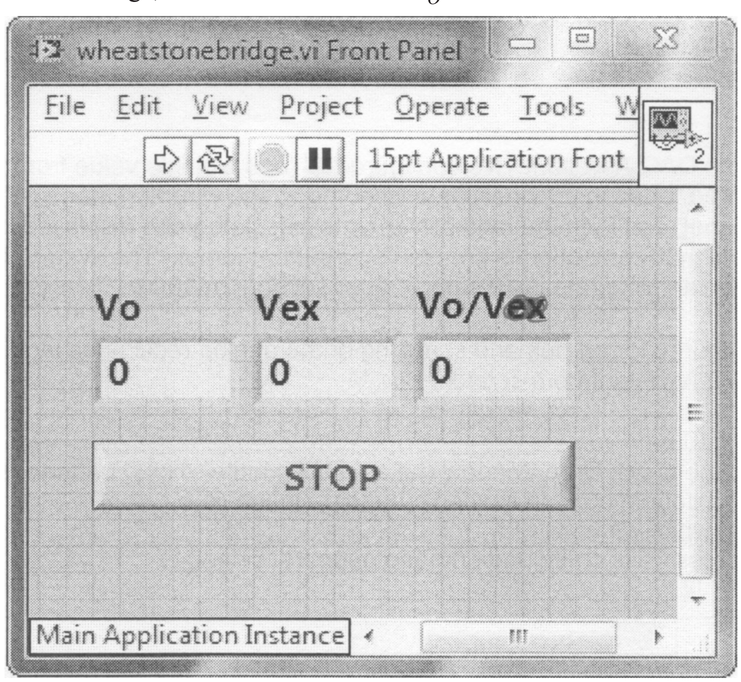


Fig. 19.10. Illustrating LabVIEW Front Panel (Courtesy: National Instruments)

Coding. In LabVIEW wee need to measure the voltage drop across the terminals, as well as the excitation voltage applied to the bridge. The voltage drop is then divided by the excitation voltage to find the ratio between the two. This value is very useful in bridge-based measurements and more logic can be built in to tailor the application as needed. Finally, we will output the results to numeric indicators on the front panel.

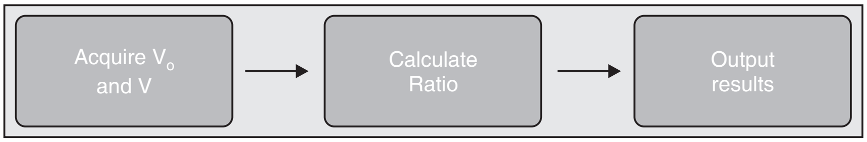


Fig. 19.11. Coding Block Diagram

Figure 19.11 shows the LabVIEW block diagram.

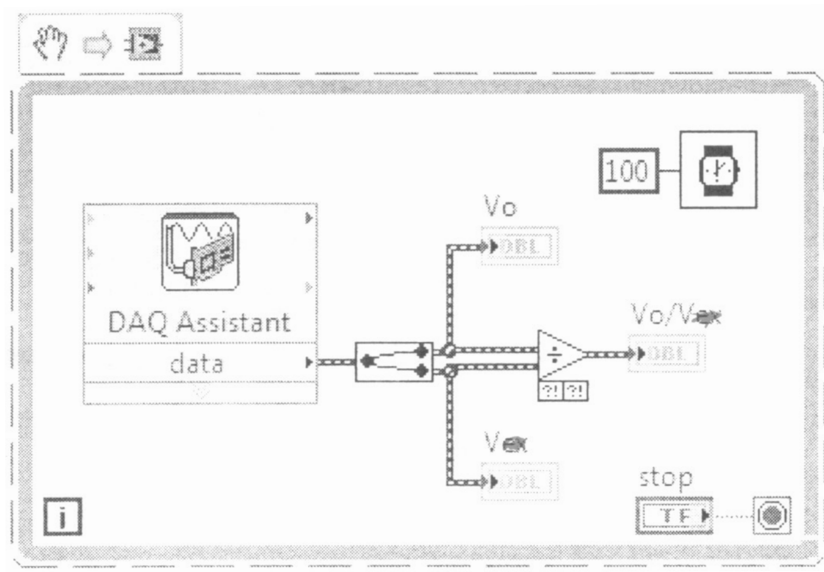


Fig. 19.12. Illustrating LabVIEW Block Diagram (Courtesy: National Instruments)

19.15 Measure Temperature Using Thermistor, DAQ, and LabVIEW

We will measure the temperature using thermistor, DAQ and LabVIEW. A constant, known current is applied across the thermistor and the voltage drop across the thermistor is recorded. By using Ohm's Law, this voltage and current can be used to determine the resistance of the thermistor, which varies with temperature. This resistance is then used to calculate temperature using the polynomial equation listed in the sensors specifications document.

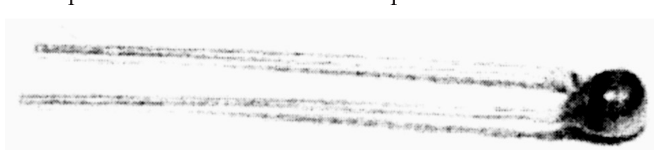


Fig. 19.13. Thermistor

The thermistor is wired in a circuit as a resistor as shown in Fig. 19.14. It requires a positive input on one side and a negative input on the other side; the orientation is not important.

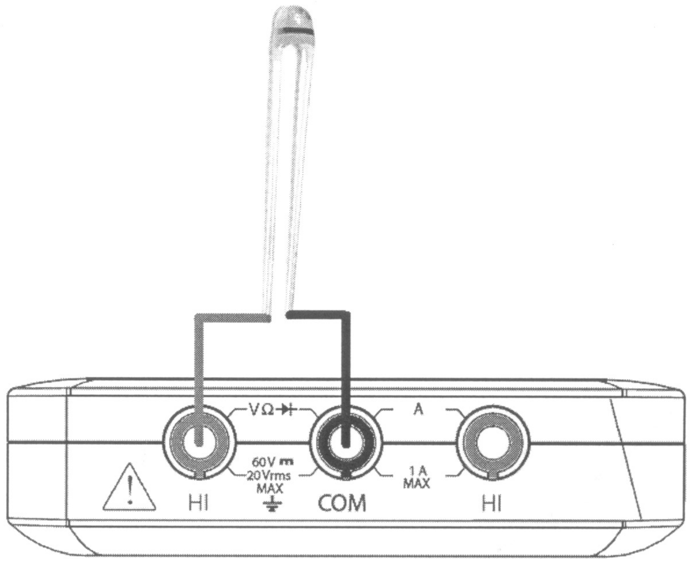


Fig. 19.14. Illustrating Wiring Diagram (Courtesy: National Instruments)

LabVIEW User Interface. The user interface is shown in Fig. 19.15. The current temperature measurement taken as well as plotting the values over time on a waveform chart. Temperature Chart stores previous values so that you can see the change in values over time.

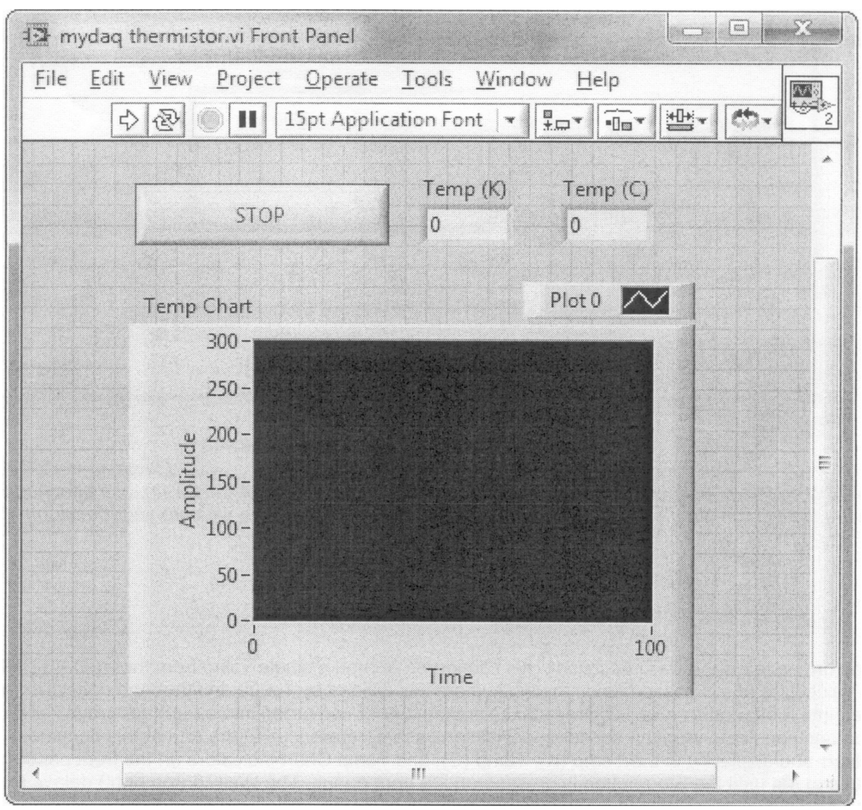


Fig. 19.15. Illustrating LabVIEW Front Panel (Courtesy: National Instruments)

Coding. In LabVIEW we need to measure the resistance signal coming from the thermistor from 100 Ω to 100 kΩ. This value is converted to a temperature using the polynomial equation from the thermistor specifications referenced at the end of this document. Finally, we will output the result to a numeric indicator and a temperature chart on the front panel.

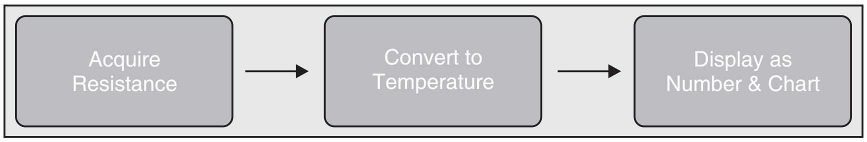


Fig. 19.16. Illusting Coding Block Diagram

Figure 19.16 show the LabVIEW block diagram looks very similar to the coding block diagram.

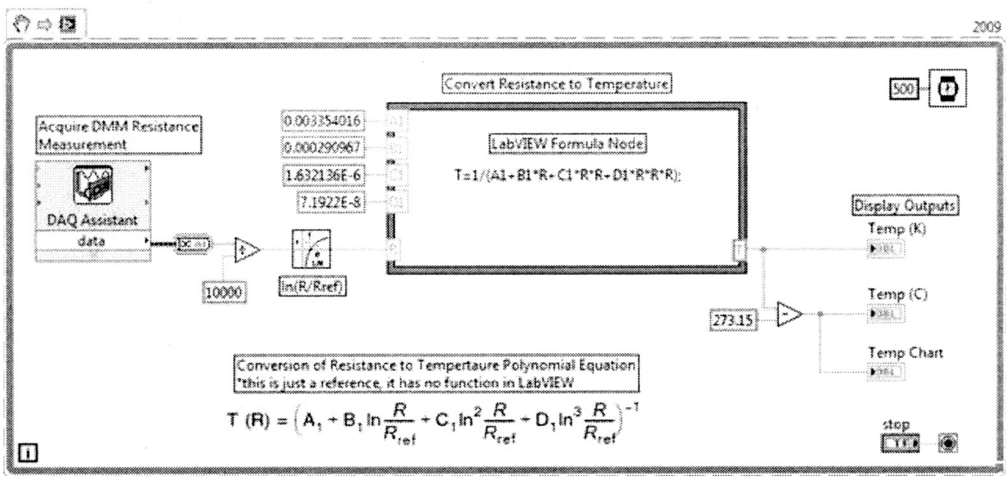


Fig. 19.17. Illustrating LabVIEW Block Diagram (Courtesy: National Instruments)

19.16 Familiarization with LabVIEW

You need to learn about (*i*) the basic components in LabVIEW 8.0 and (*ii*) understand how to use LabVIEW in a simple measurement application.

Note: Students can read up on LabVIEW 8.0 to obtain an in-depth understanding of this software. This module serves to introduce them to the basic features of LabVIEW and will not be covering the intermediate features which can be commonly used in various industrial applications. Students can approach their facilitators if they encounter any problems while reading through the resources. Now we shall study how to build a simple application using LabView.

Building a Simple Application

1. Open the LabVIEW 8.0 application.
2. Click on 'Blank VI' and press CTRL-T to tile the windows side-by-side.
3. You should see two windows 'Untitled 1 Block Diagram' and 'Untitled 1 Front Panel'.
4. All LabVIEW applications will come in the form of a Front Panel and a Block Diagram. The Front Panel shows you the interface type (buttons, sliders, knobs, etc) between the operator and the equipments, sensors, actuators, etc. The Block Diagram shows the working components and mechanisms which make the Front Panel work.
5. Right clock your mouse in the Front Panel and you should see the Controls Menu.
6. Left click on Express and you will see the `Num Ctrls' and 'Num Inds' submenu.

7. Obtain the Knob from the 'Num Ctrls' submenu and place it in the Front Panel by left clicking on it.
8. Obtain the Meter from the 'Num Inds' submenu and place it in the Front Panel by left clicking on it.
9. Your Front panel and Block Diagram should look like this:

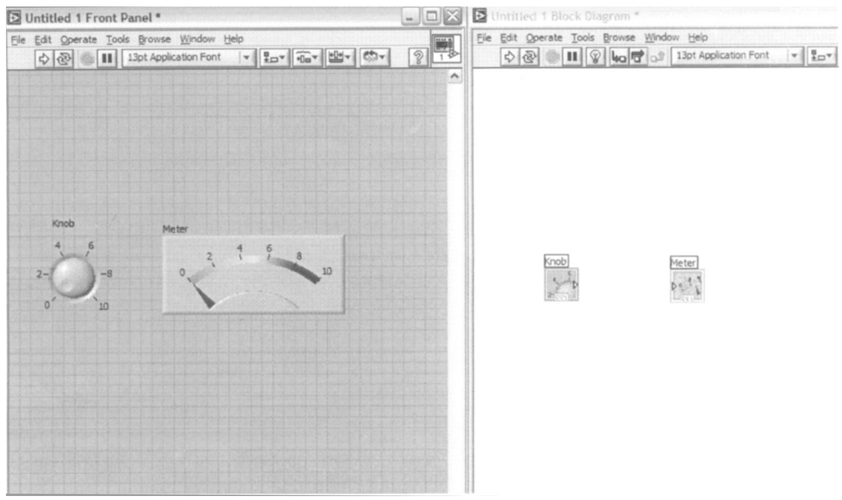


Fig. 19.18. A simple application using LabVIEW

10. Bring the cursor to the output of the Knob in the Block Diagram until you see the wiring tool and left click your mouse.
11. Bring the cursor to the input of the Meter block and left click your mouse to connect the Knob to the Meter. Your Block Diagram should look like this:

Fig. 19.19.

12. Congratulations, you have just implemented your first application using LabVIEW 8.0. In the Front Panel turn the knob to a value of 4. Click on the Run applet (the arrow button) and observe that happens. Turn the knob to other values and click on the Run applet again. What happens?
13. This program lacks one basic feature, which is the real-time updating of the Knob value on the Meter. The Knob serves as a Numeric Control, and the Meter behaves as a Numeric Indicator. There are many different types of numeric indicators and controls. You can explore the Controls Menu > Express.
14. Right clock on the Block Diagram and left click on the Express > Exec Control submenu, left click on the 'While Loop', left click at the top left corner of your components and left click again at the bottom right corner. Your Block Diagram should look like this:

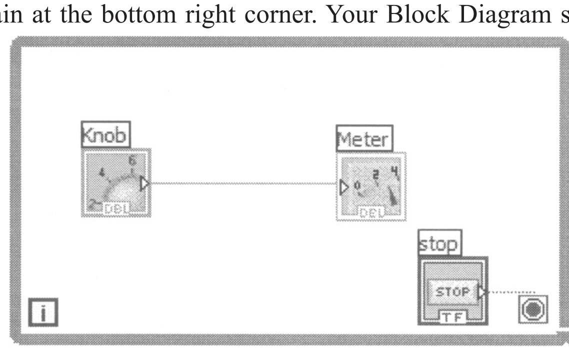


Fig. 19.20. Addition of a While Loop

15. Notice that a Stop button has just been added to the Front Panel along with the While Loop in the Block Diagram. The While Loop works just like the one in other computer programs and the Stop button is used to terminate the Loop.
16. Click on the Run applet and adjust the Knob. You will notice that there is real-time updating of the Knob value on the Meter. This program is known as a Virtual Instrument (VI). All LabVIEW files will have an extension of .vi.
17. **If the VI runs slowly, try to include a delay of 1 ms in the While Loop. You will learn how to include a delay in the While Loop later on.**
18. Click on the Stop button on the Front Panel to terminate the VI.
19. Save this file as 'Lab_08_1.vi'.

Including a Delay in the While Loop

1. There are instances when you need to include a delay in the execution of a While Loop. This may be the case when you need to wait for the input to stabilize before acquiring the signal. In the previous VI, the While Loop is executed without any delay. The speed of execution is limited by the clock speed of your laptop.
2. Let us include a delay of 1 sec, in other words, the While Loop will execute the components in the Block Diagram every 1 sec.
3. Right click on the Block Diagram to access the Function Menu. Left click on Timing. Left click on 'Wait Until Next ms Multiple' component and left click inside the While Loop. Your Block Diagram should look like this:

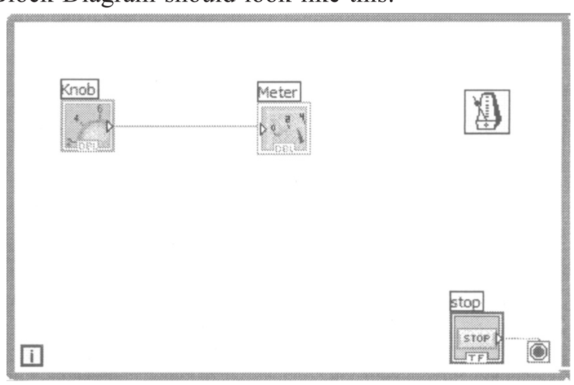


Fig. 19.21. A delay within the While Loop

4. We will now assign a constant of 1000 to the 'Wait Until Next ms Multiple' block to obtain a delay of (1000 × 1 ms = 1 sec). Your program may not run smoothly if you did not include any delay, try setting the While Loop delay to at least 1 ms.
5. Access the 'Functions' menu and left click on Numeric. Left click on Numeric Constant and left click again inside the While Loop just next to the 'Wait Until Next ms Multiple' block.
6. Double click on the Numeric Constant block and type '1000'. Place the cursor on the right side of the Numeric Constant block until you see the wiring tool.
7. Left click your mouse and bring the cursor to the left side of the 'Wait Until Next ms Multiple' block until you see a blue dot appearing at both sides of the block. Left click the mouse again. Your Block Diagram should look like this:

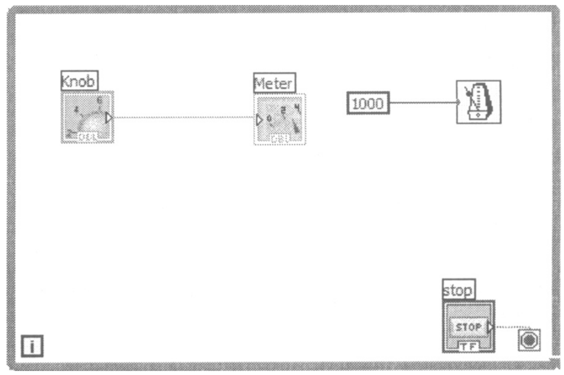


Fig. 19.22. Assigning a constant to the delay block

8. Click on the Run applet and adjust the knob to different values. What do you observe?
9. In this VI, the knob is used to simulate the values of temperature, force, pressure, etc from sensors located in different parts of a plant. You have just constructed a VI which can be used to display the values obtained from these sensors or transducers.

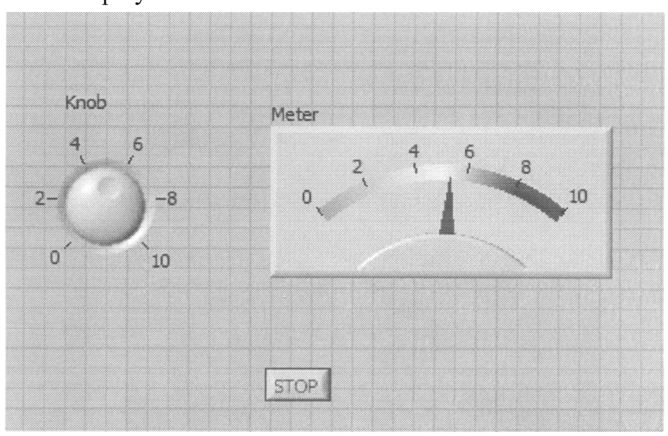


Fig. 19.23. The front panel of a simple measurement system

10. We can add more features to the Front Panel as shown above. Right click on the Knob and left click on 'Visible Items'. Left click on 'Digital Display'. Do the same to the Meter.
11. What you have added are digital displays which clearly show the values on the Knob and Meter. Your Front Panel should look like this:

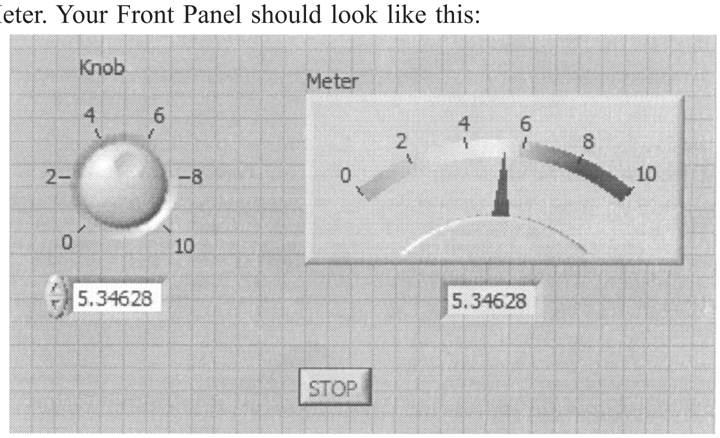


Fig. 19.24. Front Panel with digital displays

12. Run the VI and observer how the digital displays change with different values of the Knob.

19.17 A Simple Level Sensor Using LabVIEW

A pressure sensor is used as a level sensor as shown below. We will now use LabVIEW to convert the pressure reading from the sensor to liquid level. Can you still remember what is the pressure exerted by a liquid at the base of a tank?

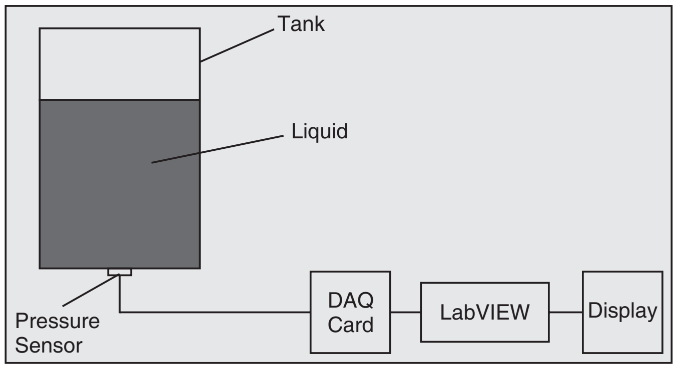


Fig. 19.25. A simple level measurement application

1. Construct the following Front Panel and use the knowledge which you have gained thus far to complete the VI. You can use the Numeric submenu under the Functions menu to help you with the computation.

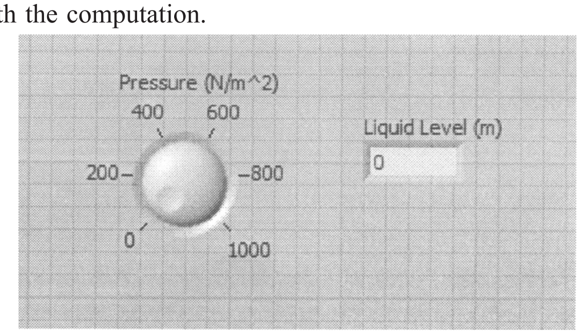


Fig. 19.26. Front Panel of a liquid level measurement system

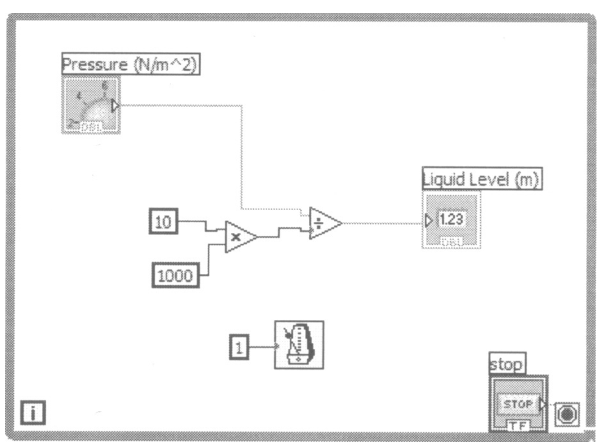


Fig. 19.27. Block diagram of a liquid level measurement system

2. You can assume that the density of the liquid is 1000 kg/m^3 and the gravitational acceleration is 10 m/s^2. In this case the Numeric Indicator Knob is used to simulate the pressure reading in N/m^2 from the pressure sensor.
3. To change the scales on the Knob to display 0 to 1000, right click on the Knob, left click on Properties > Scale. Enter the Maximum and Minimum values at corresponding fields.
4. When you turn the Knob to different values, the liquid level reading should change in accordance to the pressure reading. Call your facilitator to verify your design.
5. Above is an example of a Block Diagram which you can use to accomplish this task.
6. Save the file as Lab _08_2.vi
7. Modify the above VI so that you can change the density of the liquid as well as the gravitational acceleration from the Front Panel. Also replace the Numeric Liquid Level indicator with a Tank Level indicator which you can find to Controls > Express > Num Inds submenu. Your Front Panel should look like the one below:

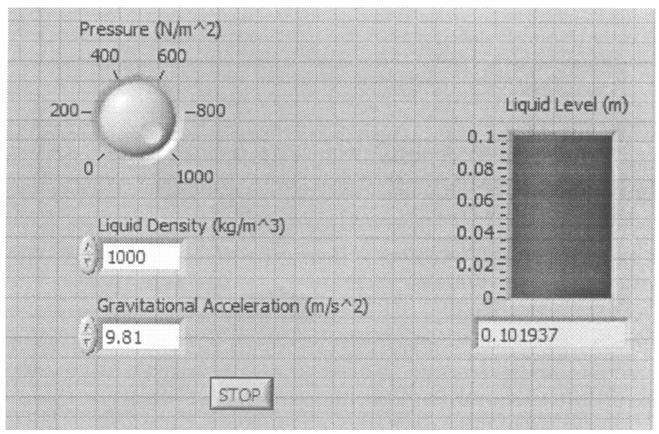


Fig. 19.28. Improved level measurement Front Panel

8. Activate the Digital Display for the Tank Level indicator.
9. Call your teacher once you have made the modifications to the Block Diagram. Run the VI to verify that it is working correctly.
10. Save this file as Lab_08_3.vi

Example: In this exercise, you will (*i*) learn how to implement Boolean functions in LabVIEW and (*ii*) know how to use the Formula Node to perform mathematical computations.

Note: Students can read up on LabVIEW to obtain an in-depth understanding of this software. This module serves to introduce them to the basic features of LabVIEW and will not be covering the intermediate features which can be commonly used in various industrial applications. Students can approach their teachers if they encounter any problems while reading through the resources.

Implementing Simple Boolean Functions

1. Open the LabVIEW 8.6.
2. Click on 'Blank VI' and press CTRL-T to tile the two windows side-by-side.
3. Right clock on the Front Panel to access the Controls menu. Left click on Express > Buttons > Toggle switch. Drag and drop the Toggle Switch on the Front Panel.
4. Drag and drop the round LED from Controls menu > Express > LEDs > Round LEDs on the Front Panel.
5. By using the wiring tool which you have used last week. Connect the Toggle Siwtch to the Round LED on the block diagram.

6. Right click on the Block Diagram and left click on Express > Exec Control > While Loop. Place the While Loop around the Toggle Switch and Round LED as shown below.
7. Include a 1 ms delay in the While Loop. Right clock on the Block Diagram to access the Functions menu, left click on Timing > Wait Until Next ms Multiple and left click again inside the While Loop.
8. Finally place a Numeric Constant inside the While Loop. Right Click on the Block Diagram, left click Numeric > Numeric Constant. Double click on its value and change it to 1.
9. Connect the Numeric Constant to the Wait Until Next ms Multiple block.
10. Your Front Panel and Block Diagram should look like the one below:

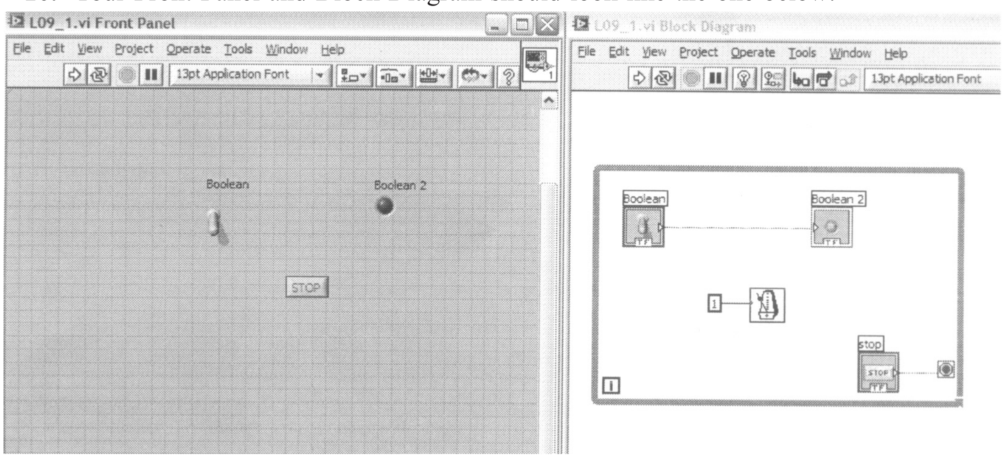


Fig. 19.29. A simple Boolean function

11. Run the VI and toggle the switch. What happens?

Temperature Controller

1. Save the previous VI, and open a new VI.
2. Place a Knob on the Front Panel and put a square LED next to it.

   Knob: Control menu > Express > Num Ctrls > Knob

   Square LED: Controls menu > Express > LEDs > Square LED
3. Change the maximum limit on the Knob to 100. You can do this by right clicking on the Knob, left click on Properties > Scale, change the value in the Maximum field.
4. Double click on the Knob and rename it to ‘Temperature degC’, we will use it to simulate a temperature reading.
5. Show the digital display for the Knob. You can do this by right clicking on the Knob, left click on Visible Items > Digital Display.
6. On the square LED rename Boolean to ‘Temp Exceeded’.
7. Right click on the Block Diagram, left click on Comparison > Greater?
8. Connect a Numeric Constant with a value of 70 to one input of the ‘Greater than’ comparator.
9. Connect the Knob to the other input of the ‘Greater than’ comparator.
10. By using the wiring tool connect the output from the ‘Greater than’ comparator to the Square LED.
11. Place all the components in the Block Diagram inside a While Loop. Include a delay of 1 ms.

12. Your Front Panel and Block Diagram should look like this:

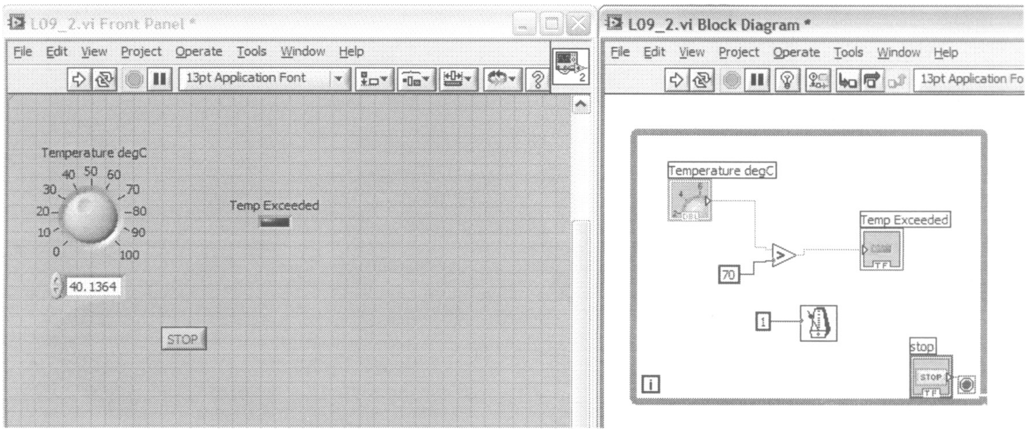


Fig. 19.30. Simple temperature controller

13. Run the VI. Adjust the temperature to above 70°C, what happens?
14. We will now modify the VI so that you can change the upper temperature limit from the Front Panel. Remove the Numeric constant from the Block Diagram.
15. Right click on the Front Panel, left click on Express > Num Ctrls > Num Ctrl and place it on the Front Panel.
16. Connect the Numeric Control block to the input of the 'Greater than' comparator which was formerly connected to the Numeric Constant.
17. On the Numeric Control block rename 'Numeric' to 'Upper Limit'. Save the VI and run it.
18. Turn the temperature Knob and observe what happens. The Numeric Control now determines the upper temperature limit. Your Front Panel and Block Diagram should look like the ones shown below:

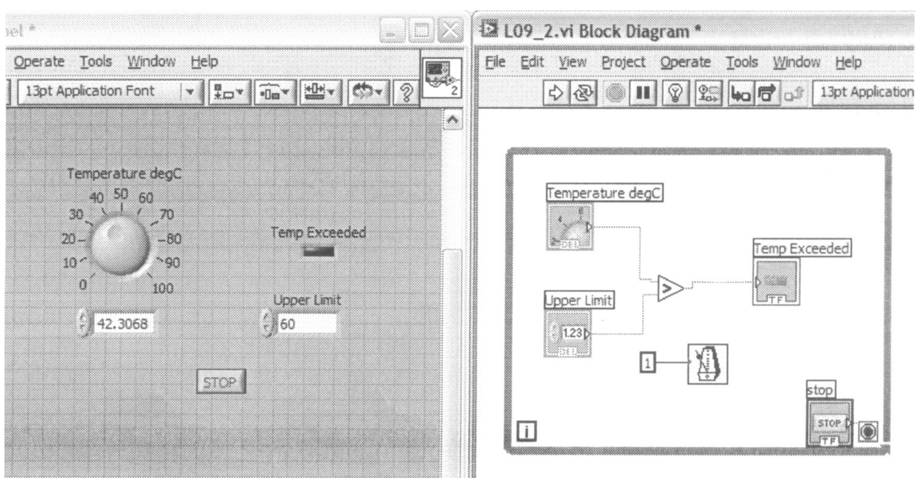


Fig. 19.31. Numeric control for the upper temperature limit

Further Improvement on Temperature Controller

1. You will make improvements to the previous VI to include a lower temperature limit selector on the Front Panel.

2. Place a Thermometer indicator on the Front Panel. It can be found under Controls menu > Express > Num Inds > Thermometer. To ensure that the thermometer displays the reading from the temperature knob you must connect it to the knob in the Block Diagram.
3. Your Front Panel and Block Diagram should look like the ones below:

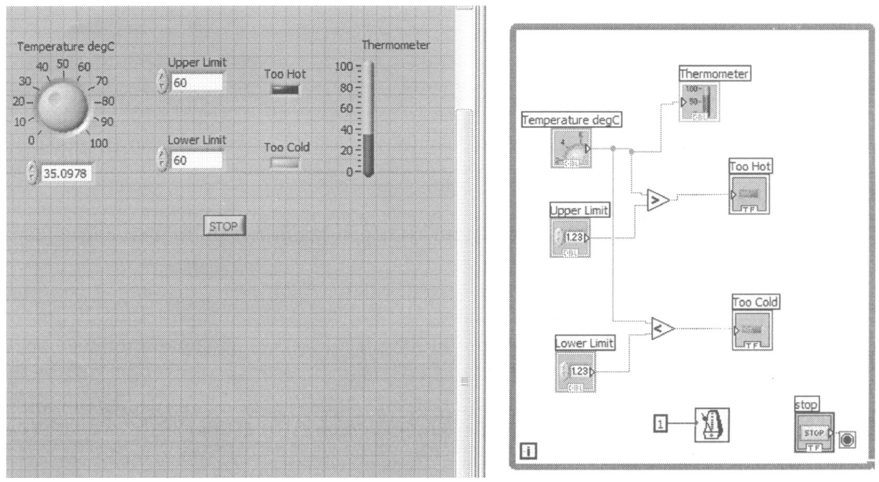


Fig. 19.32. A modified temperature controller

4. Consult your facilitator if you need any help.
5. Once you are done with the modifications, call your facilitator to verify that your VI is in good working condition.

Formula Node

1. To implement more complex mathematical functions, you can make use of the Formula Node.
2. We will now construct a VI which can be used to measure liquid flow rate based on the inputs from a restriction flow sensor. Recall that,

$$\text{Flow rate} = k\ \sqrt{p_1 - p_2}$$

3. By using the above relationship we can use LabVIEW to calculate the liquid flowrate provided we know p_1, p_2 and k.
4. Construct the following front Panel and Block Diagram.

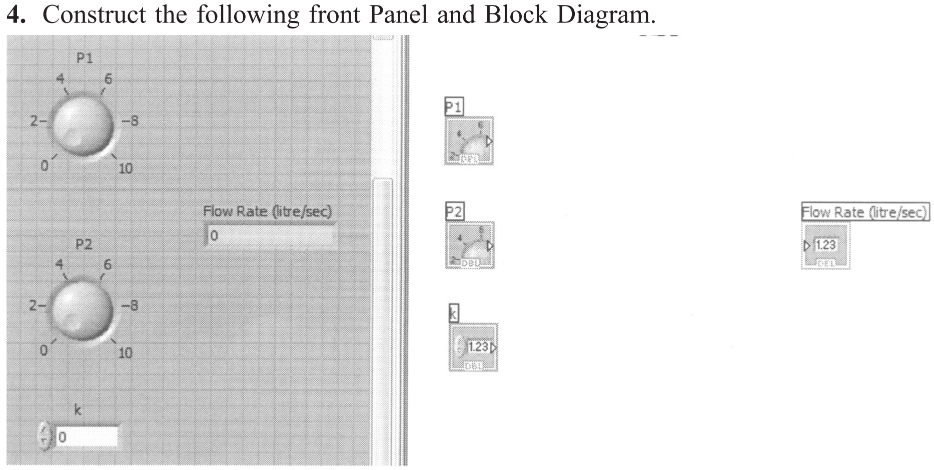


Fig. 19.33. Flow rate calculator using LabVIEW

5. The above VI is not yet functional. We have to include a Formula Node to enable the VI to calculate the liquid flow rate.
6. Right click on the Block Diagram to access the Functions menu. Left click on Structures > Formula Node. Place the Formula Node in between the knobs and the indicator as shown below.

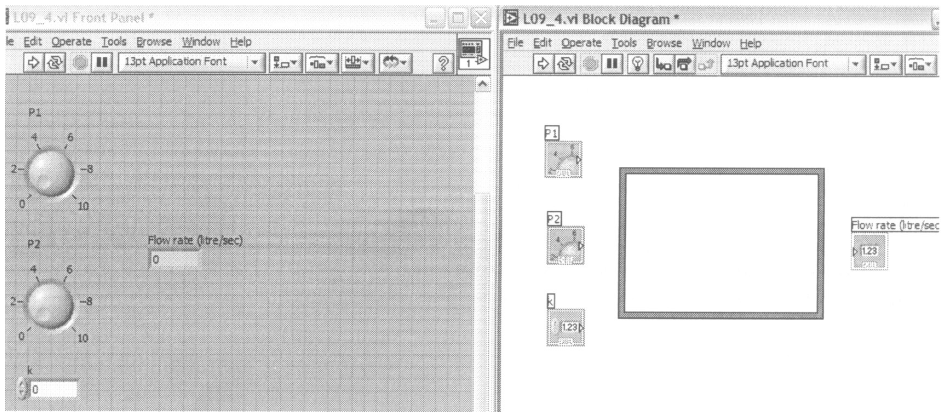


Fig. 19.34. Formula Node

7. Right clock on the left border of the Formula Node and select Add Input. Type P1.
8. Add two more inputs and name them P2 and k.
9. Connect the Knobs and Numeric Control on the left side of the screen to their respective inputs on the Formula Node.
10. Activate the Digital Display for both knobs.
11. Right click on the right border of the Formula Node and select Add Output, type F. Connect this output from the Formula Node to the Flow rate indicator.
12. Left click inside the Formula Node and type the following:

$$F = \text{sqrt}\ (P_1 - P_2)*k;$$

13. Do remember to include the semicolon (;), the syntax is similar to that of a C program.
14. Finally, place all the components inside a While Lop and set the delay to 1 ms.
15. If you have done everything correctly, your Front Panel and Block Diagram should look like this:

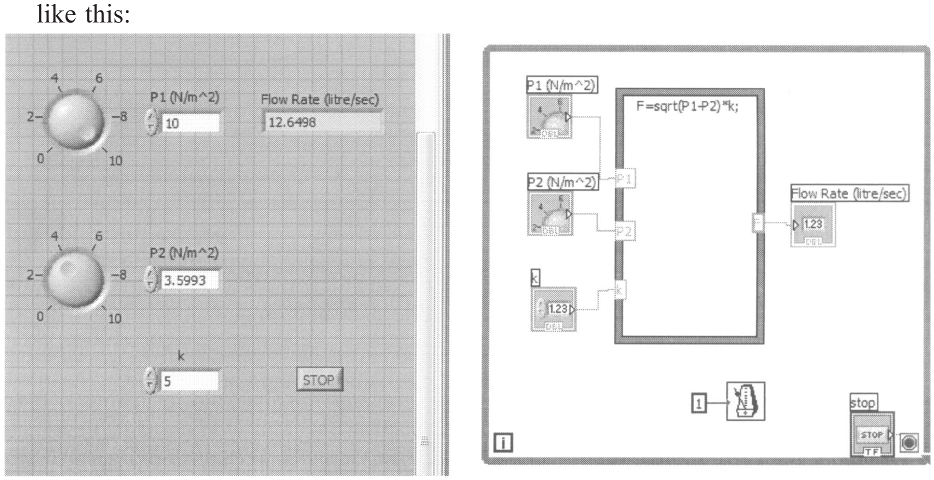
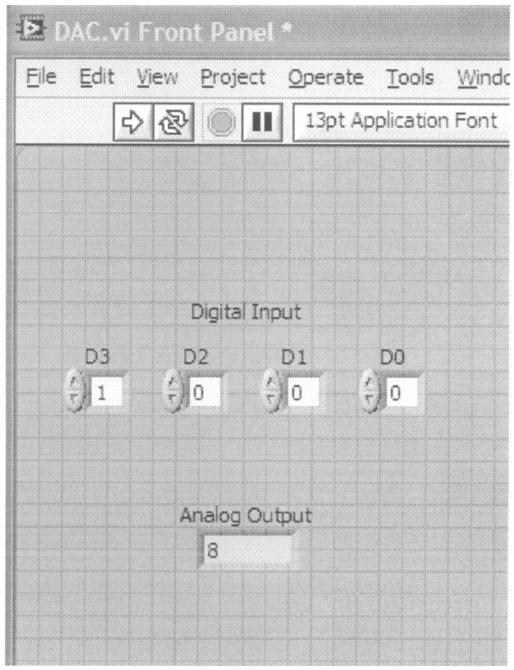


Fig. 19.35. The Formula Node in action

16. Save the VI and run it. Adjust the two knobs and the value of k. You will see that the Flow rate indicator will display the flow rate based on the formula given in part 2.

A Digital-to-Analog Converter

1. By using the formula node construct a VI which can be used as a 4-bit DAC. The Front Panel of your VI should look like the one shown below. D0, D1, D2 and D3 are the input digital codes.



Show your VI to your facilitator once it's completed.

19.18 Measurement of Strain using the Strain Gauge

Now we shall study how a strain gauge can be used to measure the strain in a laboratory setup.
Components and equipment: collect the following equipment and the components.

- (*i*) Dual DC power supply-(1 set)
- (*ii*) Desktop multi-meter (Fluke 45 Dual Display) (1 set)
- (*iii*) 330 Ω resistors (5 pcs)
- (*iv*) 100 Ω resistors (5 pcs)
- (*v*) 3 kΩ resistor (1 pc)
- (*vi*) 5 kΩ potentiometers (3 pcs)
- (*vii*) AD620 instrumentation amplifier (1 pc)
- (*viii*) KA358 operational amplifier (1 pc)
- (*ix*) Strain gauge mounted on a plastic ruler (1 set)
- (*x*) Breadboard with connecting wires (1 set)
- (*xi*) Red LED (1 pc)
- (*xii*) Green LED (1 pc)

1. Strain gauges are often used to convert mechanical action into electrical signals. Figure shows different sensors used in industry.

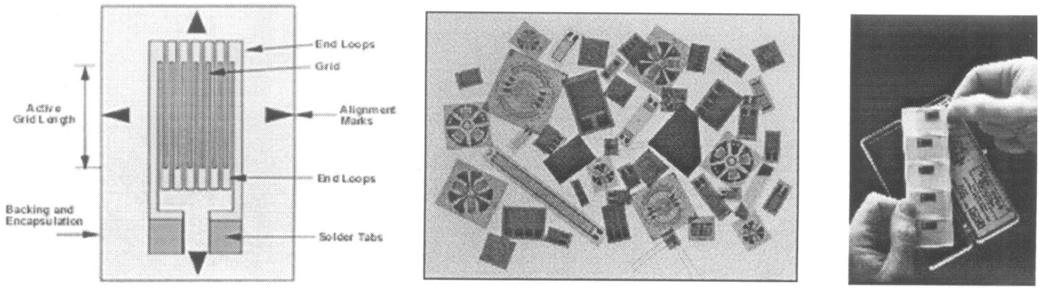


Fig. 19.36. Different sensors used in the industry

Resistance (foil) type strain gauge

Let us will first investigate the behaviour of a strain gauge when subjected to strain.

(*a*) Configure the multi-meter to measure resistance and measure that of the strain gauge as shown below.

(*b*) Apply the force at the tip of the plastic ruler and observe how the resistance of the strain gauge changes with the amount of force applied.

(*c*) Record your observations.

(*d*) The term 'Gauge Factor' is indispensable when dealing with strain gauges. It an important attribute of the gauge. How does it relate to the applied strain, the nominal resistance of the strain gauge, as well as it measured resistance?

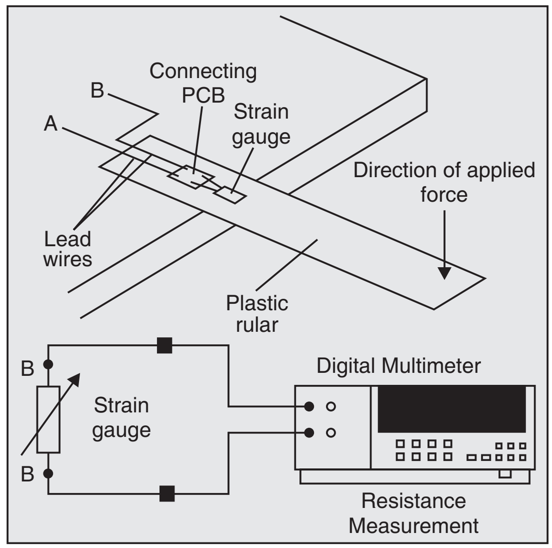


Fig. 19.37. Investigating the behavior of a strain gauge

Wheatstone Bridge as a Signal Conditioning Circuit

Most electrical circuits communicate with each other by using voltage levels. In this case we need to convert the change in resistance into a change in voltage. This is necessary if we want to turn on an LED or activate different types of load when a given strain is applied to the strain gauge.

(*a*) Construct the following circuit.

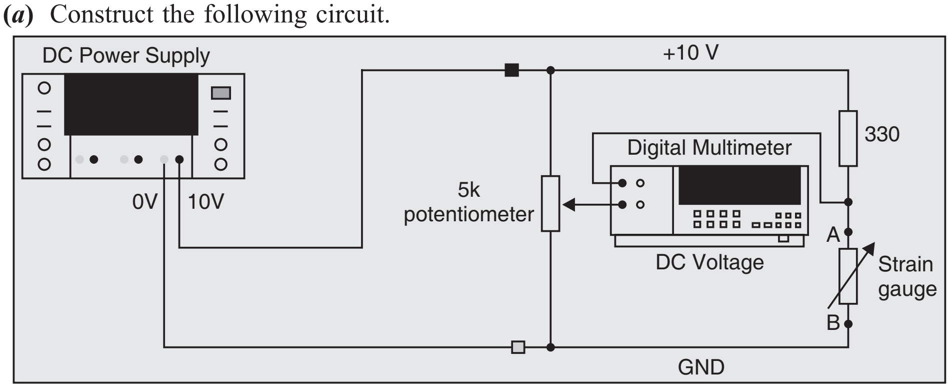


Fig. 19.38. Converting resistance to voltage

(*b*) Configure the multi-meter to measure DC voltage.

(*c*) Make sure there are no objects on the ruler and adjust the 5k potentiometer until the output voltage of the Wheatstone bridge is about 0V. Make sure the output voltage is not negative but a very small (0 ~ 5mV) positive number.

(*d*) Apply the force at the tip of the plastic ruler and observe the change in output voltage.

(*e*) Turn off the DC power supply but **do not dismantle your circuit**.

2. A single strain gauge is mounted on a Wheatstone bridge as shown below. In the unstrained state $R_G = R_1 = R_2 = R_3$ where R_G is the nominal resistance of the strain gauge. Express the output voltage V_o in terms of R_1, R_2, R_3, R_G, ΔR, V_{EX}.

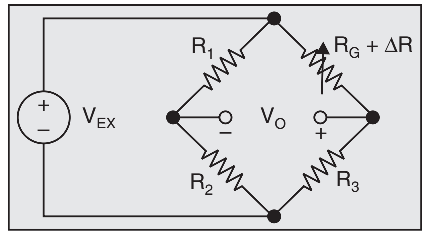


Fig. 19.39. A single strain gauge mounted on a Wheatstone bridge

3. Most sensors these days are connected to electronic circuits for signal conditioning, filtering or monitoring purposes. From the above lab experiment, you have found a way to convert the response of a strain gauge into an electrical signal. Find out what other strain gauge **bridge circuit** that can increase the sensitivity

(*a*) Quarter Bridge Configuration

(*b*) Half Bridge Configuration

(*c*) Full Bridge Configuration

19.19 VI for Air Compressor System Part II

1. You have learned about Formula Node in the previous Problem in the previous exercise. Unfortunately, you cannot straightaway use Formula Nodes to compute data from the DAQ Assistant. This is simply because the DAQ assistant generates dynamic data and the Formula Node is not able to process this data. An alternative to this is the **Formula VI**.

2. Open a new LABVIEW VI.

3. Right click on the Schematic Diagram select Mathematics > Scripts and Formulas > Formula. Place the Formula VI on the Block Diagram. You will see the following dialog box. Type (X1 + X2 + X3)/10 in the input box as shown below:

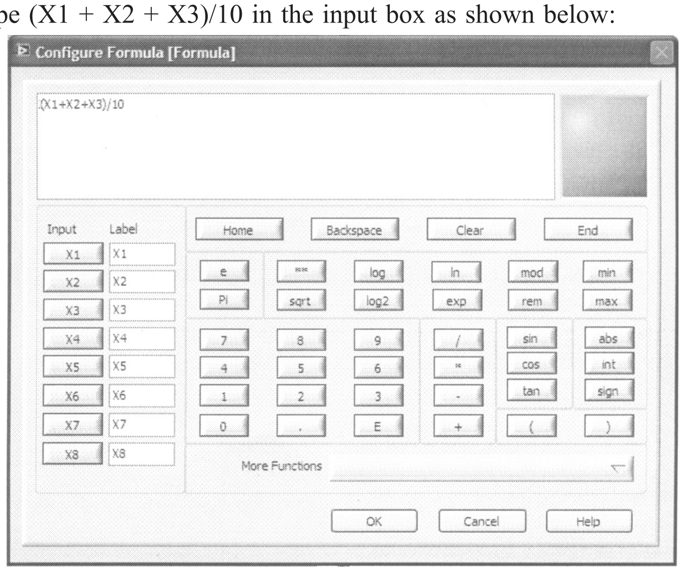


Fig. 19.40. Dialog box to configure Formula VI

4. Set up the following Front Panel and Block Diagram and comment on its behavior. Do you understand how the Formula VI works now? Use the Formula VI to convert the output voltage from the Pressure Sensor to pressure reading in bar and psi. (Note: you will need one Formula VI for each display)

Hints:

Find the relationship between pressure in bar and psi.

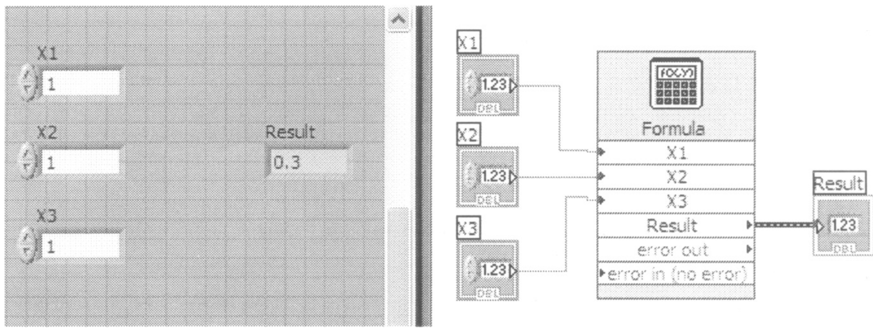


Fig. 19.41. Formula VI in action

5. Now we will use two string indicators to display the status of the pump motor (run or stop) and release valve (open or close). We can use Case Structures to generate different strings for different conditions. Right click on the Block Diagram and click on Structures > Case Structure.

   Place the Case Structure on the Block Diagram just like a Formula Node. All Case Structures have at least two conditions, namely True and False. Change the condition to True and implement the following Front Panel and Block Diagram. To place the String indicator right click on the Front Panel select Express > Text Indicators > String indicator.

   To place the String constant as shown below, right clock on the Block Diagram click on String > String Constant.

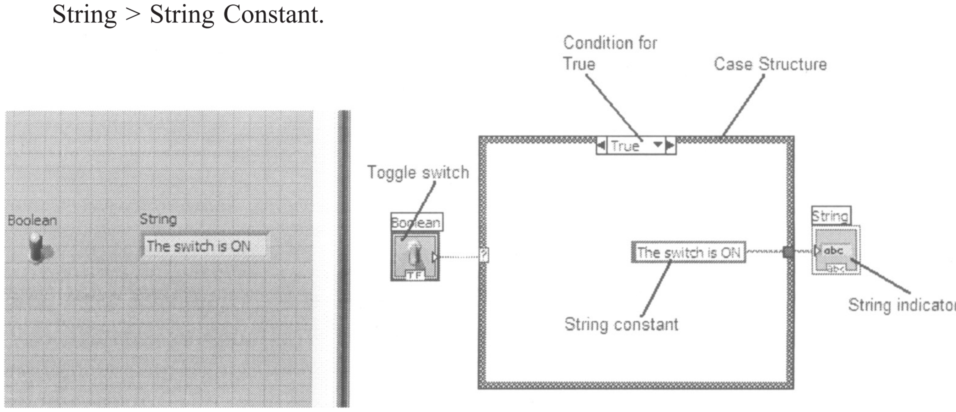


Fig. 19.42. Case Structure for String control

6. Click on the drop down box on top of the Case Structure and change it to False. Now you must include the tasks to be executed when the input to the Case Structure is false. You will notice that the Toggle switch and String Indicator will remain in their position. However, the String Constant will disappear. This is because the content of the Case Structure will be different for a True and False condition. Insert the following content in the Case Structure.

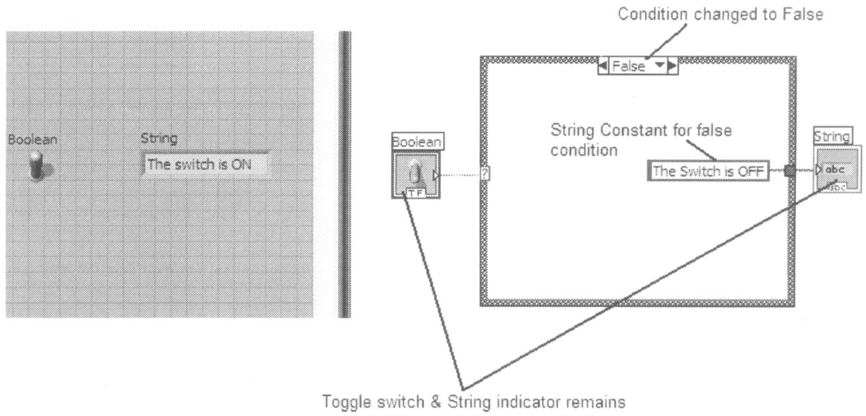


Fig. 19.43. Content of Case Structure for false condition

7. Run the VI. Change the position of the Toggle Switch and run the VI again. What happens? Think of a way how you can implement the string indicator for pump motor (run or stop) and release valve (open or close) by using the Case Structure, String Constant and String Indicator.
8. Note that besides the String Indicators for the pump motor and release valve there are two LEDs. The LED for pump motor will turn on when the motor is running. The LED for release valve will turn on when the valve is open. Can you accomplish these features by using the Case Structure you have implemented in Q7?
9. A Waveform chart is used to give a graphical representation of the measured pressure in psi. Place the DAQ Assistant VI on a new Block Diagram. The steps you need to take to use this VI is similar to the one you did in part 1.
10. Right click on the Front Panel and click on Graph > Waveform Chart. Place the Waveform Chart on the Front Panel as shown below. Connect the Data output from the DAQ Assistant to the Waveform Chart as shown below. Place a While Loop around all the components, your Front Panel and Block Diagram will look like this.

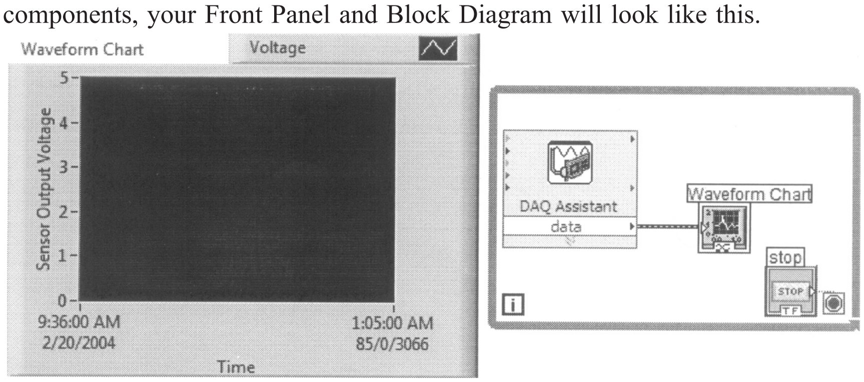


Fig. 19.44. DAQ Assistant connected to Waveform Chart

11. Your X-axis and Y-axis may not be the same as the one shown above. To change the axes. Right clock on the Waveform Chart click on Properties > Scales. Under the dropdown box, select ‘Time (X-axis)’. Untick the Autoscale option, then under formatting, select Absolute Time.
12. Under the dropdown box, select ‘Amplitude (Y-axis)’. Untick the Autoscale option and change Minimum to 0 and Maximum to 5. Click OK.

13. Connect the circuit as shown below. Notice that for simplicity sake a potentiometer is used to simulate the output of the pressure sensor. Turn on the DC power supply and adjust the output voltage to 5V. Run the VI. Turn the potentiometer. What happens?

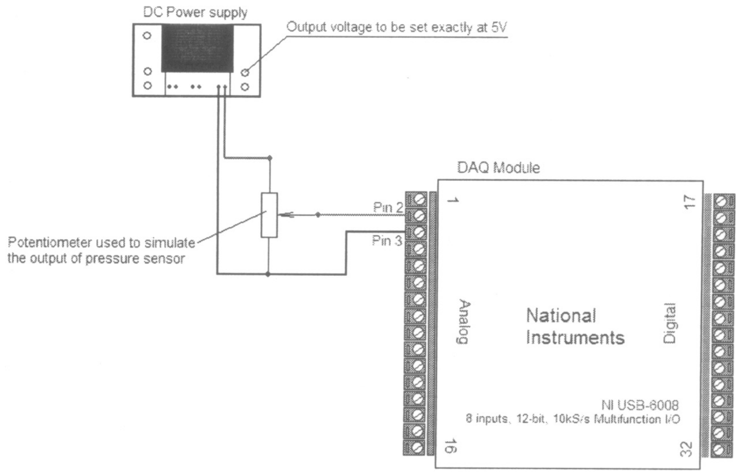


Fig. 19.45. Connection diagram

14. You should be familiar with Waveform Chart by now, use it to display the value of measured pressure in psi against time. Your X-axis should be form 0 to 1 sec, and your Y-axis is from 0 to 16 psi. Also change the label of the Y-axis from 'Amplitude' to 'Gauge Pressure (psi)'.

15. Before we start on the LabVIEW VI meant for a compressor system, let's take a look at the various parts which make up a typical air compressor as shown below.

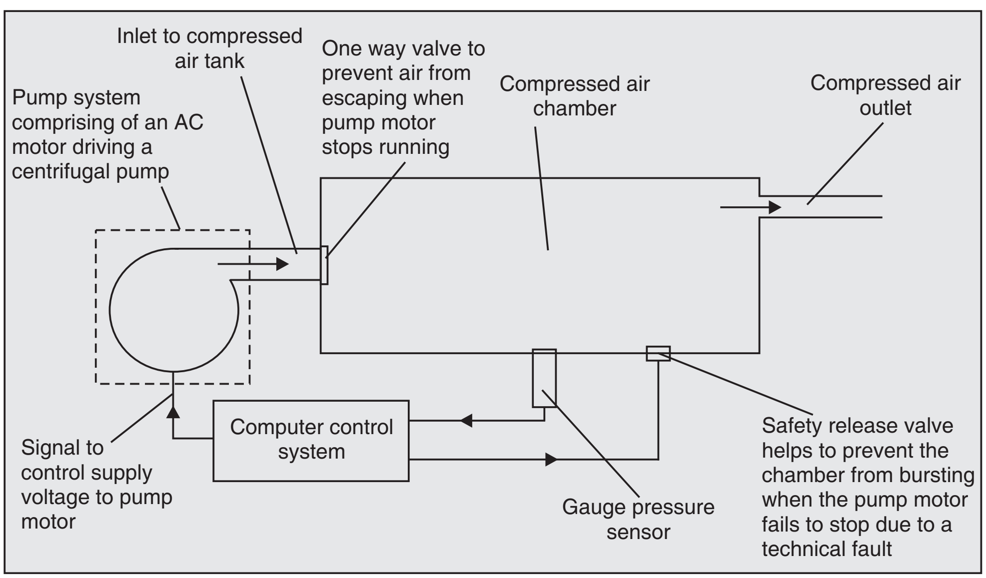


Fig. 19.46. Various parts which make up a compressor system

16. It's now time for you to develop the VI, the information from the problem statement:

Hints:

The output of the sensor is 0V at 0 bar and 5V at 1 bar. This relationship is linear. You should know how to convert any voltage reading to a gauge pressure reading in bar now.

(*a*) The pump motor will start running when the measured pressure is less than 0.5 bar.

(*b*) The output voltage to the pump motor will satisfy the following expression:

Motor voltage = (0.5 – *measured pressure in bar*) * 8

(*c*) A gauge to display the motor voltage must be included in the Front Panel.

(*d*) The motor speed in rpm will satisfy the following expression:

Motor speed = 250 * *Motor voltage*

(*e*) The safety release valve will be opened when the measured gauge pressure is larger than 0.9 bar. This is crucial to prevent the compressed air tank from bursting.

Armed with the above information, develop the VI for the central computer system with a Front Panel as shown below.

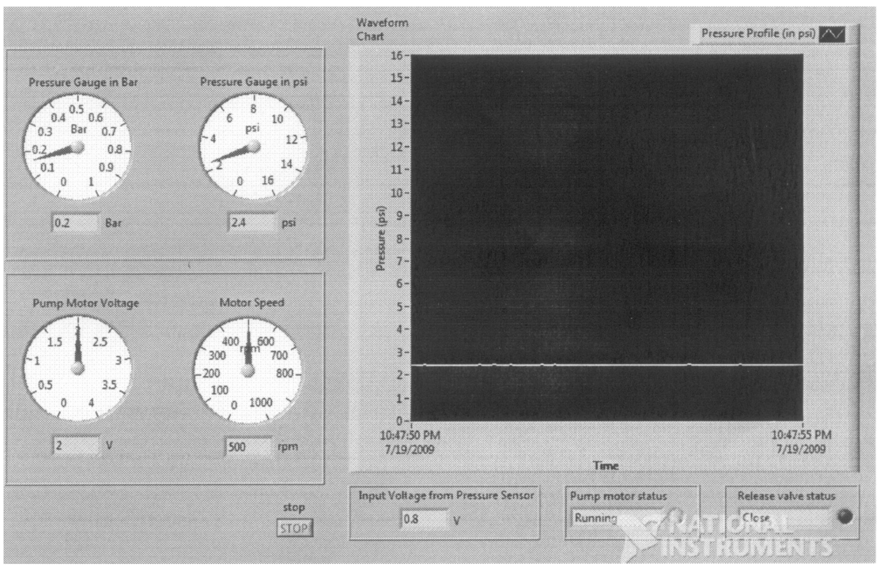
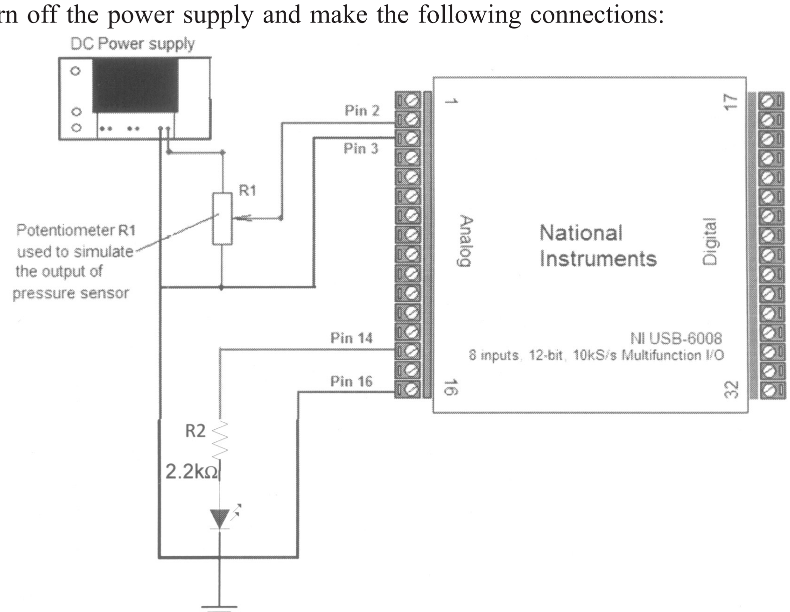
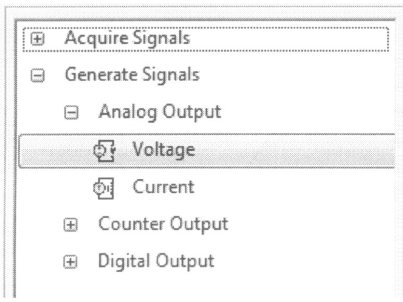


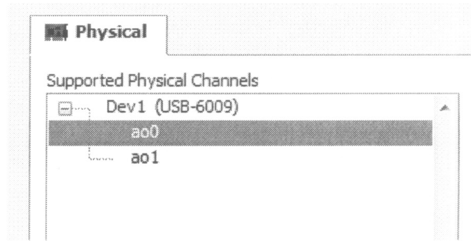
Fig. 19.47. Completed Front Panel.

17. Turn off the power supply and make the following connections:

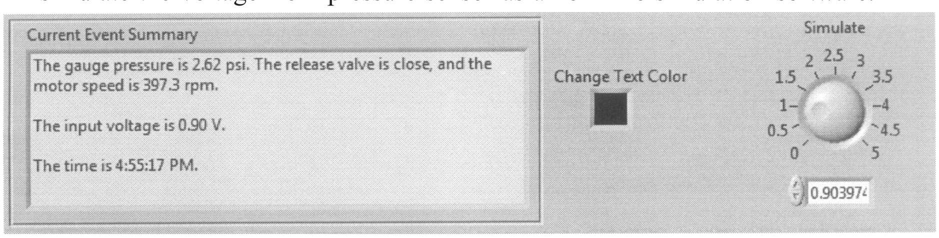


18. You are now configuring the DAQ module to read in the pressure sensor voltage. Note that the output voltage from the sensor varies from 0V to 5V depending on the pressure.
19. Use the analog output Pin 14 and 16 to output an analog voltage to drive the LED.



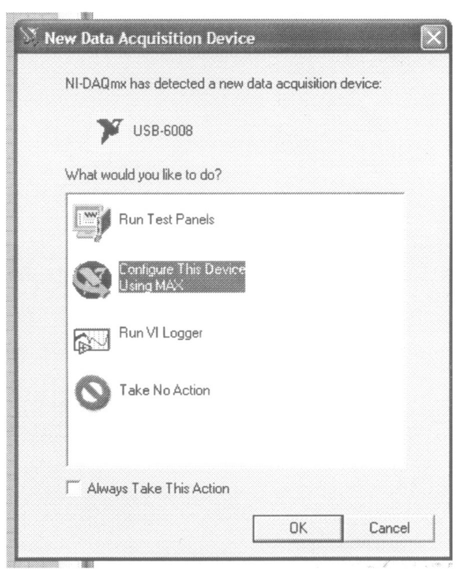


20. Adjust the potentiometer of the pressure sensor and observe your VI. What happens?
21. Besides the above functions implemented, you are also requested to achieve a real time monitoring the status of pressure, valve and motor speed as below picture. Furthermore, customer shall be able to change the text color as they wish. You may utilize a knob to simulate the voltage from pressure sensor as an off-line simulation software.

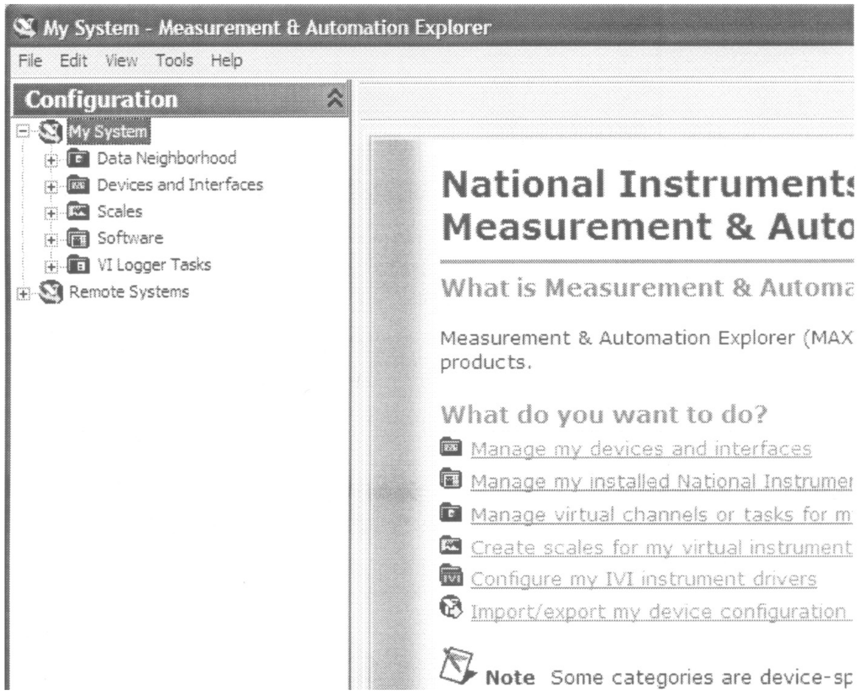


VI for Air Compressor System Part 1

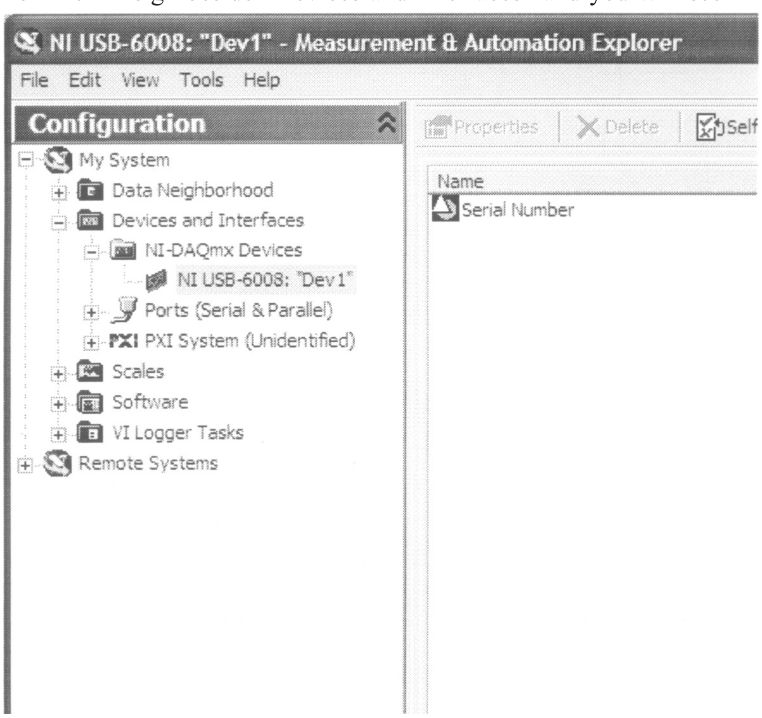
1. Install the NI-DAQmx software from the National Instruments website: *www.ni.com.*
2. Open a blank VI and press CTRL-T to tile the two windows side-by-side.
3. Plug in the NI USB-6008 module to your laptop with the aid of a USB cable. The following window will pop up. Clock on "Configure This Device Using MAX" and click OK.



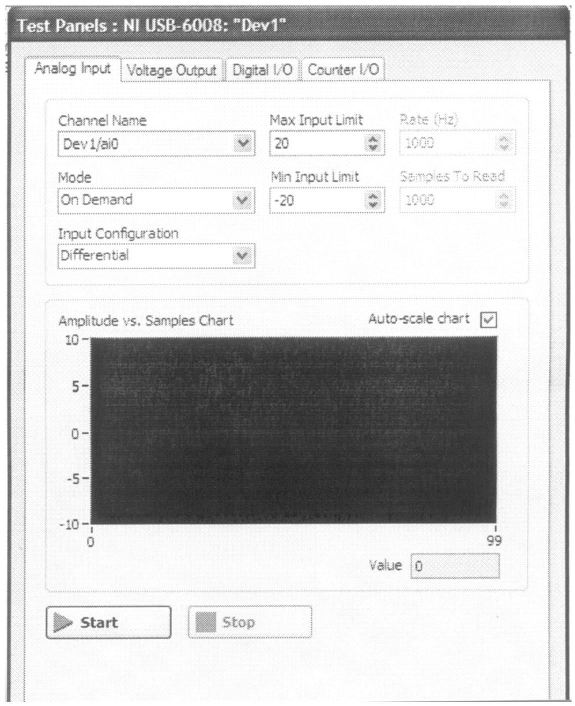
4. You will then see the following window.



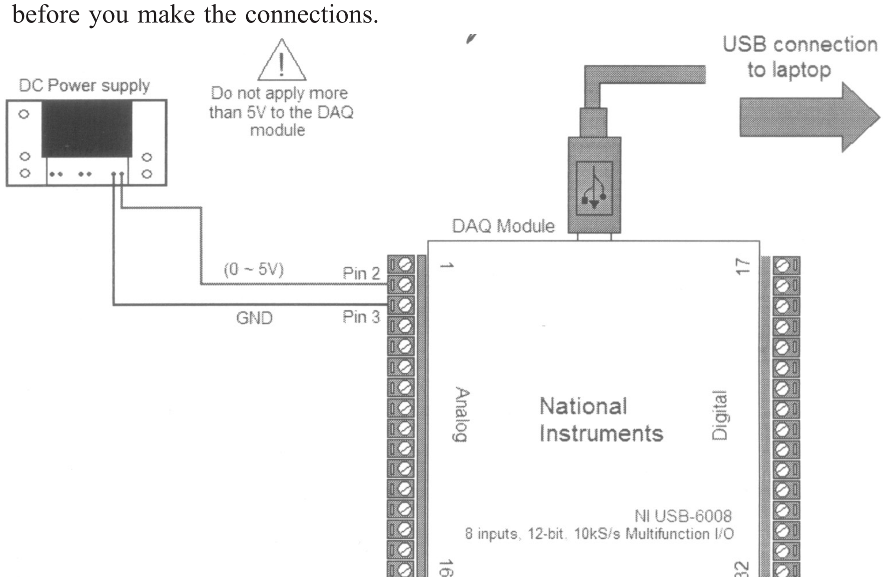
5. Click on the '+' sign beside "Devices and Interfaces" and you will see this window:



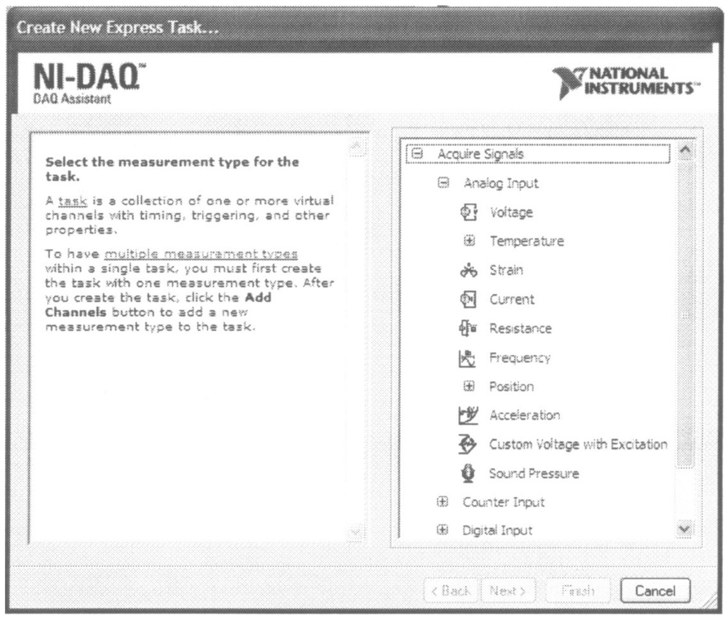
6. Right clock on NI USB-6008: "Dev 1" and choose "Test Panels" and the following window will pop up. You can close this window and make the connections in the next page.



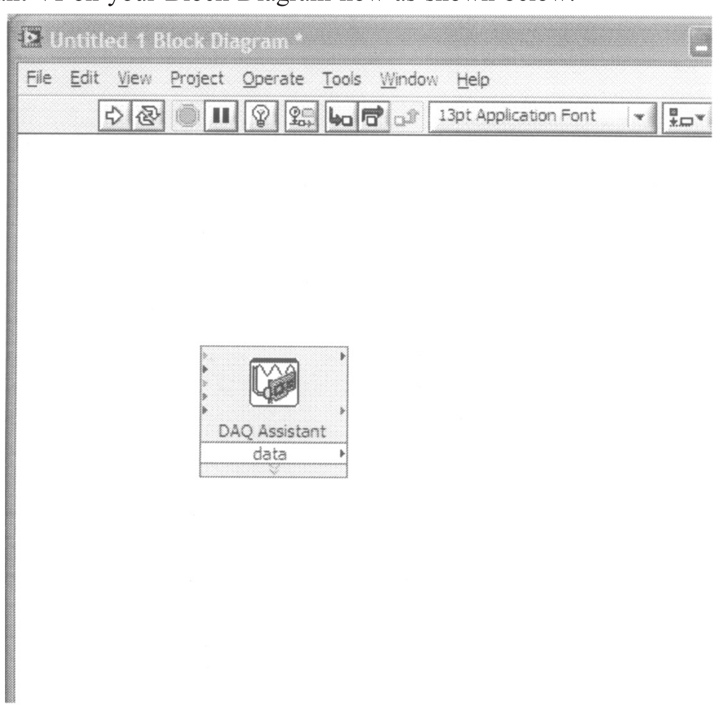
7. Implement the following connections. You are now configuring the DAQ board to acquire an analog voltage from the DC power supply. Make sure the power supply is turned off before you make the connections.



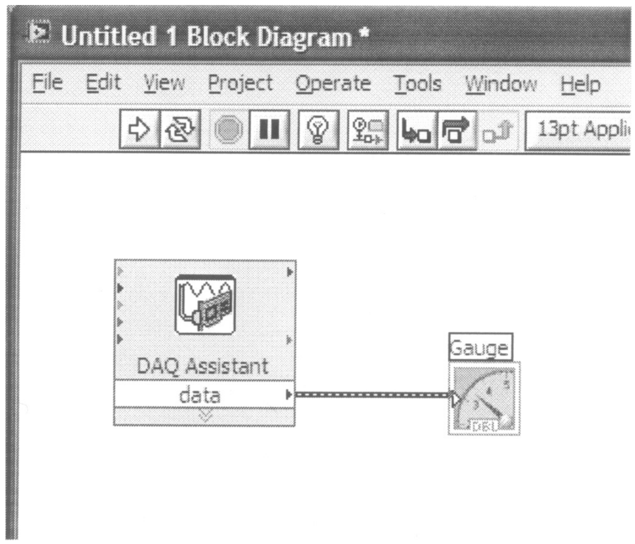
8. Go to the Block Diagram of your LabVIEW window. Right click and select *Measurement I/O*. Choose *NI-DAQmx > DAQ Assist.* Place the DAQ Assist VI on the Block Diagram. The DAQ Assist VI will perform the interface between LabVIEW and the DAQ module.
9. A new window will pop up. Clock on *Acquire Signals* > *Analog Input* > *Voltage*. Under 'Supported Physical Channels' click on "ai0" and click Finish". You have just configured port 0 to read analog voltage.



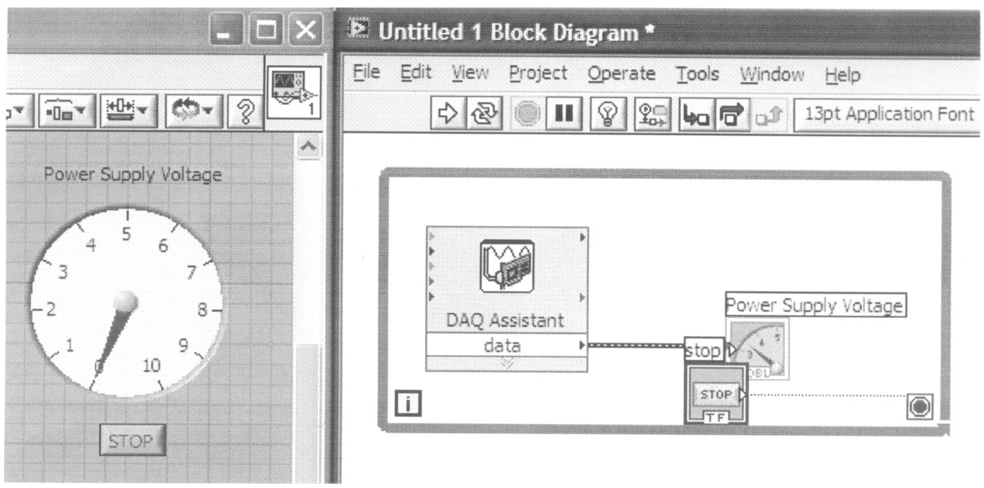
10. The ‘DAQ Assistant’ window will pop up. Just click OK. You should see the DAQ Assistant VI on your Block Diagram now as shown below:



11. Right click on the Front Panel and select *Express* > *Num Inds* > *Gauge*. Place the Gauge on the Front Panel. Connect the data output of the DAQ Assistant VI to the Gauge as shown below:



12. Place a While Loop around the DAQ Assistant and Gauge VI. What you have done is to use the DAQ Assistant acquire the voltage from the DC power supply to the Gauge. Your Front Panel and Block Diagram should look like the one shown below:



13. Make sure the voltage knobs on the DC power supply are turned fully in the anti-clockwise direction before turning it on. Ensure that the output voltage from the DC power supply is 0V.
14. Run the VI and slowly increase the output voltage of the DC power supply. **Do not exceed 5V**. What happens? Increase and decrease the output voltage and notice the response on the Gauge.

SUMMARY

In this chapter you have learned that:

1. Virtual instrumentation provides advantages in stage of the engineering process from research and design to manufacturing test.
2. A virtual instrument is powerful application software.
3. LabVIEW is short form of Laboratory Virtual Instrumentation Engineering Workbench.

GLOSSARY

LabVIEW. LabVIEW is a system design platform and development environment for a visual programming language from National Instruments.

Virtual Instrumentation. It is the use of customizable software and modular measurement hardware to create user defined measurement systems, called virtual instruments.

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