A Reference Manual on Instrumentation

For

BE COMPUTER I/II SEM

BE Electrical and Electronics II/I SEM

POKHARA UNIVERSITY

UNITED TECHNICAL COLLEGE

Bharatpur, Chitwan

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Unit 1: Introduction to Instrumentation System (10 hrs)

Introduction to Instrument and Instrumentation System

An instrument is a device that communicates, detects, denotes, indicates, observes, measures, records, or signals a quantity or controls or phenomenon, or manipulates another device. Instrumentation is a collective term for measuring instruments that are used for indicating, measuring and recording physical quantities.

An Instrumentation system exists to provide information about the physical value of some variable being measured. These Variables are called as process variable which states a condition of the process fluid (a liquid or gas) that can change the manufacturing process in some way.

In simple cases, the system can consist of only a single unit that gives an output reading or signal according to the magnitude of the unknown variable applied to it. However, in more complex measurement situations, a measuring system consists of several separate elements

Measurement

Measurement is defined as an act or the result of comparison between the unknown quantity and a predefined standard. A measurement of any quantity is characterized by a numerical value followed the unit. The numerical value is meaningless if it is not followed by the unit. For example, if you measure a length of the table, it comes out to be 2.5 metre. Then, only numerical value 2.5 is meaningless without the unit of length metre.

Intelligent vs. Dumb Measurement Systems

Intelligent instrumentation system:-In this system after a measurement has been made of the variable, further processing whether in digital or analog form is carried out to refine the data, for the purpose of presentation to an observer or to other computers. Use of computer system, Artificial intelligence and microprocessor make it easy to compile it.

Dumb instrumentation system:- In this system once the measurement is made, the data must be processed by the observer.

Methods of Measurements

There are two types of methods of measurements i.e.

1. Direct Methods: Direct measurement refers to measuring exactly the thing that you are looking to measure. So, the unknown quantity or measurand is directly compared against a standard. For example pressure, time, length, weight, etc. can be directly measured.

2. Indirect Methods: Indirect measurement refers to measuring something by measuring something else. Sometimes it is not possible to measure a quantity directly. Hence we measure a different quantity that can be easily measured and using which we can find actual measurand. For example, differential pressure on a pitot tube is used to determine airspeed.

Typical applications of Instrument systems

All our electronics enclosures are suitable for use in the measurement, control and instrumentation sector and for all enclosure solutions in the automation sector.

Typical applications include:

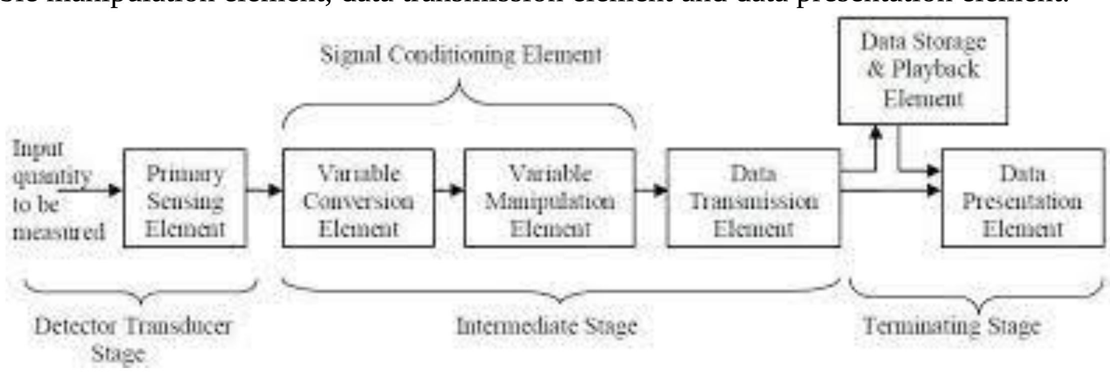
- Data loggers
- Control systems for outdoor equipment
- System modules for automation technology
- Sensor technology and optoelectronics (e.g. control and alarm devices)
- Peripheral devices and data collection in the laboratory and research

Typical example

Dairy processing unit operations mainly involve heating, cooling, separating, drying or freezing of the products. These unit operations are carried out under varying conditions of temperatures, pressures, flows and physical compositions. The measurement and control of these variable factors at the various stages of processing call for the accurate and efficient instruments, in addition to the dependence upon human skills. With the advent of large scale milk handling plants the automatic operation and control through efficient instrumentation and automation has become even more necessary. Utilities such as steam, water, electricity air, fuel etc. have to be measured and controlled at appropriate points in the plant. Automatic control instruments are employed to measure and control the temperature, pressure, flow and level of these utilities. The overall aim of the instrumentation/ automation is to improve the product quality and enhance the plant efficiency for better economic returns.

Functional Elements of Instrumentation and Measuring

The block diagram of a basic instrumentation system consists of primary sensing element, variable manipulation element, data transmission element and data presentation element.



Primary Sensing Element: The quantity under measurement makes its first contact with primary sensing element of measurement system. The quantity is first sensed or detected by primary sensor. Then detected physical quantity signal is converted into an electrical signal by a transducer. Transducer is defined as a device which converts a physical quantity into an electrical quantity. Sensor is act as primary element of transducer. In many cases the physical quantity 8 is directly converted into an electrical quantity by a transducer. So the first stage of a measurement system is known as a detector transducer stage.

Variable Conversion Element: The output of primary sensing element is electrical signal of any form like a voltage, a frequency or some other electrical parameter. Sometime this output not suitable for next level of system. So it is necessary to convert the output some other suitable form while maintaining the original signal to perform the desired function the system. For example the output primary sensing element is in analog form of signal and next stage of system accepts only in digital form of signal. So, we have to convert analog signal into digital form using an A/D converter. Here A/D converter is act as variable conversion element

Variable Manipulation Element: The function of variable manipulation element is to manipulate the signal offered but original nature of signal is maintained in same state. Here manipulation means only change in the numerical value of signal. Examples, 1. Voltage amplifier is act as variable manipulation element. Voltage amplifier accepts a small voltage signal as input and produces the voltage with greater magnitude .Here numerical value of voltage magnitude is increased.

Data Transmission Element: The elements of measurement system are actually physically separated; it becomes necessary to transmit the data from one to another. The element which is performs this function is called as data transmission element. Example, Control signals are transmitted from earth station to Space-crafts by a telemetry system using radio signals. Here telemetry system is act as data transmission element. The combination of Signal conditioning and transmission element is known as Intermediate Stage of measurement system

Data Presentation Element: The function of this element in the measurement system is to communicate the information about the measured physical quantity to human observer or to present it in an understandable form for monitoring, control and analysis purposes. Visual display devices are required for monitoring of measured data. These devices may be analog or digital instruments like ammeter, voltmeter, camera, CRT, printers, analog and digital computers. Computers are used for control and analysis of measured data of measurement system. This Final stage of measurement system is known as Terminating stage.
Some applications requires a separate data storage and playback function for easily rebuild the stored data based on the command. The data storage is made in the form of pen/ink and digital recording. Examples, magnetic tape recorder/ reproducer, X-Y recorder, X-t recorder, Optical Disc recording etc.

Introduction to Errors and Uncertainties in the Measurement

Errors in Measurement and its Types

An error may be defined as the difference between the measured and actual values. For example, if the two operators use the same device or instrument for measurement. It is not necessary that both operators get similar results. The difference between the measurements is referred to as an ERROR.

Error = Measured value – True value

Types of Errors

There are three types of errors that are classified based on the source they arise from; They are:

- Gross Errors
- Random Errors
- Systematic Errors

Gross Errors

This category basically takes into account human oversight and other mistakes while reading, recording, and readings. The most common human error in measurement falls under this category of measurement errors. For example, the person taking the reading from the meter of the instrument may read 23 as 28. Gross errors can be avoided by using two suitable measures, and they are written below:

- Proper care should be taken in reading, recording the data. Also, the calculation of error should be done accurately.
- By increasing the number of experimenters, we can reduce the gross errors. If each experimenter takes different readings at different points, then by taking the average of more readings, we can reduce the gross errors

Random Errors

The random errors are those errors, which occur irregularly and hence are random. These can arise due to random and unpredictable fluctuations in experimental conditions (Example: unpredictable fluctuations in temperature, voltage supply, mechanical vibrations of experimental set-ups, etc, errors by the observer taking readings, etc. For example, when the same person repeats the same observation, he may likely get different readings every time.

Systematic Errors:

Systematic errors can be better understood if we divide them into subgroups; They are:

- Environmental Errors
- Observational Errors
- Instrumental Errors

Environmental Errors: This type of error arises in the measurement due to the effect of the external conditions on the measurement. The external condition includes temperature, pressure, and humidity and can also include an external magnetic field. If you measure your temperature under the armpits and during the measurement, if the electricity goes out and the room gets hot, it will affect your body temperature, affecting the reading.

Observational Errors: These are the errors that arise due to an individual's bias, lack of proper setting of the apparatus, or an individual's carelessness in taking observations. The measurement errors also include wrong readings due to Parallax errors.

Instrumental Errors: These errors arise due to faulty construction and calibration of the measuring instruments. Such errors arise due to the hysteresis of the equipment or due to friction. Lots of the time, the equipment being used is faulty due to misuse or neglect, which changes the reading of the equipment. The zero error is a very common type of error. This error is common in devices like Vernier callipers and screw gauges. The zero error can be either positive or negative. Sometimes the scale readings are worn off, which can also lead to a bad reading.

Instrumental error takes place due to:

- An inherent constraint of devices
- Misuse of Apparatus
- Effect of Loading

Uncertainties in Measurements

- All measurements have a degree of uncertainty regardless of precision and accuracy. This is caused by two factors, the limitation of the measuring instrument (systematic error) and the skill of the experimenter making the measurements (random error).
- Errors are the difference between the measured value and real or expected value; uncertainty is the range of variation between measured value and expected or real value.
- To calculate uncertainty, we take the accepted or expected value and subtract the furthest value from the expected one. The uncertainty is the absolute value of this result.
- The graduated buret in Figure 1 contains a certain amount of water (with yellow dye) to be measured. The amount of water is somewhere between 19 ml and 20 ml according to the marked lines. By checking to see where the bottom of the meniscus lies, referencing the ten smaller lines, the amount of water lies between 19.8 ml and 20 ml. The next step is to estimate the uncertainty between 19.8 ml and 20 ml. Making an approximate guess, the level is less than 20 ml, but greater than 19.8 ml. We then report that the measured amount is approximately 19.9 ml. The graduated cylinder itself may be distorted such that the graduation marks contain inaccuracies providing readings slightly different from the actual volume of liquid present.

Performance Characteristics of Measurement System

The characteristics of measurement instruments which are helpful to know the performance of instrument and help in measuring any quantity or parameter, are known as **Performance Characteristics**. The performance characteristics of measuring instrument are judge by how faithfully the system measures the desired input & how thoroughly it rejects the undesired input. Performance characteristics of instruments can be classified into the following **two types**.

- Static Characteristics: value of measured variable change slowly
- Dynamic Characteristics: value of measured variable change very fast

Static Characteristics

- The characteristics of quantities or parameters measuring instruments that **do not vary** with respect to time are called static characteristics. Sometimes, these quantities or parameters may vary slowly with respect to time. Following are the list of **static characteristics**.
- The static characteristics and parameters of measuring instruments describe the performance of the instruments related to the steady-state input/output variables only. The various static characteristics and parameters are destined for quantitative description of the instruments perfections and they are well presented in the manufacturer's manuals and data sheets.
- The various static characteristics are:

i) Accuracy	ii) Precision	iii) Sensitivity	iv) Linearity
v) Reproducibility	vi) Repeatability	vii) Resolution	viii) Threshold
ix) Drift	x) Stability	xi) Tolerance	xii) Range or span
xiii) Hysteresis	xiv) Bias	xv) static error	

i) Accuracy: It is the closeness with which an instrument reading approaches the true value of the quantity being measured. Thus accuracy of a measurement means conformity to truth. It the important *static characteristic of electrical measuring instruments*.

Deviation from the true value indicates the low accurate of measurement. Accuracy can be specified in terms of inaccuracy or limits of errors and can be expressed in the following ways:

a. Point Accuracy:

This is the accuracy of the instrument only at one point on its scale. The specification of this accuracy does not give any information about the accuracy at other points on the scale or in the words, does not give any information about the general accuracy of the instrument.

b. Accuracy as Percentage of Scale Range:

When an instrument has uniform scale, it's accuracy may be expressed in terms of scale range.

c. Accuracy as Percentage of True Value:

The best way to conceive the idea of accuracy is to specify it in terms of the true value of the quantity being measured within +0.5% or -0.5% of true value.

ii) Precision: It is the measure of reproducibility i.e., given a fixed value of a quantity, precision is a measure of the degree of agreement within a group of measurements.

If an instrument indicates the same value repeatedly when it is used to measure the same quantity under same circumstances for any number of times, then we can say that the instrument has high precision.

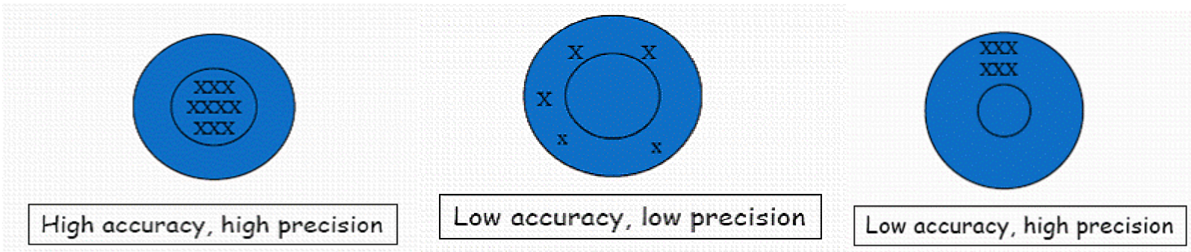
The precision is composed of two characteristics:

a) **Conformity**: Consider a resistor having true value as 2385692, which is being measured by an ohmmeter. But the reader can read consistently, a value as 2.4 M due to the nonavailability of proper scale. The error created due to the limitation of the scale reading is a precision error.

b) **Number of Significant Figures**: The precision of the measurement is obtained from the number of significant figures, in which the reading is expressed. The significant figures convey the actual information about the magnitude & the measurement precision of the quantity.

Q. Accuracy and Precision are dependent on each other, explain.

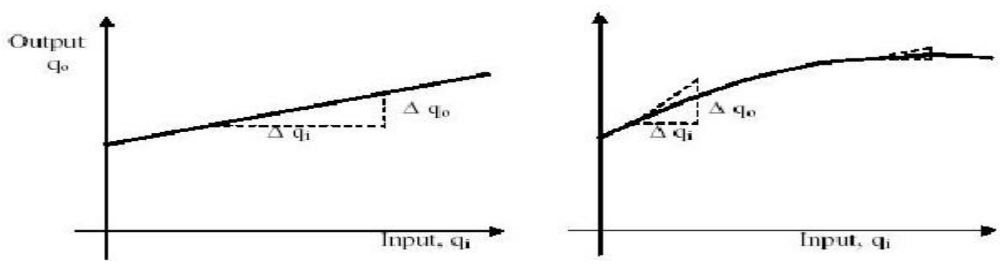
Consider a shooter aiming at the target. Fig below illustrate difference between them,



Sensitivity: The sensitivity denotes the smallest change in the measured variable to which the instrument responds. It is defined as the ratio of the changes in the output of an instrument to a change in the value of the quantity to be measured. Mathematically it is expressed as,

$$\text{Sensitivity} = \frac{\Delta\theta o = \text{Change in output}}{\Delta\theta i = \text{Change in input}}$$

The term *sensitivity* signifies the smallest change in the measurable input that is required for an instrument to respond.



- If the calibration curve is **linear**, then the sensitivity of the instrument will be a constant and it is equal to slope of the calibration curve.
- If the calibration curve is **non-linear**, then the sensitivity of the instrument will not be a constant and it will vary with respect to the input.

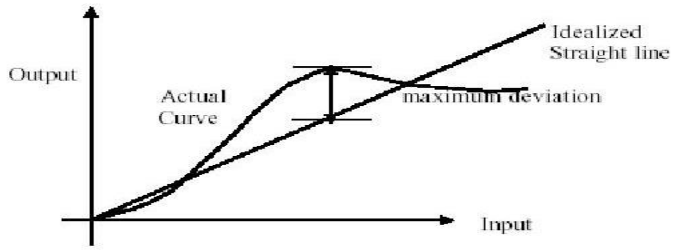
Q) A wheat stone bridge has a change in resistance of 7 ohms in unknown arm if a change in deflection of 3mm. determine sensitivity.

Soln,

$$\text{Sensitivity} = \frac{\Delta\theta o = \text{Change in output}}{\Delta\theta i = \text{Change in input}} = 3\text{mm}/7\text{ ohms} = 0.49\text{ mm/ohm}$$

Linearity: Linearity is an indicator of the consistency of measurements over the entire range of measurements. In general, it is a good indicator of performance quality.

It is also defined as ability to reproduce the input characteristics symmetrically and linearly. The curve shows actual calibration curve and idealized straight line.



$$\% \text{ non-linearity} = \frac{\text{Max. deviation of output from idealized straight line}}{\text{Full scale reading}}$$

Threshold: If the instrument input is increased very gradually from zero there will be some minimum value below which no output change can be detected. This minimum value defines the threshold of the instruments. In specifying threshold, the first detectable output change is often described as being any noticeable measurable change.

Resolution: The smallest change in a measurement variable to which an instrument will respond is resolution. If the output of an instrument will change only when there is a specific increment of the input, then that increment of the input is called **Resolution**. That means, the instrument is capable of measuring the input effectively, when there is a resolution of the input.

Q) A voltmeter has 100 scale divisions and can measure up to 100 V. Each division can be read to 1/2 division. Determine the resolution of the voltmeter in volts.

Solution

Resolution is the smallest change in input that can be measured. The meter can be read to ½ division.

The resolution is 1/2 division and its value in volts is

100 div = 100 V

1 div = 1 V

1/2 div = 0.5 V

Therefore, the resolution of the instrument is 0.5 V.

Hysteresis-Threshold Resolution: When testing an instrument for repeatability, it is often noted that the input-out value does not coincide with the inputs, which are continuously ascending and descending values. This occurs because of hysteresis, which is caused by internal friction, sliding, external friction, and free play mechanisms. Hysteresis can be eliminated by taking readings corresponding to the ascending and descending values of the input and calculating their arithmetic mean.

Drift

Drift is a departure in the output of the instrument over the period of time. An instrument is said to have no drift if it produces same reading at different times for the same variation in the measured variable. Drift is unrelated to the operating conditions or load. The following factors could contribute towards the drift in the instruments:

- Wear and Tear
- Mechanical Vibrations
- Stresses Developed in the parts of the Instrument
- Temperature Variations
- Stray Electric and Magnetic Fields
- Thermal Emf

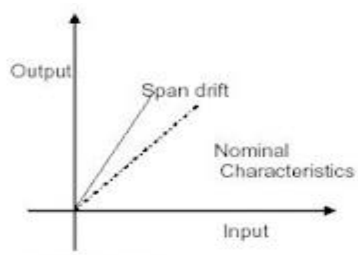
Drift can occur in the flow meters due to wear of nozzle or venturi. It may occur in the resistance thermometer due to metal contamination etc.

Drift may be of any of the following types;

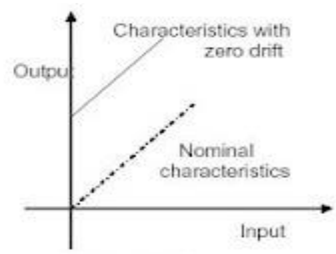
a) **Zero Drift**: Drift is called zero drift if the whole of instrument calibration shifts over by the same amount. It may be due to shifting of pointer or permanent set.

b) **Span Drift**: If the calibration from zero upwards changes proportionately it is called span drift. It may be due to the change in spring gradient.

c) **Zonal Drift**: When the drift occurs only over a portion of the span of the instrument it is called zonal drift.



(Fig) span drift



(fig) zero drif

Drift is an undesirable quality in industrial instruments because it is rarely apparent and cannot be easily compensated for. Thus, it must be carefully guarded against by continuous fields can be prevented from affecting the measurements for proper shielding. Effect of mechanical vibrations can be minimized by having proper mountings. Temperature changes during the measurement process should be preferably avoided or otherwise be properly compensated for.

Range or Span:

The input range of an measuring device is specified by the minimum and maximum values of input variable (*Xmin to Xmax*). The output range of an measuring device is specified by the minimum and maximum values of output variable (*Ymin to Ymax*). Span and range are the two terms that convey the information about the lower and apa calibration points. The range of indicating instruments is normally from zero to full scale value and the Span is simply the difference between the full scale and lower scale value.

The minimum & maximum values of a quantity for which an instrument is designed to measure is called its range or span. For exapmple: For a standard thermometer given the range 0° C to 100°C then span is 100°C . If the thermometers range is ¬30 to 220°C, then the span is equal to 250°C.

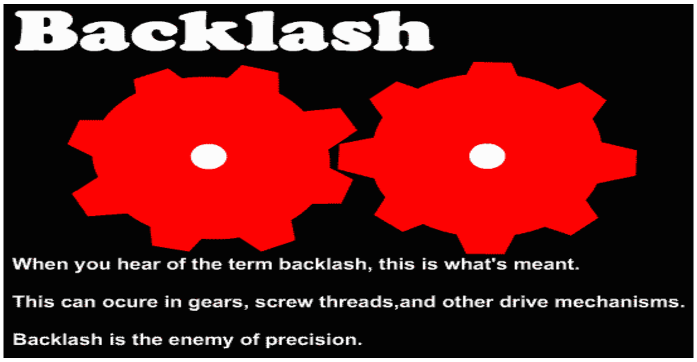
Numerical

a) **A voltmeter whose accuracy is 2% of full-scale reading is used on its 0-50 volts scale. The voltage measured by meter is 15 V and 42 V. Calculate the possible percentage error of both readings. Comments on your answer**

<u>Backlash</u>:

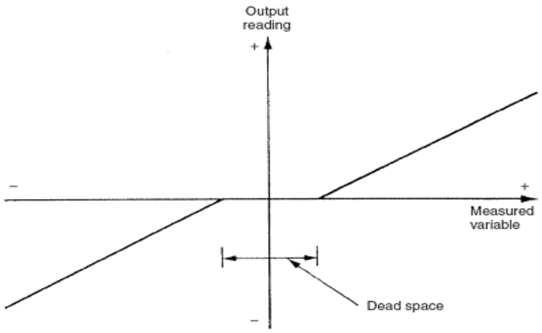
The maximum distance or angle through which any part of mechanical system may be moved in one direction without applying appreciable force or motion to the next part in a mechanical sequence.

It is often defined as the difference between the position of a mechanism's input and output when the input is moved in one direction, and then in the opposite direction. Backlash is a common problem in gear systems and can cause inaccuracies in the measurement of position or velocity.



Dead Band and Dead Time

Dead band, sometimes called a neutral zone, is an area of a signal range or band where no action occurs, that is, the system is dead. e.g. 10 g weight on a 10 kg balance. It is the largest change in the physical variable to which the measuring instrument does not respond. In other words it is defined as the range of input values over which there is no change in output value.



Dead Zone: For the largest changes in the measured variable, the instrument does not respond.

Bias: Bias describes a constant error which exits over the full range of measurement of an instrument. The error is normally removable by calibration

Dynamic Characteristics:

The characteristics of the instruments, which are used to measure the quantities or parameters that vary very quickly with respect to time are called dynamic characteristics.

Dynamic characteristic are concerned with the measurement of quantities that vary with time.

Following are the list of **dynamic characteristics**.

i) Speed of Response
ii) Dynamic Error
iii) Fidelity
iv) Measuring Lag
v) Bandwidth
vi) Time Constant

Impedance Loading and Matching

Loading Effects

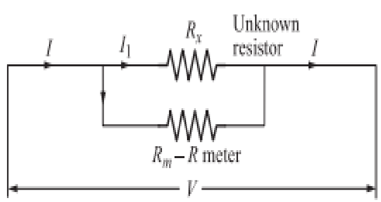
The ideal situation in a measurement system is that when an element is used for any purpose may be for signal sensing, conditioning, transmission or deflection is introduced into the system, the original signal should remain unmolested. This means that the original signal should not be distorted in ·any form by introduction of any element in the measurement system.

However, under practical conditions it has been found that introduction of any element in a system results, invariably, in extraction of energy from the system thereby distorting the original signal. This distortion may take the form of attenuation (reduction in magnitude), waveform distortion, phase shift and many a time all these undesirable features put together. This makes ideal measurements impossible.

The incapability of the system to faithfully measure, record, or control the input signal (measurand) in undistorted form is called the loading effect

<u>**Numerical**</u>

Q) A voltmeter having a sensitivity of 10 kΩ/V reads 75 V in its 100 V scale when connected across an unknown resistor when the current through the resistor is 1.5 mA. Calculate the percentage error due to loading effect.



Consider Fig. Owing to the finite resistance of the voltmeter, it draws some current from the source. Ideally, the voltmeter must have infinite resistance and should not draw any current. Therefore, the net resistance measured V/I is the parallel combination of Rx and Rm and not Rx alone. This is called loading of the source by the meter and results in certain error in measurement.

$R_{apparent} = 75V/1.5\ mA = 50\ k\Omega$

$R_{meter} = 100\ V \times \frac{10\ k\ \Omega}{V} = 1\ M\Omega = 1000\ k\Omega$

Rx parallel with

$$Rm = \frac{Rx * Rm}{Rx + Rm} = 50\ k\Omega$$

$$Rm = 1\ m\Omega;\ Rx = ?$$

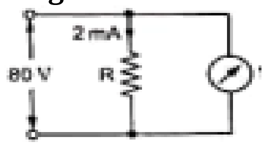
$$Rx = 52.63\ k\Omega$$

Percentage error due to loading effect: The true value of the unknown resistor Rx is 52.63 kΩ. The measured value is 50 kΩ.

$$\%\ error = \frac{(52.63-50)}{52.63} \times 100 = 4.99\%$$

Numerical

a) **A Voltmeter having a sensitivity of 15kΩ/V reads 80V on a 100V scale, when connected across an unknown resistor. The current through the resistance is 2mA. Calculate the % error due to loading effect.**



Soln

Solution: Resistance of voltmeter,

$$R_V = \text{Sensitivity of voltmeter in k}\Omega\text{/V} \times \text{range of voltmeter}$$

$$= 15 \times 100 = 1{,}500\ k\Omega$$

Voltage across unknown resistor,

$$V = \text{Reading of voltmeter connected across the circuit}$$

$$= 80\ V$$

True value of unknown resistance,

$$R_T = \frac{\text{Voltage across resistor}}{\text{Current through resistor}}$$

$$\frac{80}{2 \times 10^{-3}} = 40{,}000\ \Omega \text{ or } 40\ k\Omega$$

Apparent value of unknown resistance,

$$R_m = \text{Equivalent resistance of the circuit}$$

$$= 40\ k\Omega \,||\, 1{,}500\ k\Omega$$

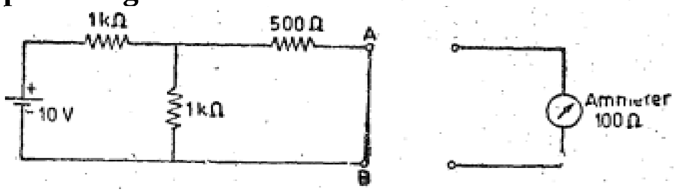
$$= \frac{40 \times 1{,}500}{40 + 1{,}500} = 38.961\ k\Omega$$

% error due to loading effect,

$$\epsilon_r = \frac{R_m - R_T}{R_T} \times 100$$

$$= \frac{38.961 - 40}{40} \times 100 = -2.56\% \quad \textbf{Ans.}$$

b) **It is desired to measure the value of current in the 500 ohms resistor as shown in Fig. by connecting a 100 ohms ammeter. Find: (a) the actual value of current (b) measured value of current c) percentage error in the measurement and accuracy.**



Solution. (*a*) Let us reduce the actual circuit to an equivalent Thevenin's source.

Open circuit voltage as applying at terminals A and B is :

$$E_0 = 10 - \frac{10}{2000} \times 1000 = 5 \text{ V}.$$

Output impedance of source as looking into terminals A and B is :

$$Z_0 = \frac{1000 \times 1000}{1000 + 1000} + 500 = 1000 \ \Omega.$$

∴ The Thevenin equivalent circuit is as shown in Fig. 2·15.

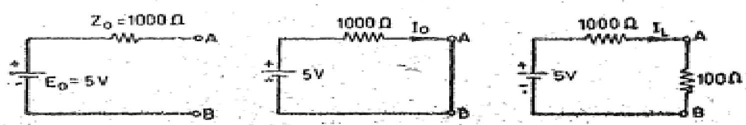


Fig. 2·15

∴ Actual value of current $I_0 = \frac{E_0}{Z_0} = \frac{5}{1000} \text{ A} = 5 \text{ mA}.$

(*b*) When the ammeter is introduced into the circuit the value of current is modified.

∴ Measured value of current $I_L = \frac{E_0}{Z_0 + Z_L} = \frac{5}{1000 + 100} \text{ A} = 4{\cdot}55 \text{ mA}.$

(*c*) Error $= \frac{4{\cdot}55 - 5}{5} \times 100 = -9\% = 9\%$ low.

Accuracy of measurement $= 100 - 9 = 91\%$.

Impedance Matching

Impedance matching is defined as the process of designing the input impedance and output impedance of an electrical load to minimize the signal reflection or maximize the power transfer of the load.

An electrical circuit consists of power sources like amplifier or generator and electrical load like a light bulb or transmission line have source impedance. This source impedance is equivalent to resistance in series with reactance.

According to the maximum power transfer theorem, when the load resistance is equal to the source resistance and load reactance is equal to negative of the source reactance, the maximum power is transferred from source and load. It means that the maximum power can be transfer if the load impedance is equal to the complex conjugate of the source impedance.

Errors: Statistical Analysis of Error in Measurement

Statistical Evaluation of measured data is obtained in two methods of tests as shown in below.

Multi Sample Test: In multi sample test, repeated measured data have been acquired by different instruments, different methods of measurement and different observer.

Single Sample Test: measured data have been acquired by identical conditions (same instrument, methods and observer) at different times. Statistical Evaluation methods will give the most probable true value of measured quantity.

The mathematical background statistical evaluation methods are Arithmetic Mean, Deviation Average Deviation, Standard Deviation and variance.

- **Average (Mean) x̄** = $\frac{X1+X2+X3+\cdots\ldots\ldots+Xn}{n}$
- **Deviation from Mean d,**

  d1 = x̄ - x1

  d2 = x̄ - x2

  d3 = x̄ - x3

  ………………..

. **dn** = $\bar{x}$ - xn

- **Average Deviation** $d = \frac{|d_1| + |d_2| + \ . \ . \ . \ + |d_N|}{N}$

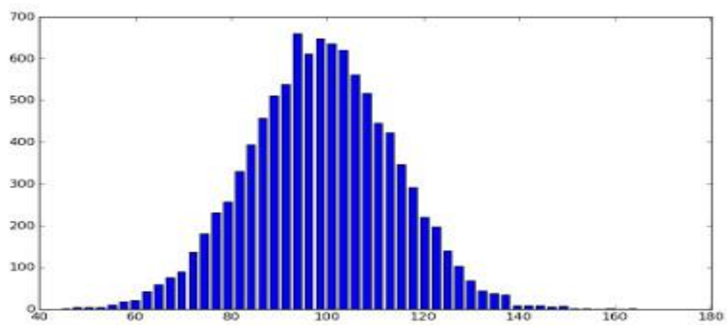
- **Standard Deviation s** = $\sqrt{\frac{d1^2+d2^2+d3^2+\cdots.....dn^2}{n}}$ if n≥20

  = $\sqrt{\frac{d1^2+d2^2+d3^2+\cdots.....dn^2}{n-1}}$ if n<20

- **Variance V** = s^2
- **Probable Error PE** = (+-) 0.6745 s

Normal Distribution/Probability Distribution

- Probability distributions are a function, table, or equation that shows the relationship between the outcome of an event and its frequency of occurrence.
- Probability distributions are helpful because they can be used as a graphical representation of your measurement functions and how they behave.
- A histogram is a graphical representation used to understand how numerical data is distributed. Take a look below at the histogram of a Gaussian distribution.
- Look at the histogram and view how the majority of the data collected is grouped at the center. This is called central tendency.
- Now look at height of each bar in the histogram. The height of the bars indicate how frequent the outcome it represents occurs. The taller the bar, the more frequent the occurrence.



Probability of Errors and Gaussian Curve

A method of presenting test results is in the form of a histogram or block diagram. The number of readings of the same quantity is taken and the measured value readings obtained are as given in Table.

Table: Set of measurements to estimate random errors

Measured Value (Hz	Number of Readings
49.6	5
49.7	8
49.8	12

49.9	19
50.0	20
50.1	19
50.2	12
50.3	10
50.4	4

Now a graph is plotted between the number of readings and the value of frequency (Fig). The is graph is called a HISTOGRAM. The distribution and the shape of the curve indicate that the average value is the most probable value. The deviation on the positive and negative sides of the average value is uniform. Therefore, the middle or the average value is the most appropriate one

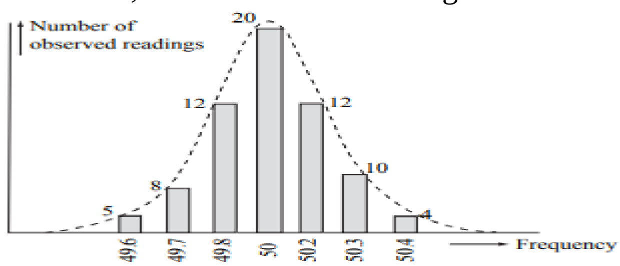


Figure: Histogram showing distribution of parameter readings

The Gaussian law or normal law: The Gaussian law of error is the basis for the study of random effects. When random errors are predominant, the probable error in a particular measurement can be estimated. The equation for the Gaussian law is

$$y = \frac{h}{\sqrt{\pi}} e^{-h^2\omega^2}$$

Where, h = constant = $1/\sqrt{2}\sigma$ = standard deviation

ω = magnitude of deviation from the mean

y = probability of occurrence of deviation ω

For each reading, the probability of occurrence of deviation is calculated. A graph is plotted between y and ω as shown in Fig

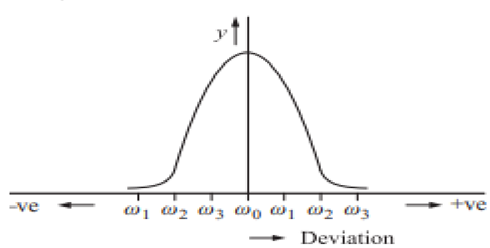


Figure: Probability of occurrence of deviations ω

The deviation is calculated in terms of σ on both sides of the average value, and a graph is plotted. If the average value is the true value, the probability of occurrence of zero deviation is maximum. Therefore, corresponding to the average value, we will have a peak. If the shape of the graph is as shown in Fig, we can confidently say that average value is the most correct value.

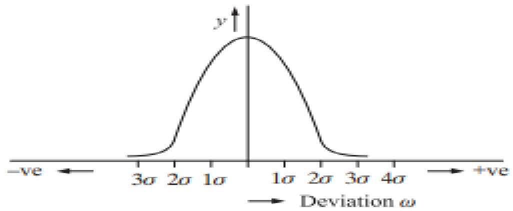


Figure: versus σ curve

Numerical

Example . The following 10 observations were recorded when measuring a voltage:

1	2	3	4	5	6	7	8	9	10
41.7	42	41.8	42	42.1	41.9	42.5	42	41.9	41.8

Find (*i*) mean (*ii*) standard deviation (*iii*) probable error of one reading.

Solution: (*i*) Arithmetic mean,

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

$$= \frac{41.7 + 42 + 41.8 + 42 + 42.1 + 41.9 + 42.5 + 42 + 41.9 + 41.8}{10}$$

$$= \frac{419.7}{10} = 41.97 \quad \text{Ans.}$$

Deviations from the mean

$d_1 = 41.7 - 41.97 = -0.27$
$d_2 = 42 \quad - 41.97 = +0.03$
$d_3 = 41.8 - 41.97 = -0.17$
$d_4 = 42 \quad - 41.97 = +0.03$
$d_5 = 42.1 - 41.97 = +0.13$
$d_6 = 41.9 - 41.97 = -0.07$
$d_7 = 42.5 - 41.97 = +0.53$
$d_8 = 42 \quad - 41.97 = +0.03$
$d_9 = 41.9 - 41.97 = -0.07$
$d_{10} = 41.8 - 41.97 = -0.17$

(*ii*) Since the number of reading is 10, which is less than 20, the standard deviation is calculated from the equation

$$s = \sqrt{\frac{\Sigma d^2}{n-1}}$$

Standard deviation,

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

$$= \sqrt{\frac{(-0.27)^2 + (+0.03)^2 + (-0.17)^2 + (+0.03)^2 + (+0.13)^2 + (-0.07)^2 + (+0.53)^2 + (+0.03)^2 + (-0.07)^2 + (-0.17)^2}{9}}$$

$$= \sqrt{\frac{0.4410}{9}} = 0.221 \quad \text{Ans.}$$

(*iii*) Probable error of one reading,

$$r = 0.6745 \times s = 0.6745 \times 0.221 = 0.149 \quad \text{Ans.}$$

Tutorial Numerical

1) **The following set of 8 measurement was recorded during an experiment were: 532, 548, 543, 535, 546, 531, 543, 546. Calculate**
    - **a. Arithmetic mean** **b. Deviation from mean** **c. Average deviation**
    - **d. Standard deviation** **e. Varience** **f. Range**
    - **e. Probable error of one reading** **f. Probable error of mean reading**
2) **The following 10 observations were recorded: 41.7, 42, 41.8, 42, 42.1, 41.9, 42, 41.9, 42.5, 41.8 for an ammeter. Find**
    - a. **Mean.** **b. Standard deviation.** **C. Probable error of one reading.**
    - d. **Probable error of mean.** **e. Range**
3) **In a test, temperature is measured 100 times with variation in apparatus and procedure. After applying the correction the result are**

Temp	**397**	**398**	**399**	**400**	**401**	**402**	**403**	**404**	**405**
Freq of Occurance	**1**	**3**	**12**	**23**	**37**	**16**	**4**	**2**	**2**

Calculate
- **a. Arithmetic mean** **b. Deviation from mean** **c. Average deviation**
- **d. Standard deviation** **e. Varience** **f. Probable error**

4) **How probable error is determined from Gaussian Probability Curve?**

Standards in Measurements

A measurement standard is the point of reference to which the testing equipment refers. A measuring device will measure the part in question and then compare this to the standard. Without the measurement standard as a reference point, the likelihood of incorrect results greatly increases. Depending on the functions and applications, Different Types of Standards of Measurement are classified in categories

1. **International Standards,**
2. **Primary Standards,**
3. **Secondary Standards, and**
4. **Working Standards**

International Standards: International standards are defined by International agreement. They are periodically evaluated and checked by absolute measurements in terms of fundamental units of Physics. They represent certain units of measurement to the closest possible accuracy attainable by the science and technology of measurement. These International Standards of Measurement are not available to ordinary users for measurements and calibrations.

Primary Standards/Master Standards: The principle function of primary standards is the calibration and verification of secondary standards. Primary standards are maintained at the National Standards Laboratories in different countries. The primary standards are not available for use outside the National Laboratory. These primary standards are absolute standards of high accuracy that can be used as ultimate reference standards.

Secondary Standards/Calibration Standards: Secondary standards are basic reference standards used by measurement and calibration laboratories in industries. These secondary standards are maintained by the particular industry to which they belong. Each industry has its own secondary standard. Each laboratory periodically sends its secondary standard to the National standards laboratory for calibration and comparison against the primary standard. After comparison and calibration, the National Standards Laboratory returns the Secondary standards to the particular industrial laboratory with a certification of measuring accuracy in terms of a primary standard.

Working Standards/Workshop Measuring Standards: Working standards are the principal tools of a measurement laboratory. These standards are used to check and calibrate laboratory instrument for accuracy and performance. For example, manufacturers of electronic components such as capacitors, resistors, etc. use a standard called a working Standards of Measurement for checking the component values being manufactured, e.g. a standard resistor for checking of resistance value manufactured.

Exan If $R_x = \frac{R_1 R_2}{R_3}$ where $R_1 = 100 \pm 1\%$, $R_2 = 200 \pm 2.5\%$ and $R_3 = 100 \pm 2\%$. Find:

(*i*) The nominal value

(*ii*) The limiting error and

(*iii*) The percentage limiting error of R_x

Solution: (*i*) Nominal value of R_x

$$= \frac{R_1 \times R_2}{R_3} = \frac{100 \times 200}{100} = 200\ \Omega \text{ Ans.}$$

(*ii*) Limiting error $= \pm\left[\frac{\delta R_1}{R_1} + \frac{\delta R_2}{R_2} \pm \frac{\delta R_3}{R_3}\right] \times R_x$ ohms

$$= \pm\left(\frac{1}{100} + \frac{2.5}{100} + \frac{2}{100}\right) \times 200 = \pm 11\ \Omega$$

(*iii*) Percentage limiting error

$$= \pm\frac{11}{200} \times 100 = \pm 5.5 \text{ Ans.}$$

Example The solution for the unknown resistance for a Wheatstone bridge is

$$R_x = \frac{R_2 R_3}{R_1}$$

where $R_1 = 100 \pm 0.5\%\ \Omega$, $R_2 = 1000 \pm 0.5\%\ \Omega$, $R_3 = 842 \pm 0.5\%\ \Omega$

Determine the magnitude of the unknown resistance and the limiting error in percent and in ohm for the unknown resistance R_x.

Solution : Unknown resistance

$$R_x = \frac{R_2 R_3}{R_1} = \frac{1000 \times 842}{100} = 8420\ \Omega$$

Relative limiting error of unknown resistance is :

$$\frac{\delta R_x}{R_x} = \pm\left(\frac{\delta R_2}{R_2} + \frac{\delta R_3}{R_3} + \frac{\delta R_1}{R_1}\right) = \pm(0.5 + 0.5 + 0.5) = \pm 1.5\%$$

Limiting error in ohm is :

$$= \pm\frac{1.5}{100} \times 8420 = \pm 126.3\ \Omega$$

Guaranteed values of resistance are between.

$8420 - 126.3 = 8293.7\ \Omega$, $8420 + 126.3 = 8546.3\ \Omega$

Q) The value of resistance R was determined by measuring current I flowing through the resistance with an error +- 1.5%. and power loss P in it with an error +-1%.. Determine maximum possible relative error to be expected a measuring a resistance R.

Soln,

We have, $R=P/I^2$

Thus,

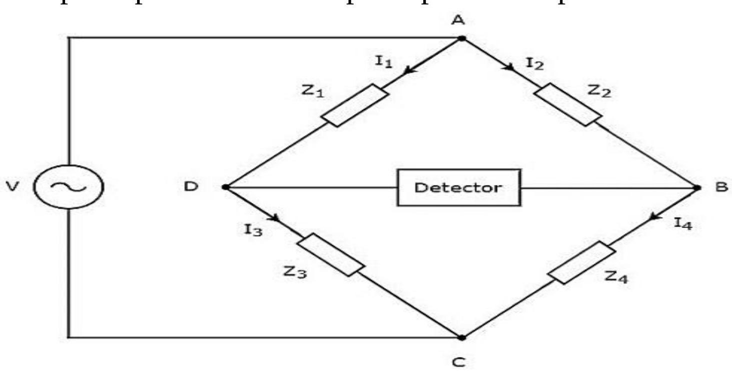
% error in R = % error in P + 2* % error in R

= 1% + 2*1.5%

= 4%

Bridge Measurement:

Bridges are often used for the precision measurement of component values, like resistance, inductance, capacitance, etc. The simplest form of a bridge circuit consists of a network of four resistance arms forming a closed circuit as shown in Fig. A source of current is applied to two opposite junctions and a current detector is connected to other two junctions. The bridge circuit operates on null detection principle and uses the principle of comparison measurement methods.



The two Types of Bridges are,

1. D.C Bridges
    - Wheatstone Bridge
    - Kelvin Bridge
2. A.C Bridges
    - Inductance Bridge (Hay and Maxwell Bridge)
    - Capacitance Bridge (Schering Bridge)
    - Wein Bridge

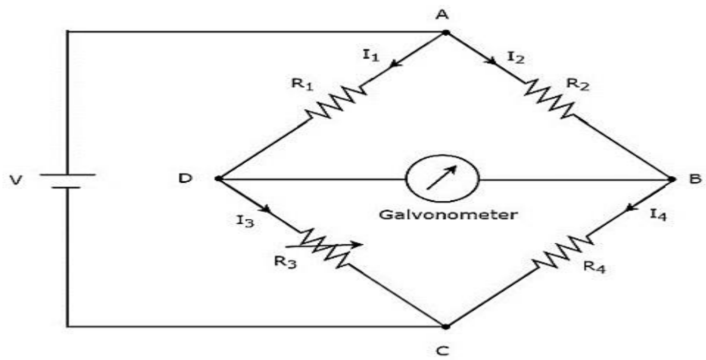
The D.C bridges are used to measure the resistance while the A.C bridges are used to measure the impedances consisting capacitance and inductances.

DC Bridges-

Wheat-Stone Bridge

Wheatstone's bridge is a simple DC bridge, which is mainly having four arms. These four arms form a rhombus or square shape and each arm consists of one resistor.

To find the value of unknown resistance, we need the galvanometer and DC voltage source. Hence, one of these two are placed in one diagonal of Wheatstone's bridge and the other one is placed in another diagonal of Wheatstone's bridge.
Wheatstone's bridge is used to measure the value of medium resistance. The **circuit diagram** of Wheatstone's bridge is shown in below figure.
Here, the resistor, R_3 is a standard variable resistor and the resistor, R_4 is an unknown resistor. We can **balance the bridge**, by varying the resistance value of resistor R_3.



At balanced condition, when no current flows through the diagonal arm, DB. That means, there is **no deflection** in the galvanometer, when the bridge is balanced.
The bridge will be balanced, the voltage across arm AD is equal to the voltage across arm AB.

$$V_{AD} = V_{AB}$$

$$I_1 R_1 = I_2 R_2$$

$$\frac{V}{R1 + R3} R1 = \frac{V}{R2 + R4} R2$$

Solving we get,

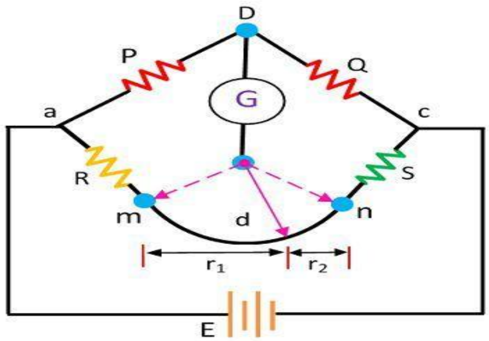
$$R_1 R_4 = R_2 R_3$$

$$R_4 = \frac{R2\, R3}{R1}$$

By substituting the known values of resistors R_1, R_2 and R_3 in above equation, we will get the **value of resistor R_4.**

Kelvin Bridge

Kelvin bridge or Thompson bridge is used for measuring the unknown resistances having a value less than 1Ω but if we want to measure the resistance below 1 – ohm, it becomes difficult because the leads which are connected to the galvanometer adds up the resistance of the device along with the resistance of leads leading to variation in the measurement of the actual value of resistance. Hence in order to overcome this problem, we can use a modified bridge called kelvin bridge. It is the modified form of the Wheatstone Bridge.



Prinicple of Kelvin's Bridge

r is the resistance of the contacts that connect the **unknown resistance R** to the **standard resistance S**. The **'m'** and **'n'** show the range between which the galvanometer is connected for obtaining a null point.

When the galvanometer is connected to point 'm', the lead resistance r is added to the standard resistance S. Thereby the very low indication obtains for unknown resistance R. And if the galvanometer is connected to point n then the r adds to the R, and hence the high value of unknown resistance is obtained. Thus, at point n and m either very high or very low value of unknown resistance is obtained.

So, instead of connecting the galvanometer from point, m and n we chose any intermediate point say d where the resistance of lead r is divided into two equal parts, i.e., r_1 and r_2

$$\frac{r_1}{r_2} = \frac{P}{Q} \dots\dots\dots equ(1)$$

The presence of r_1 causes no error in the measurement of unknown resistance.

$$R + r_1 = \frac{P}{Q}.(S + r_2)$$

$$\frac{r_1}{r_1 + r_2} = \frac{P}{P + Q}$$

From equation (1), we get $$r_1 = \frac{P}{P + Q}.r$$

$$r_1 + r_2 = r$$

As $$r_2 = \frac{Q}{P + Q}.r$$

$$R + \frac{P}{P + Q}.r = \frac{P}{Q}\left(S + \frac{Q}{P + Q}r\right)$$

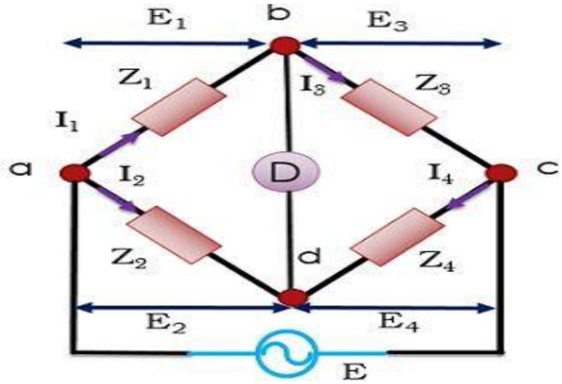
$$R = \frac{P}{Q}.S$$

The above equation shows that if the galvanometer connects at point d then the resistance of lead will not affect their results.

The above mention process is practically not possible to implement. For obtaining the desired result, the actual resistance of exact ratio connects between the point m and n and the galvanometer connects at the junction of the resistor.

AC Bridges

AC bridges are the circuits that are used for the measurement of **electrical quantities** such as inductance, capacitance, resistance.



Let, $Z_1 = (Z_1\angle\theta_1)$

$Z_2 = (Z_2\angle\theta_2)$

$Z_3 = (Z_3\angle\theta_3)$

$Z_4 = (Z_4\angle\theta_4)$

For the bridge to be balanced, considering the above-shown figure The current through detector must be 0 that requires the potential difference V_{bd} to be 0.

In such a condition voltage drop from a to b will get equal to voltage drop from a to d, both in magnitude and phase.

So, we can write the above-stated condition as, At balance,

$$\mathbf{E_1 = E_2}$$

$$\mathbf{I_1 Z_1} \angle\theta_1 = \mathbf{I_2 Z_2} \angle\theta_2$$

But,

$$I_1 = I_3 = \frac{E}{\mathbf{Z1} \angle\theta 1 + \mathbf{Z3} \angle\theta 3}$$

And

$$I_2 = I_3 = \frac{E}{\mathbf{Z2} \angle\theta 2 + \mathbf{Z4} \angle\theta 4}$$

So,

$$\mathbf{I_1 Z_1} \angle\theta_1 = \mathbf{I_2 Z_2} \angle\theta_2$$

$$\frac{E}{\mathbf{Z1} \angle\theta 1 + \mathbf{Z3} \angle\theta 3} \mathbf{Z1} \angle\theta 1 = \frac{E}{\mathbf{Z2} \angle\theta 2 + \mathbf{Z4} \angle\theta 4} \mathbf{Z_2} \angle\theta_2$$

The above equation can be written as

$$\mathbf{(Z_1\angle\theta_1) \text{ X } (Z_4\angle\theta_4) = (Z_2\angle\theta_2) \text{ X } (Z_3\angle\theta_3)}$$

So, here impedance parameters will get multiplied and angles will be added.

$$\mathbf{Z_1 Z_4 \angle \theta_1+\theta_4 = Z_2 Z_3 \angle \theta_2+\theta_3}$$

Hence for AC circuit to be balanced, two condition must be satisfied

1) Product of Magnitude of impedance of opposite arm must be equal

$$\mathbf{Z_1 Z_4 = Z_2 Z_3}$$

2) Sum of angle of impedance of opposite arm must be equal

$$\mathbf{\angle\theta_1+\angle\theta_4 = \angle\theta_2+ \angle\theta_3}$$

Numerical

The four impedances of an AC bridge having 1000Hz has following arms:
Branch AB with impedance Z_1= 400Ω<80˚, Branch BC with impedance Z_2= 200Ω<40˚, Branch CD with impedance Z_3= 400Ω<-30˚; Branch DA with impedance Z_4= 800Ω< 20˚;
Find out whether bridge is balanced or not.

Measurement of Inductance/AC inductance bridge

Following are the two AC bridges, which can be used to measure **inductance**.

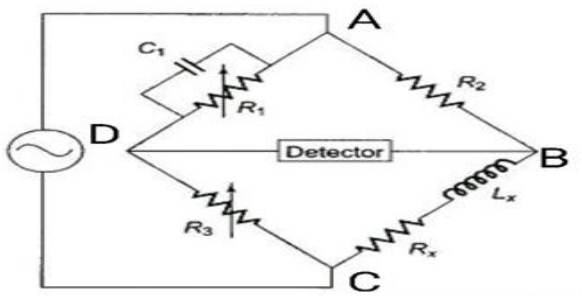
- Maxwell's Bridge
- Hay's Bridge

Now, let us discuss about these two AC bridges one by one.

Maxwell's Bridge

Maxwell's bridge is used to measure the value of medium inductance. The **circuit diagram** of Maxwell's bridge is shown in the below figure.

i) Maxwells Inductance Capacitance Bridge



$Y_1 = \frac{1}{R1} + jwc1$

$Z_2 = R_2$

$Z_3 = R_3$

$Z_x = Rx + jwLx$

At balanced condition

$Z_1 Z_x = Z_2 Z_3$

$Z_x = \frac{Z2\, Z3}{Z1} = Z_3 Z_2 Y_1$

$Rx + jwLx = R_2 R_3 (\frac{1}{R1} + jwc1\ )$

Comparing real and imaginary parts

$Rx = \frac{R2\, R3}{R1}$

$Lx = R_2 R_3 C_1$

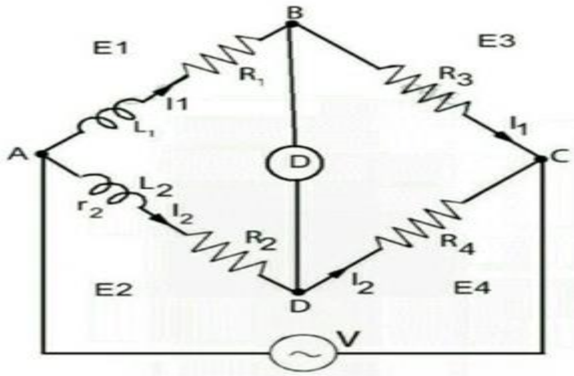
The quality factor of Maxwell's bridge circuit is given as,

$Q = \omega L_1/R_1 = \omega C_4 R_4$

Problems

Q) How can we measure the self-Inductance by comparing it with a standard variable capacitance? Show the derivation with figure.

ii) Maxwells Inductance Bridge



Let, L_1 – unknown inductance of resistance R_1.
L_2 – Variable inductance of fixed resistance r_1.
R_2 – variable resistance connected in series with inductor L_2.
R_3, R_4 – known non-inductance resistance
We have,

$Z_1 = R_1 + jwL_1$
$Z_2 = R_2 + r2 + jwL_2$
$Z_3 = R_3$
$Z_x = Rx + jwLx$

Under balanced condition (i.e., when detector shows null deflection), we have,

$$Z_1\, Z_4 = Z_2\, Z_3$$

$$(R_1 + j\omega L_1) \times R_4 = (R_2 + r_2 + j\omega L_2) \times R_3$$

$$R_1R_4 - R_2R_3 - r_2R_3 + j\omega(L_1R_4 - L_2R_3) = 0$$

On equating the real and imaginary parts on both sides, we get,

$$L_1 = \frac{R_3}{R_4} L_2$$

$$R_1 = \frac{R_3}{R_4}(R_2 + r_2)$$

Hence, the unknown self-inductance and resistance of the inductor are obtained in terms of known standard values. Also, both the equations are independent of frequency term.

Advantages of Maxwell's Bridge

The advantages of a Maxwell Bridge are:

1. The frequency does not appear in the final expression of both equations, hence it is independent of frequency.
2. Maxwell's inductor capacitance bridge is very useful for the wide range of measurement of inductor at audio frequencies.

Disadvantages of Maxwell's Bridge

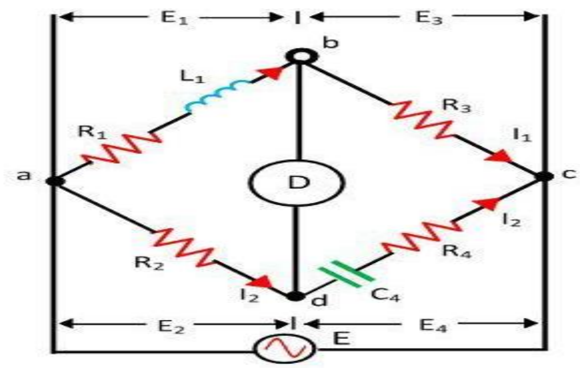
The disadvantages of a Maxwell Bridge are:

1. The variable standard capacitor is very expensive.
2. The bridge is limited to measurement of low quality coils (1 < Q < 10) and it is also unsuitable for low value of Q (i.e. Q < 1) from this we conclude that a Maxwell bridge is used suitable only for medium Q coils.

The above all limitations are overcome by the modified bridge which is known as Hay's bridge which does not use an electrical resistance in parallel with the capacitor.

Hay's Bridge

The bridge is the advanced form **of** Maxwell's bridge. The Maxwell's bridge is only appropriate for measuring the medium quality factor. Hence, for measuring the high-quality factor Q_f >10, the Hays bridge is used in the circuit.



Let,

L_1 – unknown inductance having a resistance R_1

R_2, R_3, R_4 – known non-inductive resistance.

C_4 – standard capacitor

$$(R_1 + j\omega L_1)(R_4 - j/\omega C_4) = R_2 R_3$$

At balance condition,

$$R_1 R_4 + \frac{L_1}{C_4} + j\omega L_1 R_4 - \frac{jR_1}{\omega C_4} = R_2 R_3$$

Separating the real and imaginary term, we obtain

$$R_1 R_4 + \frac{L_1}{C_4} = R_2 R_3 \quad and\ L_1 = \frac{-\ R_1}{\omega^2 R_4 C_4}$$

$$L_1 = \frac{R_2 R_3 C_4}{1 + \omega^2 R_4^2 C_4^2}$$

Solving the above equation, we have

$$R_1 = \frac{\omega^2 C_4^2 R_2 R_3 R_4}{1 + \omega^2 R_4^2 C_4^2}$$

The quality factor of the coil is

$$Q = \frac{\omega L_1}{R_1} = \frac{1}{\omega^2 C_4 R_4}$$

The equation of the unknown inductance and capacitance consists frequency term. Thus for finding the value of unknown inductance the frequency of the supply must be known.

For the high-quality factor, the frequency does not play an important role.

$$Q = \frac{1}{\omega^2 C_4 R_4}$$

Substituting the value of Q in the equation of unknown inductance, we get

$$L_1 = \frac{R_2 R_3 C_4}{1 + (1/Q)^2}$$

For greater value of Q the 1/Q is neglected and hence the equation become

$$L_1 = R_2 R_3 C_4$$

Advantages of Hay's Bridge

The following are the advantages of Hay's Bridge.

1. The Hays bridges give a simple expression for the unknown inductances and are suitable for the coil having the quality factor greater than the 10 ohms.
2. It gives a simple equation for quality factor.
3. The Hay's bridge uses small value resistance for determining the Q factor.

Disadvantages of Hay's Bridge

The only disadvantage of this type of bridge is that it is not suitable for the measurement of the coil having the quality factor less than 10 ohms.

Q) Why Hay bridge is used for measurement of the coil having quality factor high only?

Numerical

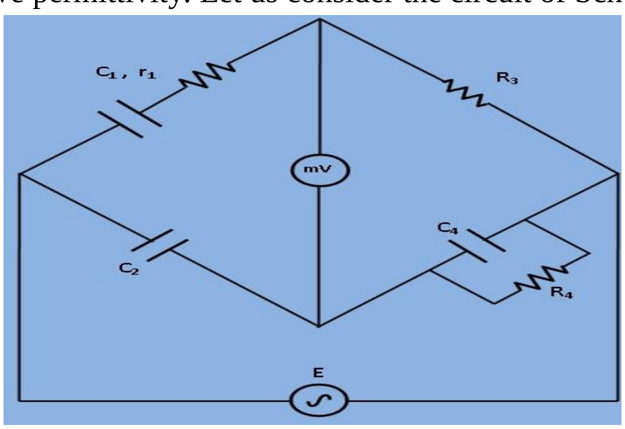
State Wheatstone principle for circuit to be balance. A 1000Hz bridge with ABCD branch has following constants arms,

AB, R=1000Ω in parallel with C= 0.5μf
BC, R=1000Ω in series with C= 0.5μf
CD, L=30 mH in series with R= 200Ω
Find the constants of arms DA to balance the bridge.

Measurement of Capacitance

i) Schering Bridge

This bridge is used to measure to the capacitance of the capacitor, dissipation factor and measurement of relative permittivity. Let us consider the circuit of Schering Bridge.



Let, C_1 = Capacitor whose capacitance is to be measured.

r_1 = A Series Resistance representing the loss in the Capacitor C1C1.

C_2 = A Standard Capacitor.

R_3 = A Non Inductive Resistance.

C_4 = A Variable Capacitor.

R_4 = A Variable Non Inductive Resistance.

At balance condition

$Z_1 Z_4 = Z_2 Z_3$

$$\left(r_1 + \frac{1}{j\omega C_1}\right) \cdot \left(\frac{R_4}{j\omega C_4 R_4 + 1}\right) = \frac{R_3}{j\omega C_2} \text{......(1)}$$

$$r_1 R_4 - \frac{jR_4}{\omega C_1} = -\frac{jR_3}{\omega C_2} + \frac{R_3 R_4 C_4}{C_2} \text{......(2)}$$

Or Equating the real and imaginary terms in equa. (2), we obtain

$$r_1 = R_3 \cdot \frac{C_4}{C_2} \text{......(3)}$$

$$C_1 = R_4 \cdot \frac{C_2}{R_3} \text{......(4)}$$

And, Two independent balance equations (3) and (4) are obatined if C_4 and R_4 are chosen as the variable elements.

Dissipation factor

$$D_1 = \omega C_1 r_1 \text{......(5)}$$

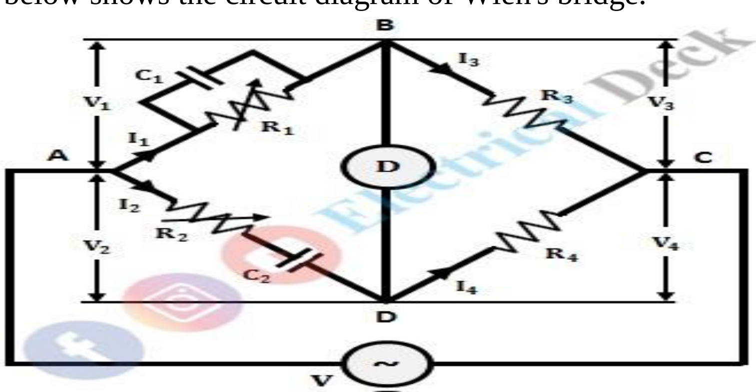
Numerical

The Schering Bridge has the following constraints, R1 = 1.5kΩ, C1 = 0.4µF, R2=3kΩ and C3=0.4µF at frequency 1kHz. Determine the unknown resistance and capacitance of the bridge and dissipation factor.

Measurement of Frequency

i) Wien Bridge

The circuit consists of four arms, one arm with a series combination of resistor and capacitor and another with a parallel combination resistor and capacitor. The other two arms compress a resistance. The below shows the circuit diagram of Wien's bridge.



A balance detector or null indicator is connected across two junctions (i.e., across BD as shown above). The indicator shows null deflection when the bridge is balanced i.e. when the junctions B and D will be at the same potential.

When the bridge is balanced, we have,

$$Z_1 Z_4 = Z_2 Z_3$$

$$\left(\frac{R_1}{1 + j\omega C_1 R_1}\right) \times R_4 = \left(R_2 - \frac{1}{j\omega C_2}\right) \times R_3$$

$$\frac{R_4}{R_3} = \left(\frac{1 + j\omega C_2 R_2}{j\omega C_2}\right)\left(\frac{1 + j\omega C_1 R_1}{R_1}\right)$$

$$\frac{R_4}{R_3} = \frac{1}{j\omega C_2 R_1} + \frac{C_1}{C_2} + \frac{R_2}{R_1} + j\omega C_2 R_2$$

Equating the real terms, we get,

$$\frac{R_4}{R_3} = \frac{C_1}{C_2} + \frac{R_2}{R_1}$$

The above equation is used to determine the resistance ratio (R_4/R_3). Now equating the imaginary terms

$$\frac{1}{j\omega C_2 R_1} + j\omega C_2 R_2 = 0$$

$$-\omega C_2 R_1 + \omega C_2 R_2 = 0$$

$$\omega = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$2\pi f = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$$

$$f = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}}$$

If suppose **the bridge components** are chosen such that $R_1 = R_2 = R$ and $C_1 = C_2 = C$. Then the above equation is given as,

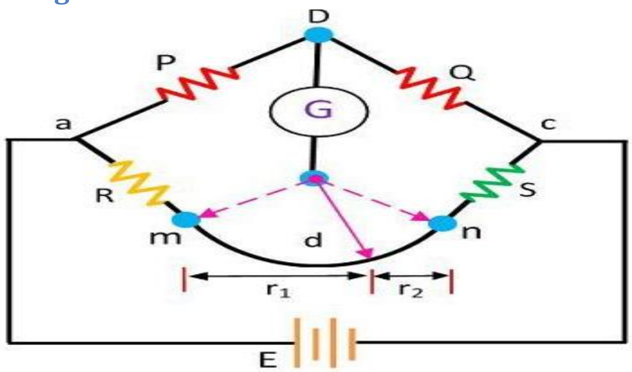
$$f = \frac{1}{2\pi\, RC}\ Hz$$

<u>Numerical</u>

1) **An AC bridge has the following constants. Arm AB:R = 800 Ω in parallel with C= 0.4 µF; BC:R = 500 Ω in series with C = 1.0 µF; CD:R = 1.2 kΩ; DA: pure resistance of unknown values. Find the frequency for which the bridge is in balance and the value of R in arm DA to produce a balance.**

Measurement the low-value Resistance

i) Kelvin Bridge



The **r** is the resistance of the contacts that connect the **unknown resistance R** to the **standard resistance S**. The **'m'** and **'n'** show the range between which the galvanometer is connected for obtaining a null point.

When the galvanometer is connected to point 'm', the lead resistance r is added to the standard resistance S. Thereby the very low indication obtains for unknown resistance R. And if the galvanometer is connected to point n then the r adds to the R, and hence the high value of unknown resistance is obtained. Thus, at point n and m either very high or very low value of unknown resistance is obtained.

So, instead of connecting the galvanometer from point, m and n we chose any intermediate point say d where the resistance of lead r is divided into two equal parts, i.e., r_1 and r_2

$$\frac{r_1}{r_2} = \frac{P}{Q} \ldots \ldots \ldots equ(1)$$

The presence of r_1 causes no error in the measurement of unknown resistance.

$$R + r_1 = \frac{P}{Q}.(S + r_2)$$

From equation (1), we get

$$\frac{r_1}{r_1 + r_2} = \frac{P}{P + Q}$$

$$r_1 = \frac{P}{P + Q}.r$$

As

$$r_1 + r_2 = r$$

$$r_2 = \frac{Q}{P + Q}.r$$

$$R + \frac{P}{P + Q}.r = \frac{P}{Q}\left(S + \frac{Q}{P + Q}r\right)$$

$$R = \frac{P}{Q}.S$$

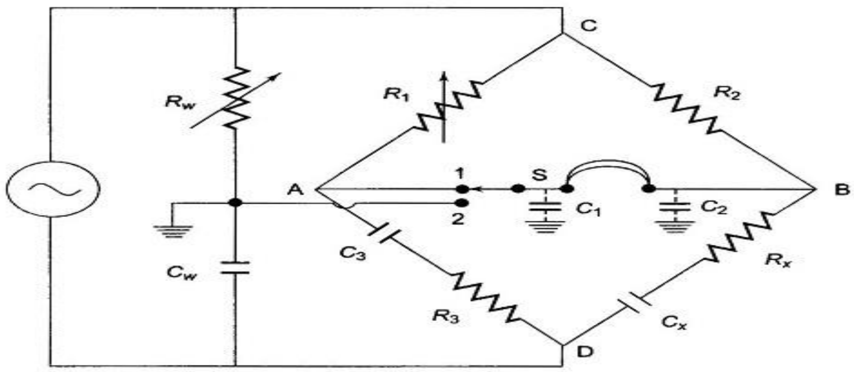
The above equation shows that if the galvanometer connects at point d then the resistance of lead will not affect their results.

Wagner Ground Connection

When performing measurements at high frequency, stray capacitances between the various bridge elements and ground, and between the bridge arms themselves, become significant. This introduces an error in the measurement, when small values of capacitance and large values of inductance are measured.

An effective method of controlling these capacitances, is to enclose the elements by a shield and to ground the shield. This does not eliminate the capacitance, but makes it constant in value.

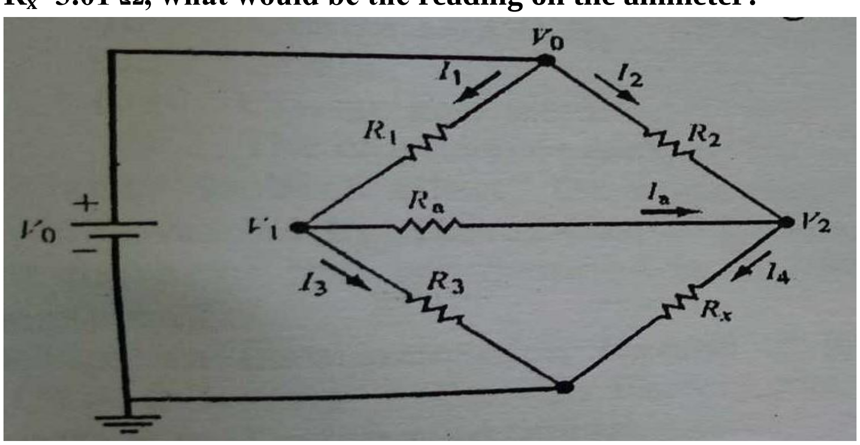
Another effective and popular method of eliminating these stray capacitances and the capacitances between the bridge arms is to use a Wagner Ground Connection. Figure shows a circuit of a capacitance bridge. C_1 and C_2 are the stray capacitances.



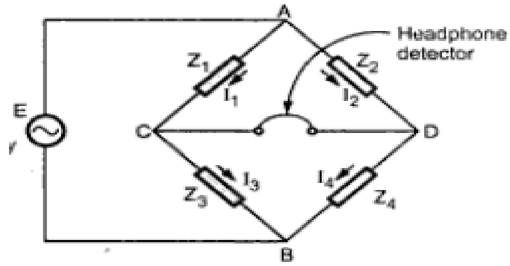
In Wagner's Ground Connection, another arm, consisting of R_w and C_w forming a potential divider, is used. The junction of R_w and C_w is grounded and is called Wagner Ground Connection. The procedure for adjustment is as follows.

Numerical

1) **Solve the following problem**
   i) **If R_1= 1 Ω, R_2 = 2 Ω and R_x= 3 Ω. What value should be R_3 be adjusted so as to achieve a balance condition?**
   ii) **If V = 6V, R_a= 0.1 Ω and R_x were then to deviate by a small amount to R_x=3.01 Ω, what would be the reading on the ammeter?**



2)



Example : *The impedances of the basic a.c. bridge are,*

$Z_1 = 50\ \Omega \angle 80°$, $Z_2 = 250\ \Omega \angle 0°$, $Z_3 = 200\ \Omega \angle 30°$

Calculate the constants of the unknown impedance.

Solution : The bridge balance equation is,

$$Z_1 Z_4 = Z_2 Z_3 \quad \text{magnitude condition}$$

$$\therefore \quad 50 \times Z_4 = 250 \times 200$$

$$\therefore \quad Z_4 = 1000\ \Omega$$

Thus the magnitude of Z_4 is 1000 Ω.

While the phase angle condition is,

$$\theta_1 + \theta_4 = \theta_2 + \theta_3$$

$$\therefore \quad 80° + \theta_4 = 0 + 30°$$

$$\therefore \quad \theta_4 = 30° - 80° = -50°$$

Hence the unknown impedance is,

$$\bar{Z}_4 = 1000 \angle -50°\ \Omega$$

The negative angle indicates, it is capacitive in nature. Converting it to rectangular form we get,

$$\bar{Z}_4 = \mathbf{642.79 - j\ 766.1\ \Omega} \quad \text{(using P} \rightarrow \text{R on calculator)}$$

Comparing with $R - jX_C$, we can say that the resistance part of Z_4 is **642.79 Ω while it is in series with capacitive reactance of 766.1 Ω.**

3)

Example : *The wheatstone bridge is shown in the Fig. . The galvanometer has a current sensitivity of 12 mm / μA. The internal resistance of galvanometer is 200 Ω. Calculate the deflection of the galvanometer caused due to 5 Ω unbalance in the arm BD.*

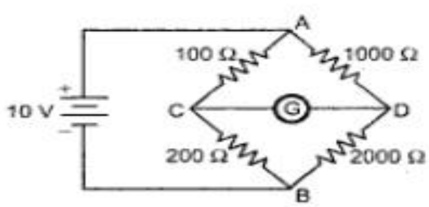


Fig.

Solution :

From the given bridge,

$$R_1 = 100\ \Omega, \quad R_2 = 1000\ \Omega$$

$$R_3 = 200\ \Omega, \quad R_4 = 2000\ \Omega$$

Now $$R_1 R_4 = 100 \times 2000 = 200000$$

$$R_2 R_3 = 200 \times 1000 = 200000$$

For $R_4 = 2000\ \Omega$, the bridge is balanced. But there is unbalance of 5 Ω in the resistance of arm BD i.e. R_4.

$$R_4 = 2000 + 5 = 2005\ \Omega$$

Due to this imbalance current will flow through the galvanometer.

By Thevenin's equivalent,

$$V_{TH} = E\left[\frac{R_3}{R_1 + R_3} - \frac{R_4}{R_2 + R_4}\right]$$

$$= 10\left[\frac{200}{100+200} - \frac{2005}{1000+2005}\right]$$

$$= 10\,[0.6667 - 0.6672]$$

$$= \mathbf{-5.213\ mV}$$

The negative sign indicates that D is more positive than C.

$$R_{eq} = \frac{R_1 R_3}{R_1 + R_3} + \frac{R_2 R_4}{R_2 + R_4}$$

$$= \frac{100 \times 200}{(100+200)} + \frac{1000 \times 2005}{(1000+2005)}$$

$$= \mathbf{733.888\ \Omega}$$

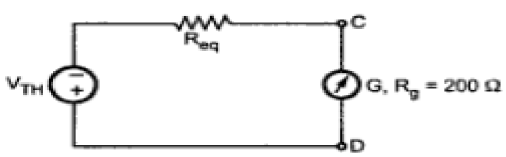


Fig. 4.56 (a)

Hence Thevenin's equivalent is,

$$\therefore \quad I_g = \frac{V_{TH}}{R_{eq} + R_g}$$

$$= \frac{5.213 \times 10^{-3}}{733.888 + 200}$$

$$= \mathbf{5.582\ \mu A}$$

Now deflection of galvanometer is proportional to its sensitivity.

$$S = \frac{D}{I}$$

$$\therefore \quad D = S \times I = 12\ \text{mm}/\mu\text{A} \times 5.582\ \mu\text{A}$$

$$= \mathbf{66.98\ mm}$$

4)

Example No. : *The four arms of the Wheatstone bridge have the following resistances, AB = 1000 Ω, BC = 1000 Ω, CD = 120 Ω, DA = 120 Ω. The bridge is used for strain measurement and supplied from 5 V ideal battery. The galvanometer has sensitivity of 1 mm/ μA with internal resistance of 200 Ω. Determine the deflection of the galvanometer if arm DA increases to 121 Ω and arm CD decreases to 119 Ω.*

Solution : The bridge given is shown in the Fig.

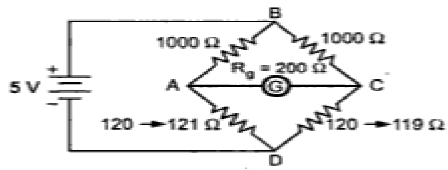


Fig.

Now $R_1 = 1000\ \Omega,\quad R_2 = 1000\ \Omega$

$R_3 = 121\ \Omega,\quad R_4 = 119\ \Omega$

Let us calculate Thevenin's equivalent due to change in R_3 and R_4.

$$V_{TH} = E\left[\frac{R_3}{R_1+R_3} - \frac{R_4}{R_2+R_4}\right]$$

$$= 5\left[\frac{121}{1000+121} - \frac{119}{1000+119}\right]$$

$$= 5\,[0.1079 - 0.1063]$$

$$= \mathbf{7.975\ mV}$$

$$R_{eq} = \frac{R_1 R_3}{R_1+R_3} + \frac{R_2 R_4}{R_2+R_4}$$

$$= \frac{121\times1000}{121+1000} + \frac{119\times1000}{119+1000}$$

$$= 107.9393 + 106.3449$$

$$= \mathbf{214.2842\ \Omega}$$

Thevenin's equivalent circuit is,

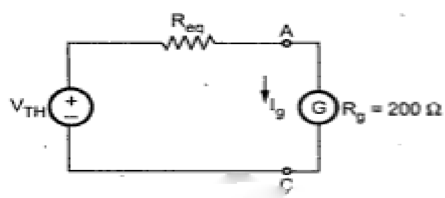


Fig.

$$I_g = \frac{V_{TH}}{R_{eq}+R_g}$$

$$= \frac{7.975\times10^{-3}}{214.2842+200}$$

$$= \mathbf{19.24\ \mu A}$$

Now the deflection of the galvanometer is proportional to its sensitivity.

$$S = \frac{D}{I}$$

$$\therefore \quad D = S\times I = 1\ \text{mm}/\mu\text{A} \times 19.24\ \mu\text{A}$$

$$= \mathbf{19.24\ mm}$$

This is the deflection of the galvanometer.

Physical Variable

A quantity whose value varies when subjected to changes and may depend from system to system. The physical variables are the quantities required to be measured. All these quantities require primary detection elements to be converted into another analogous form which is acceptable by a later stage of the measurement system.

The variable may be either electrical or non-electrical quantities depending upon the condition or system we have to deal.

Physical variable can be classified as,

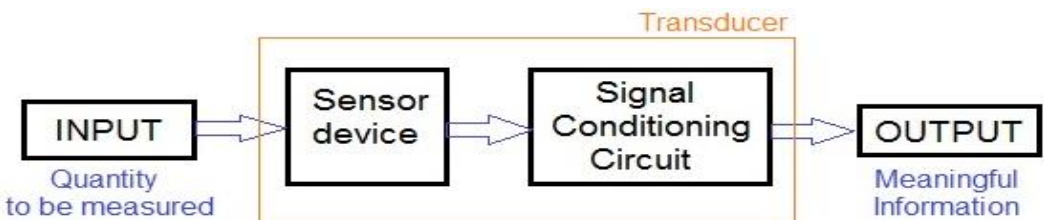
- Electrical Variable: E.g. Voltage, Current, Flux, Magnetic Field, Frequency.
- Mechanical Variable: E.G. Force, Torque, Weight, Displacement.
- Bio-physical Variable: E.g.

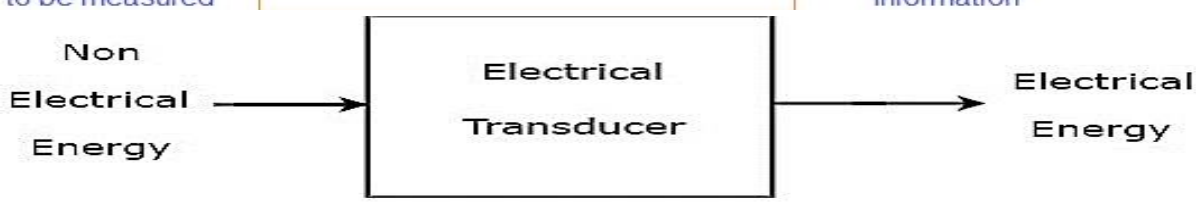
  ECG (Electro cardiogram): Records bioelectric potential of heart)

  EEG (Electroencephalogram): Electrical activity of brain)

  EMG (Electromyogram): Skeletal Muscle
- Sensor/Transducer converts one form of physical variable into another form.

Transducers



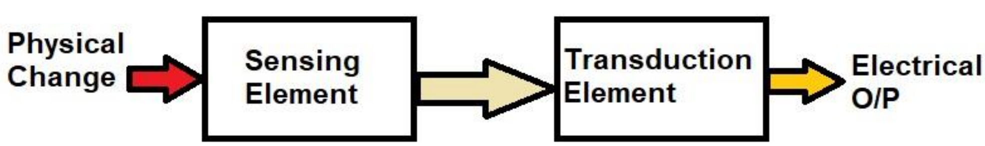


Transducer is a device which converts one form of energy into another form i.e,. the given non-electrical energy is converted into an electrical energy.

Transducers play an important role in the field of instrumentation and control engineering. Any energy in a process should be converted from one form into another form to make the communication from one rectification sector to another.

Working of Transducer

In general, **Transducer works on the principle of Transduction.** Whereas Transduction is the process of converting input physical quantities into proportional electrical output signal.



A Transducer uses sensors and signal conditioning unit to perform transduction function. In other words we can say that Transducer is the combination of sensor and signal conditioning unit.
The Sensor unit is responsible for detecting any changes in input physical quantities that has to be measured. The output of sensor is always non-electrical in nature.
Whereas signal conditioning unit converts output of sensor into an electrical signal proportional to the magnitude of input.

Transducers Types

1) On Whether an External Power Source is Required or not

Active Transducer : Active transducer is a device which converts the given non-electrical energy into electrical energy by itself i.e. does not need external source. E.g Piezoelectric Crystal, Photo-Voltaic Cell, Tacho-Generator, Thermocouples, Photovoltaic cell

Passive Transducers: Passive transducer is a device which converts the given non-electrical energy into electrical energy by external force. E.g. Capacitive, Resistive and Inductive Transducers

2) Based on Transduction Phenomenon

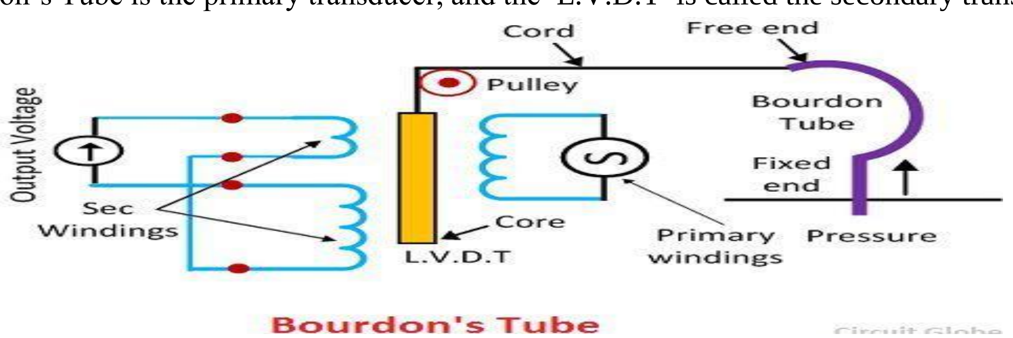
Transducers: Devices which convert a non-electrical quantity into an electrical quantity is popularly known as Transducers.

Inverse Transducers: Devices which convert an electrical quantity into non-electrical quantity is called Inverse Transducer. Example of Inverse transducers is piezoelectric crystal. When voltage across the surface of a piezoelectric crystal is applied, it changes its dimension. Another example is a coil carrying current and kept in magnetic field. Due to interaction of current of coil with the magnetic field, it starts to rotate or translate

3) Based on the Physical Phenomenon

Primary and Secondary Transducer:

Primary Transducer is the detecting or sensing element which responds to the change in physical phenomena, whereas the **Secondary Transducer** converts the output of primary transducer (output in the form of mechanical movement) into electrical output.
E.g. Consider the Bourdon's Tube shown in below. There are two type of transduction occurs in the Bourdon's tube. First, the pressure is converted into a displacement and then it is converted into the voltage by the help of the L.V.D.T.
The Bourdon's Tube is the primary transducer, and the L.V.D.T is called the secondary transducer.



4) Based on Quantity to be Measured/Application

- Temperature Transducers (e.g. a Thermocouple)
- Pressure Transducers (e.g. a Diaphragm)
- Displacement Transducers (e.g. LVDT)
- Humidity Transducer

5) Based on the Type of Output the Classification of Transducers are Made

Analog & Digital Transducer

Analog Transducer: Analog Transducers are those whose output is continuous in time domain. This essentially means that the electrical output signal will be continuous function of time. e.g. LVDT, Thermocouple, Strain Gauge & Thermistor

Digital Transducer: Transducers which convert the input quantity into an electrical output signal which is in the form of pulse is called Digital Transducers. Note that, the output is not continuous rather it is in the form of pulse which means that it is discrete. e.g. Shaft Encoders, Digital Resolvers, Digital Tachometers, Hall Effect Sensors & Limit Switches

6) On the Principle of Transduction/ Physical Principle Involved

- Resistive Transducer :
- Inductive Transducer:
- Capacitive Transducer:
- Piezoelectric Transducer:
- Thermoelectric Transducer:
- Hall Effect Transducer:

A) **Resistive Transducer**: Here, the input being measured into change into resistance. The resistive transducer converts the physical quantities into variable resistance. The change in resistance is measured by the ac or dc measuring devices. The resistive transducer is used for measuring the physical quantities like Temperature, Displacement, Vibration etc.

Eg: Potentiometer
Strain Gauge
Thermistor
Resistance Temperature Detectors (Rtd)

b) **Inductive Transducer**: Here, the input being measured into change into inductance. Inductive transducers work on the principle of inductance change due to any appreciable change in the quantity to be measured i.e. measured. A transducer that works on the principle of electromagnetic induction or transduction mechanism is called an inductive transducer. A self-inductance or mutual inductance is varied to measure required physical quantities like displacement (rotary or linear), force, pressure, velocity, torque, acceleration, etc. These physical quantities are noted as measurands.

e.g. Linear Variable Differential Transducer (LVDT)
Rotatory Variable Differential Transducer (RVDT)

c) **Capacitive Transducer**: Here, the input being measured into change into capacitance. in the capacitive transducer, the change in the capacitance is used to measure the physical quantities. Capacitive transducers are passive transducers that determine the quantities like displacement, pressure and temperature etc. by measuring the variation in the capacitance of a capacitor. In these transducers, the capacitance between the plates is varied because of the distance between the plates, overlapping of plates, due to dielectric medium change, etc.
e.g. Capacitive Displacement transducer

Working of Different Types of Transducer

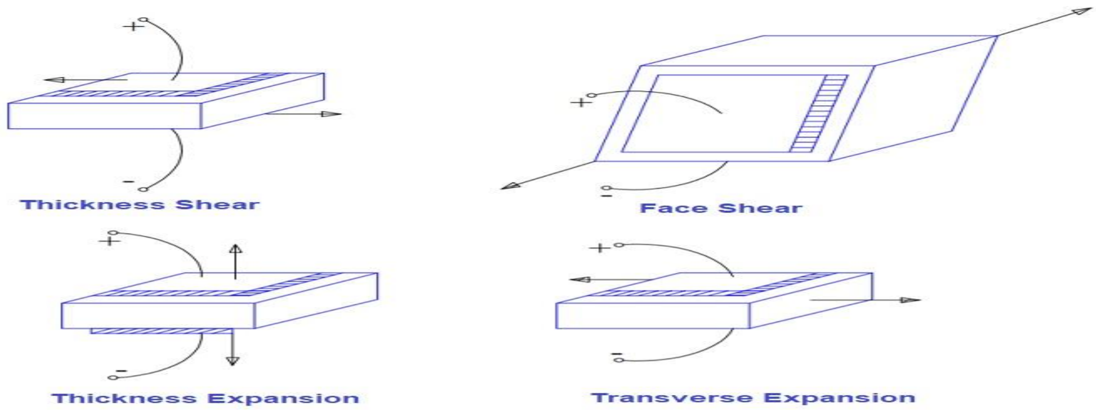
Piezoelectric Transducer:

The piezoelectric transducer is an active transducer that converts physical quantity (force or pressure or stress) into an electric potential. The piezoelectric transducer consists of a piezoelectric crystal made up of piezoelectric material which develops electrical potential across its surface on application mechanical stress. They are self-generating transducers.
The process is reversible which means if potential difference across some specified surface is changed, the dimension of the piezoelectric material will also change. This effect is known is ***Piezoelectric Effect***
The electrical energy generated is proportional to the application of mechanical force on the surface of the piezoelectric crystal. A charge will be produced on the surface of the crystal, these results in creating a potential difference between the two surfaces of the crystal thus inducing an electric potential.
Rochelle Salt, Ammonium Di-hydrogen Phosphate, Lithium Sulphate, Di-potassium tartarate, Quartz and Ceramic are common example of piezoelectric material.
Basically, there are two types of piezoelectric materials:

i) **Natural**: Quartz and Ceramic
ii) **Synthetic**: Lithium Sulphate, Ethylene diamine tartarate

Working Principle of Piezoelectric Transducer

When a mechanical force is applied on a piezoelectric crystal, a voltage is produced across its faces. Thus, mechanical phenomena is converted into electrical signal. Piezoelectric Transducer responds to the mechanical force / deformation and generate voltage. There may be various modes of deformation to which these transducers can respond. The modes can be: thickness expansion, transverse expansion, thickness shear and face shear.



Expression

- Due to this charge at the electrode, an output voltage E_o will be generated which can be given by

  $Eo = \frac{Q}{Cp}$ ………………..1)

  Where,

- The polarity of the charge depends on the direction of the applies forces.

  $Q = d \times F$ *(in coulombs)* …….(2)

  Where, F = Force applied in Newtons

  d = Charge sensitivity of the crystal.

- The young's modulus E can be defined as the ratio of stress to strain i.e.

  $Y = \frac{\text{Stress}}{\text{Strain}} = \frac{F/A}{\Delta t/t}$ where, t = thickness

- The force F causes a change in thickness of crystal,

  $F = Y \ \frac{\Delta t}{t} A$ ………3)

- Using equation 2) and 3)

  $Q = d \times F = d \times Y \ \frac{\Delta t}{t} A$ ……….4)

- Also, The capacitance formed by the electrodes and the piezoelectric material is given by Cp

  $Cp = \frac{\varepsilon A}{t}$……………..5)

- Due to this charge at the electrode, an output voltage E_o will be generated which can be given by

  - $Eo = \frac{Q}{Cp} = \frac{d \times Y \frac{\Delta t}{t} A}{\frac{\varepsilon A}{t}} = \frac{d \times Y \frac{\Delta t}{t} A}{\frac{\varepsilon o \varepsilon r A}{t}} = \frac{d}{\varepsilon o \varepsilon r} Y \Delta t$

    $= \frac{d}{\varepsilon o \varepsilon r} \frac{F/A}{\Delta t/t} \Delta t$

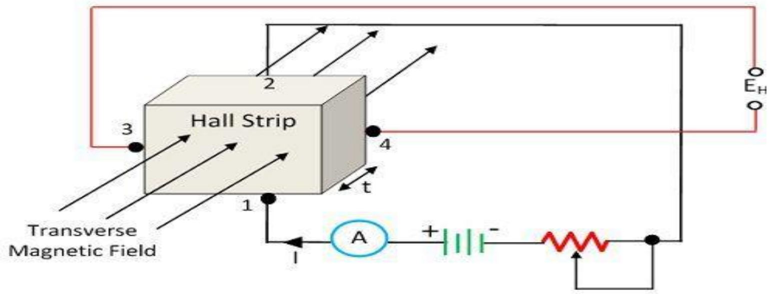
    $= \frac{d}{\varepsilon o \varepsilon r} \frac{F}{A} t$

    = g.p.t

Where, g is the voltage sensitivity of the crystals in Vm/N

Hall Effect Transducer

Hall Effect element is a type of transducer used for measuring the magnetic field by converting it into an emf. The principle of Hall Effect transducer is that if the current carrying strip of the conductor is placed in a transverse magnetic field, then the EMF develops on the edge of the conductor. The magnitude of the develop voltage depends on the density of flux, and this property of a conductor is called the Hall effect.



Consider the Hall Effect element shown in the figure below. The current supply through the lead 1 and 2 and the output is obtained from the strip 3 and 4. The lead 3 and 4 are at same potential when no field is applied across the strip.

When the magnetic field is applied to the strip, the output voltage develops across the output leads 3 and 4. The develops voltage is directly proportional to the strength of the material,

$$E_H = K_H \frac{I\,B}{t}$$

Where, K_H = Constant of proportionality called the Hall Effect Coefficient

"t" = T hickness of strip. I = current in ampere and the B is the flux densities in Wb/m^2

Thermoelectric Transducer

Thermoelectric conversion means the conversion of thermal energy to electric energy and vice versa. The following two transducers are the examples of thermo-electric transducers.

i) Thermistor Transducer

ii) Thermocouple Transducer

The term "thermoelectric effect" encompasses three separately identified effects:

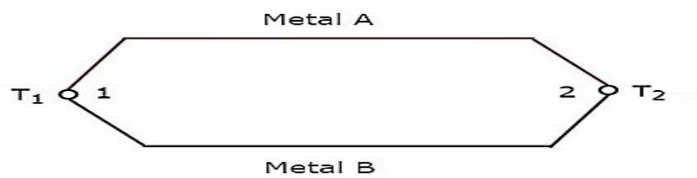
a) Seebeck Effect,

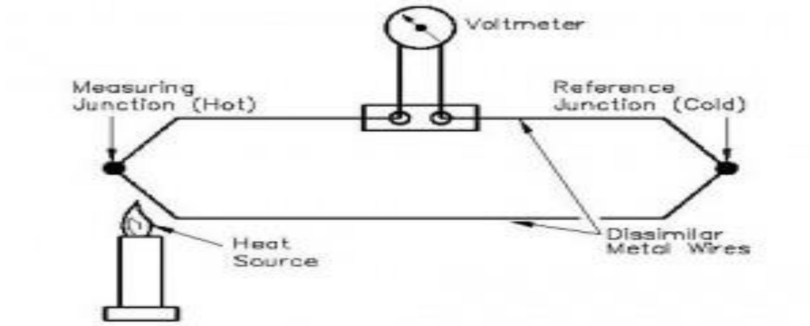
b) Peltier Effect, and

c) Thomson Effect.

Thermocouple

"Thomas Seebeck" revealed that when two different metal wires were linked at both ends of one junction in a circuit when the temperature applied to the junction, there will be a flow of current through the circuit which is known as electromagnetic field (EMF). The energy which is produced by the circuit is named the Seebeck Effect/**Seebeck voltage.**





The above thermocouple has two metals, A & B and two junctions, 1 & 2. Consider a constant reference temperature, T_2 at junction 2. Let the temperature at junction, 1 is $T1_1$. Thermocouple generates an **emf** (electro motive force), whenever the values of T_1 and T_2 are different.

That means, thermocouple generates an emf, whenever there is a temperature difference between two junctions, 1 & 2 and it is directly proportional to the temperature difference between those two junctions.

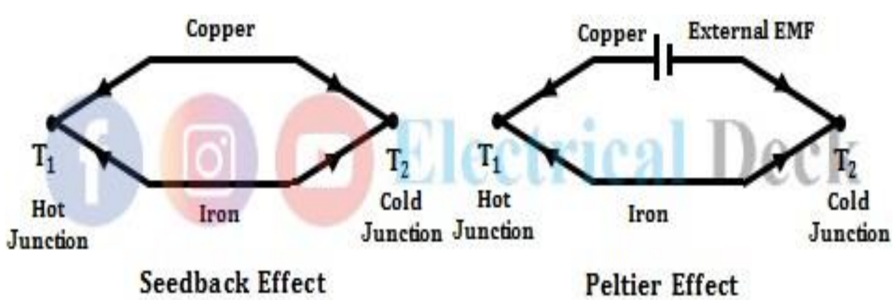
Mathematically, it can be represented as $E \alpha (T_1 - T_2)$ Where, e is emf generated by thermocouple. The electromagnetic force induced in the circuit is calculated by the following equation

$$\mathbf{E = a\,(\Delta\Theta) + b\,(\Delta\Theta)^2}$$

Where $\Delta\Theta$ = temperature difference among the hot thermocouple junction end as well as the reference thermocouple junction end, a & b are constants

<u>Thermocouple Working Principle</u>

The **thermocouple principle** mainly depends on the three effects namely Seebeck, Peltier, and Thompson.



See beck-effect

This type of effect occurs among two dissimilar metals. When the heat offers to any one of the metal wires, then the flow of electrons supplies from hot metal wire to cold metal wire. Therefore, direct current stimulates the circuit.

Peltier-effect

This Peltier effect is opposite to the Seebeck effect. This effect states that the difference of the temperature can be formed among any two dissimilar conductors by applying the potential variation among them.

Thompson-effect

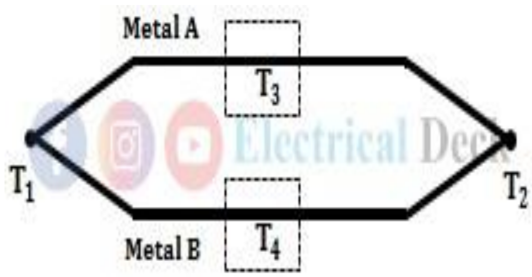
This effect states that as two disparate metals fix together & if they form two joints then the voltage induces the total conductor's length due to the gradient of temperature. This is a physical word that demonstrates the change in rate and direction of temperature at an exact position.

<u>List of error in Thermocouple</u>

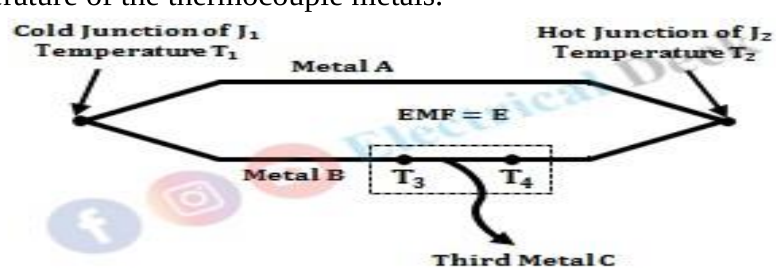
1) Open Junction
2) De-calibration
3) Insulation Degradation
4) Galvanic Action
5) Thermal Conduction

1) The **e.m.f. of a Thermocouple depends only on the Temperatures** of the junctions and is independent of the temperatures of the wires connecting the junctions. This means that the leads connecting the instrument can be exposed to temperature fluctuations without affecting the measurement.

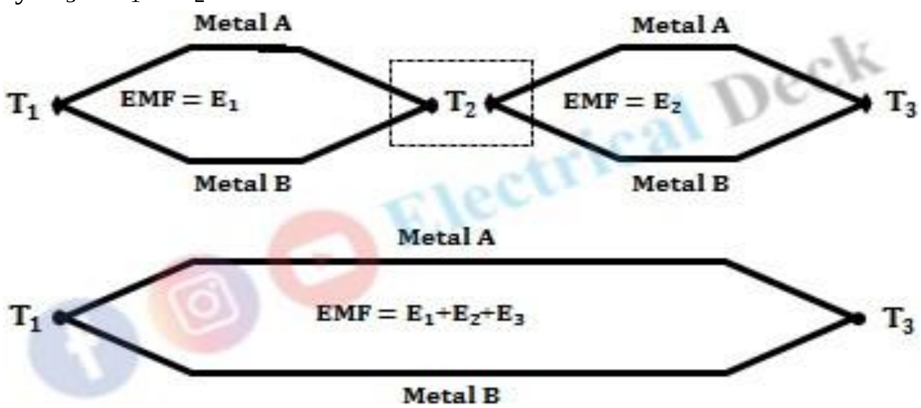
2) <u>Law of Homogeneous Circuits</u>: According to law of homogeneous circuits, an electric current can't flow in a circuit made of a single homogeneous metal when heat alone applied to it. In above Figure, a thermocouple is shown with junction temperatures at T1 and T2. Along the thermocouple wires, the temperature is T_3 and T_4. The thermocouple emf is, however, still a function of only the temperature gradient $T_2 - T_1$.



3) **<u>Law of Intermediate Metals</u>** :The law of intermediate metals states that the emf developed in a circuit made of two dissimilar homogeneous metals with the junctions at two different temperatures will not get affected when a third homogeneous metal is introduced into the thermocouple circuit as long as the temperature of the two junctions formed by the third metal is same as the temperature of the thermocouple metals.



4) **Law of Intermediate Temperatures** : The law of intermediate temperature states that the emf developed by a thermocouple having junctions at temperatures T_1 and T_3 is equal to the sum of emf's developed by two thermocouples having junctions at temperatures T_1 and T_2, T_2 and T_3 respectively. $E_3 = E_1 + E_2$

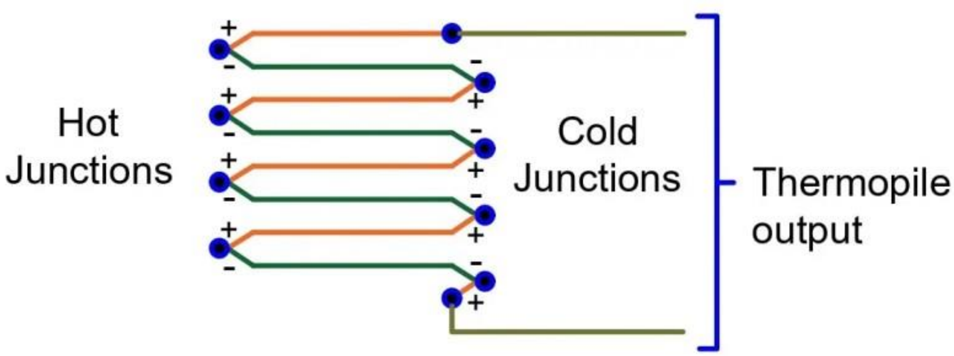


Thermopile

A thermopile is a temperature-measuring device that is made up of thermocouples and it converts thermal energy into electrical energy.

A thermopile is a type of temperature measurement device used in the field of instrumentation and control. It is used for measuring high temperatures. It consists of several thermocouples which are connected in the series. The junctions of several thermocouples are connected together to form a single sensing thermopile.

The thermocouples are connected in such a manner that all the 'hot junctions' voltages add to each other, as well as 'cold junctions' voltages. This series configuration of the thermocouples allows the thermopile to generate a larger output voltage as compared to a single thermocouple. Hence, it is suitable for measuring high temperatures.



The output voltage generated by a thermopile is calculated by using the following formula:

$$V = n * \varepsilon * \Delta T$$

where,

V is the output voltage

n is the total number of thermocouples connected in series in the thermopile

ε is the Seebeck coefficient of the metal which is used in the thermocouples

ΔT is the temperature difference that is present across the thermopile.

Temperature Transducers

▫ Thermocouples
▫ Resistance-Temperature Detectors (RTD)
▫ Thermistors

Resistance-Temperature Detectors (RTD)

An RTD (Resistance Temperature Detector) is a sensor whose resistance changes as its temperature changes i.e. used to determine the temperature by measuring the resistance of an electrical wire The resistance increases as the temperature of the sensor increases. The resistance vs temperature relationship is well known and is repeatable over time.

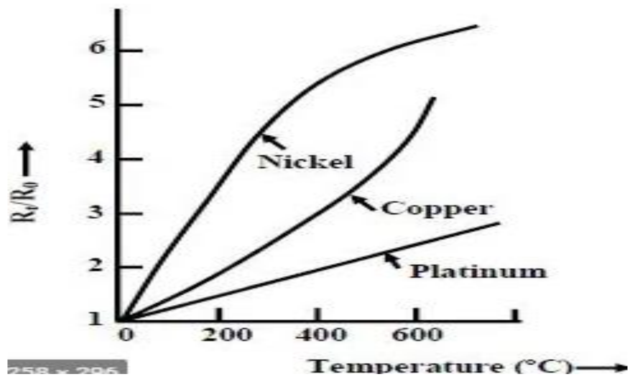
The variation of resistance of the metal with the variation of the temperature is given as

$$\mathbf{R_t = R_o[1+ \alpha\,(t - to) + \beta(t - to)^2 + \ldots\ldots\ldots.]}$$

Where, R_t and R_0 are the resistance values at t^oC and $t_0{}^oC$ temperatures. α and β are the constants depends on the metals.

The element of an RTD sensor is the sensing component that changes in resistance when there is a change in temperature. The most common element is platinum. Other element metals are Copper, Nickel, Tungsten, Balco, and Iridium.

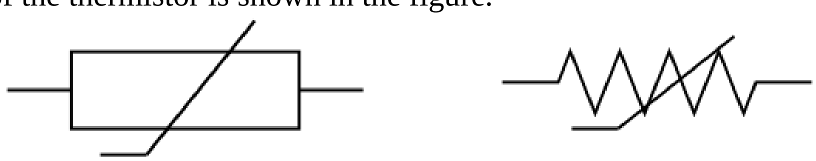
Resistance-temperature characteristics curve of the three different metals is shown below



Thermistors

The Thermistor or simply **Therm**ally Sensitive Res**istor** is a temperature sensor that works on the principle of varying resistance with temperature. Although all resistors' resistance will fluctuate slightly with temperature, a thermistor is particularly sensitive to temperature changes..

The circuit symbol of the thermistor is shown in the figure.



They are made of semiconducting materials of oxides of metals such as Nickel, Manganese, Cobalt, Copper, Uranium etc. Thermistors are a type of semiconductor, meaning they have greater resistance than conducting materials, but lower resistance than insulating materials. The relationship between a thermistor's temperature and its resistance is highly dependent upon the materials from which it's composed.

The working principle of a thermistor is that its resistance is dependent on its temperature. We can measure the resistance of a thermistor using an ohmmeter.
Thermistors are available in two types:

Negative Temperature Coefficients (NTC thermistors)

Positive Temperature Coefficients (PTC thermistors).

Negative Temperature Coefficients (NTC thermistors): NTC thermistors' resistance decreases as their temperature increases and vice-versa. Hence in an NTC thermistor temperature and resistance are inversely proportional. The relationship between resistance and temperature in an NTC thermistor is governed by the following expression:

$$R_T = R_o e\, \beta \left(\frac{1}{T} - \frac{1}{To} \right)$$

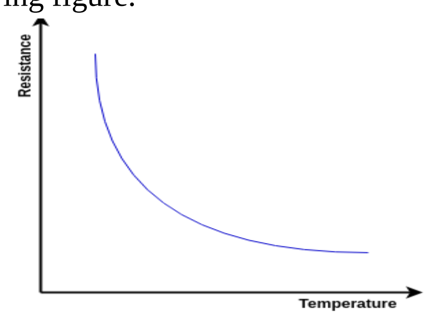
Where, R_T = Resistance at temperature T (K) R_0 = Resistance at temperature T_0 (K)

T_0 = Reference temperature (normally 25°C)

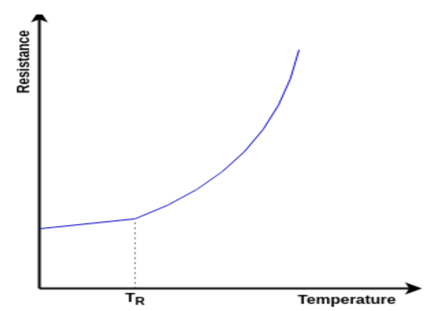
β is a constant, its value is dependent on the characteristics of the material. The nominal value is taken as 4000.

Only NTC thermistors are commonly used in temperature measurement. As the temperature increases, an NTC thermistor's resistance will increase in a non-linear fashion, following a particular "curve." The shape of this resistance vs. temperature curve is determined by the properties of the materials that make up the thermistor.

Positive Temperature Coefficients (PTC thermistors): PTC thermistors' resistance increases as their temperature increases and when temperature decreases, resistance decreases. Hence in a PTC thermistor temperature and resistance are inversely proportional.
Although PTC thermistors are not as common as NTC thermistors, they are frequently used as a form of circuit protection. Similar to the function of fuses, PTC thermistors can act as current-limiting device. The temperature resistance characteristics of an NTC and a PTC are shown in the following figure.



NTC Characteristics



PTC Characteristics

Q) Among RTD, Thermocouple and thermistor, which one you used for linear scale measurement?
Ans, RTD???

Measurement of Mechanical Variables (Displacement, Strain. Velocity. Acceleration and Vibration)

Measurement of mechanical variables, including displacement, strain, velocity, acceleration, and vibration, plays a crucial role in various fields such as engineering. These are described below.

1. **Displacement**: Displacement refers to the change in position of an object from its original reference point. Displacement transducer/sensors includes such as **linear variable differential transformers (LVDTs), potentiometers**.

2. **Strain**: Strain is the measure of deformation or elongation experienced by an object when subjected to external forces or stress. It indicates how much an object's shape changes under the applied load. Strain is typically measured as a dimensionless quantity or expressed as a percentage change in length. **Strain gauges**, which are devices that change their electrical resistance in response to strain, are commonly used to measure strain accurately.

3. **Velocity**: Velocity is the rate of change of displacement over time. It indicates how fast an object is moving and in which direction. Various instruments which can measure velocity, includes **Doppler radar, anemometers, and tachometers**.

4. **Acceleration**: Acceleration is the rate of change of velocity over time. It represents how quickly an object's velocity is changing. Acceleration is also a vector quantity and is typically measured in units such as meters per second squared (m/s^2) or gravitational acceleration (g). Accelerometers are widely used to measure acceleration in applications such as vehicle dynamics, structural analysis, and motion tracking.

5. **Vibration**: Vibration refers to the oscillating or vibrating motion of an object around its equilibrium position. Vibration measurement involves analyzing the frequency, amplitude, and other characteristics of the vibration. Vibration sensors, such as **accelerometers or piezoelectric sensors** are commonly used to measure and analyze vibrations in machines, structures, and various mechanical systems.

Measurement of Process Variables - (Temperature Pressure, Level, Fluid Flow, Chemical Constituents in Gases or Liquids, pH and Humidity)

Measurement of process variables such as temperature, pressure, level, fluid flow, chemical constituents in gases or liquids, pH, and humidity is essential in various industrial processes, laboratories, and environmental monitoring. Here's an overview of these measurements:

Temperature: Temperature measurement is crucial in a wide range of applications. It is typically measured using temperature sensors such as **thermocouples, resistance temperature detectors (RTDs), or thermistors**.

Pressure: Pressure measurement is used to monitor and control the pressure of gases or liquids in different processes. Pressure sensors or transducers, such as **pressure gauges, manometers, or pressure transmitters**, are commonly employed for measuring pressure.

Level: Level measurement is used to determine the height or volume of liquids, solids, or slurries in containers or tanks. Various techniques are employed for level measurement, **including float switches, capacitance sensors, ultrasonic sensors, and radar sensors.**

Fluid Flow: Measurement of fluid flow is crucial in processes that involve the transportation or control of fluids. Flow meters, such as **electromagnetic flow meters, turbine flow meters, or thermal mass flow meters**, are commonly used to measure the flow rate of liquids or gases.

Chemical Constituents: Measurement of chemical constituents in gases or liquids is necessary for quality control, process optimization, and safety purposes. Techniques such as **gas chromatography, spectrophotometry, or titration** are used to measure the concentration or composition of specific chemicals or compounds.

pH: pH measurement is used to determine the acidity or alkalinity of a solution. **pH meters or electrodes** are employed to measure the hydrogen ion concentration in a solution, providing information about its chemical properties. pH is typically measured on a scale from 0 to 14.

Humidity: Humidity measurement is used to determine the moisture content or water vapor concentration in the air or gases. **Hygrometers**, such as **capacitive** or **resistive humidity sensors**, are commonly used to measure relative humidity (RH) expressed as a percentage.

Measurement of Bio-Physical Variables Blood Pressure & Myoelectric Potentials

Measurement of bio-physical variables such as blood pressure and myoelectric potentials is important in medical diagnostics, research, and monitoring. Here's an overview of these measurements:

Blood Pressure: Blood pressure is a measure of the force exerted by circulating blood against the walls of blood vessels. It is typically expressed as two values: systolic pressure and diastolic pressure. Systolic pressure represents the maximum pressure in the arteries during a heartbeat, while diastolic pressure represents the minimum pressure between heartbeats. Blood pressure is measured using devices called sphygmomanometers, which can be manual (mercury or aneroid) or digital.

Myoelectric Potentials: Myoelectric potentials refer to the electrical signals generated by **muscle activity**. These signals can provide insights into muscle function, activity, and health. Two common types of myoelectric measurements are **Electromyography (EMG) and Electroneurography (ENG).**

Electromyography (EMG): EMG measures the electrical activity produced by **skeletal muscles** during contraction and relaxation. It involves placing surface electrodes or needle electrodes into the muscle of interest. EMG signals can help diagnose and assess muscle disorders, nerve injuries, and neuromuscular diseases.

Electroneurography (ENG): ENG measures the electrical activity in peripheral nerves that control **muscle movement**. It involves **stimulating a nerve and recording the electrical response**. ENG can be used to diagnose and assess nerve damage, such as peripheral neuropathy or nerve entrapment syndromes.

EMG and ENG measurements are typically performed using specialized equipment that amplifies and records the electrical signals generated by muscles and nerves. The recorded signals are then analyzed to evaluate muscle and nerve function.

Calibration and Error in Transducer

The accuracy of the measurement depends upon various factors. The equipment used for measurements can lose their precision when used at higher temperatures, high moisture or humidity conditions, subjected to degradation, subjected to external shocks, etc…This can be observed as the error in the measurement. To tackle this error and make necessary changes to the equipment calibration methods are used. Calibration plays a crucial role in removing the errors in sensor measurements and increasing the performance of the sensor.

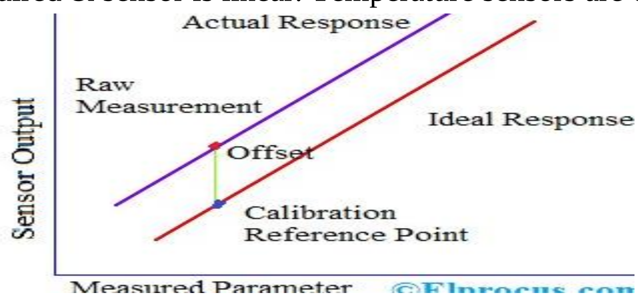
Sensor calibration is an adjustment or set of adjustments performed on a sensor or instrument to make that instrument function as accurately, or error free, as possible.

Calibration Methods

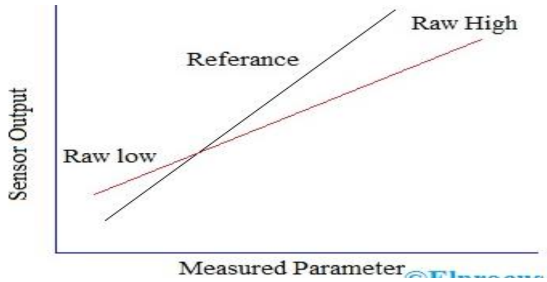
There are three standard calibration methods used for sensors. They are-

- One Point Calibration.
- Two-Point Calibration.
- Multi-Point Curve Fitting.

One Point Calibration is used to correct the sensor offset errors when accurate measurement of only a single level is required & sensor is linear. Temperature sensors are one point calibrated.



Two-Point Calibration is used to correct both slope and off-set errors. This calibration is used in the cases when the sensor we know that the sensor output is reasonably linear over a measurement range. Here two reference values are needed- reference High, reference Low.



Multi-Point Curve fitting is used for sensors that are not linear over the measurement range and require some curve-fitting to get the accurate measurements. Multi-point curve fitting is usually done for thermocouples when used in extremely hot or extremely cold conditions.

Errors Seen in Sensors/Transducers

- Due to improper zero-reference
- Errors due to shifts in sensor range,
- Error due to mechanical damage/wear
- Scale Error
- Error on account of noise and drift
- Errors due to change in frequency.

Numerical

1) **A Linear Resistance potentiometer is 50mm long & is uniformly wound with a wire having a resistance of 10,000Ω. Under normal conditions, the slider is at the center of the potentiometer. Find the linear displacement when the resistances of the potentiometer as measured by Wheatstone bridge for two cases are; (a) 3850Ω (b) 7560Ω.**
Are the two displacements in same direction if it is possible to measure a minimum value of 10Ω resistance with the above arrangement, find the resolution?
Ans.
The resistance at normal position = 10000/2 = 5000Ω
Resistance of potentiometer per unit length = 10000/50 = 200Ω/mm
a. Change of resistance form normal position = 5000 – 3850 =1150Ω
Therefore, Displacement of slider from its normal position = 1150 200 = 5.75mm
b. Displacement = (7560−5000)/200 = 12.8mm
Resolution = minimum × 1/200 = 0.05mm

2) **A capacitive transducer uses two quartz diaphragms of area 750 mm^2 separated by a distance of 3.5 mm. a pressure of 900 KN/m^2 when applied to the top diaphragm produces a deflection of 0.6 mm. the capacitance is 370 pF when no pressure applied to the diaphragms. Find the value of capacitance after the application of a pressure of 900kN/m^2.**

Solution:

Suppose C_1 and C_2 are respectively the values of capacitance before and after application of pressure.

Let d_1 and d_2 be the values of distances between the diaphragms for the corresponding pressure conditions.

$C_1 = \in A/d_1$

And $C_2 = \in A/d_2$

Or, $C_2/C_1 = d_1/d_2$

$\therefore C_2 = C_1 \times d_1/d_2$

But d_1 = 3.5mm and d_2 = 3.5-0.6 = 2.9mm

$\therefore$ Value of capacitance after application of pressure $C_2 = 370 \times 3.5/2.9 = 446.5$ pF

3) **A capacitive transducer is made up of two concentric cylindrical electrodes. The outer diameter of the inner diameter is 3mm and the dielectric medium is air. The inner diameter of the outer electrode is 3.1 mm. Calculate the dielectric stress when a voltage of 100 V is applied across the electrodes. Is it within safe limits? The length of electrodes is 20mm. calculate the change in capacitance if the inner electrode is moved through a distance of 2mm. The breakdown strength of air is 3kV/mm.**

Solution:

Length of air gap between the two electrodes, lg = (3.1- 3)/2 = 0.05mm.

$\therefore$ Dielectric stress = 100/0.05 = 2000 V/mm = 2 kV/mm.

The breakdown strength of air is 3kV/mm and hence the dielectric is safe.

Capacitance of the transducer C = $(2\pi\epsilon l)/ \log(D2/D1)$

$= (2\pi \times 8.85 \times 10^{-12} \times 20 \times 10^{-3}/(\log e(3.1/3)$ F

= 33.9 Pf.

The moving is electrode is shifted through a distance of 2mm.

$\therefore$ l = 20-2 = 18mm

New value of capacitance = $(2\pi \times 8.85 \times 10^{-12} \times 18 \times 10^{-3}) / (\log(3.1/3)$

= 30.5 pF

$\therefore$ Change in value of capacitance ΔC = 33.9-30.5 = 3.4 Pf.

4) **The output of an LVDT is connected to a 10 V voltmeter through an amplifier with a gain of 250. The voltmeter scale has 100 divisions and the scale can be read up to $1/5^{th}$ of a division. An output of 2 mV appears across the terminals of the LVDT, when core is displaced through a 0.5 mm. Determine the following:**

i) Sensitivity of the measuring system

ii) Resolution of instrument

Solution

Given that

The output voltage of LVDT: V_0 = 2 mV

Displacement = 0.5 mm

Sensitivity of LVDT = $\frac{V_0}{Displacement} = \frac{2mV}{0.5mm} = 4mV/mm$

Sensitivity of measuring system =Amplification factor x Sensitivity of LVDT

= 250 x 4 mV/mm = 1000 mV/mm or 1 V/mm.

Full-scale of voltmeter = 0 - 10 V

No. of divisions on voltmeter scale = 100

1 Scale division = 10 / 100 = 0.10 V or 100 mV

Minimum voltage that can be read on voltmeter = $\frac{100mV}{5} = 20mV$

$$Resoluton\ of\ instrument = \frac{20mV}{1000mV/mm} = 0.02$$

5) **A strain gauge having a resistance of 200 Ω and a gauge factor of 2.5 is connected in series with a load resistance of 400 Ω across 24 V. Determine the change in o/p voltage when a stress of 140 mgf/m^2 is applied. The modulus of elasticity is 200 GN/m^2.**

Soln.

Voltage across strain gauge = $24 \times \frac{200}{200+400} = 8$ V

Strain $\varepsilon = \frac{\text{Stress}}{\text{Modulus of elasticity}} = \frac{140*10^{-3}}{200}$

$$\frac{\Delta R}{R} = \frac{\rho}{\varepsilon}$$

$$\frac{\Delta R}{R} = G\,F\,\frac{\Delta l}{l}$$

$$\frac{\Delta l}{l} = = \frac{\text{Stress}}{\text{Modulus of elasticity}} = \frac{140*10^{-3}}{200}$$

$\therefore \frac{\Delta R}{R} = 0\ 007$

ΔR = R × E × G = 200 × .0007 × 2.5 = 0.35 Ω

Voltage across strain gauge under

Strained conditioned = $24 \times \frac{200+0.35}{200+0.35+400} = 8.00933$.

Change in o/p voltage = 8.00933 − 8 = 0.00933 = 9.33 mV

6) **A platinum resistance thermometer has a resistance of 120 Ω at 25°C. Determine its resistance at 75°C. The temperature coefficient of resistance is 0.00392 at 25°C. If the resistance 180 Ω, what is temperature T_3?**

Solution

Resistance at 25°C, R_1 = 120 Ω α_T = 0.00392

$R_2 = R_1 [1 + \alpha_T [T_2 - T_1]]$ **Note: temperature in RTD must be in °C.**

= 120[1 + 0.00392(75 − 25)] = 143.52 Ω

for 180 Ω, temp T_3 = ?

$R_3 = R_1[1 + \alpha_T(T_3 - T_1)]$

$= 120\ (1 + 0.00392(T_3 - 25))$

$T_3 = \frac{180/120 - 1}{0.00392} + 25 = 152.55°C$

7) **In a variable inductive transducer, the coil has an inductance of 2.5 mH when the effective turns on the coil arc are 50. Determine the inductance of the coil when the effective turns on the coil are 52.**

Solution

No. of turns on the coil, N1 = 50

L1 = 2.5 mH

N2 = 52

We have, $L \propto N^2$

$L_2 = L_1 \times \frac{N2^2}{N1^2} = 2.7$ mH

8) **A thermistor used for temperature measurement has □=3140 K and the resistance at 27°C is 1050 ohms. If the resistance of the thermistor is measured as 2330 ohms, find the temperature.**

Solution

The resistance-temperature characteristic of the thermistor is given by:

$$R = R_0\, exp\left[\beta\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

As per the data given in the statement:

$R_0 = 1050$ ohm

$T_0 = 273 + 27 = 300$ K **Note: temperature thermistor must be in kelvin**

□ = 3140 K

R = 2330 ohm

Taking the logarithm of both sides of equation and rearranging we get,

$$\frac{1}{T} = \frac{In\ R - LnR_0}{\beta} + \frac{1}{T_0}$$

$$= \frac{7.754 - 6.957}{3140} + \frac{1}{300}$$

$$= 3.587 \times 10^{-3}$$

So, T = 278.78 K

9) **A barium Titanate pickup has dimensions of 5mm × 5*mm* × 1.25*mm*. The force acting on it is 5 N. The charge sensitivity of barium Titanate is 150pC/N and its permittivity is 12.5×10-9 F/m. If the modulus of elasticity of Barium Titanate is $12\times10^6 N/m^2$, calculate the strain. Also calculate the charge and the capacitance.**

Soln:

Solution: Area of plates $A = 5\times5\times10^{-6} = 25\times10^{-6}\ m^2.$

Pressure $P = 5/(25*10^{-6}) = 0.2\ MN/m^2.$

Voltage sensitivity $g = \frac{d}{\epsilon_o\epsilon} = \frac{150\times10^{-12}}{12.5\times10^{-9}} = 12\times10^{-3} Vm/N,$

Voltage generated $E_0 = g\ t\ P = 12\times10^{-3} \times 1.25\times10^{-3} \times 0.2 \times 10^6 = 3\ V.$

Strain $\in = \Delta t = \frac{sterss}{young'smodulus} = \frac{0.2\times10^6}{12\times10^6} = 0.0167,$

Charge $Q = dF = 150\times10^{-12} \times 5\ C = 750\ pC.$

Capacitance $C_p = \frac{Q}{E0} = \frac{750\times10^{-12}}{3} F = 250 Pf.$

Example - Ex The output of an LVDT is connected to a 5 volt voltmeter through an amplifier whose amplification factor is 250. An output of 2 mv appears across the terminals of LVDT when the core moves through a distance of 0.5 mm. Calculate the sensitivity of the LVDT and that of the whole set up. The milli voltmeter scale has 100 divisions. The scale can be read to 1/5 of a division. Calculate the resolution of the instrument in mm.

Solution:

Given, output voltage, E_0 = 2 mV, displacement = 0.5 mm

∴ Sensitivity of LVDT $= \frac{2\times10^{-3}}{0.5}$ V/mm $= 4 \times 10^{-3}$ V/mm

Also, sensitivity of the whole setup/instrument = Amplification factor * sensitivity of LVDT

$= 4\times10^{-3}\times250 = 1$ V/mm

Now, One scale division $= \frac{5}{100}$ V = 50 mV

Minimum voltage that can be read on the voltmeter $= \frac{1}{5}\times50 = 1$ mV

∴ Resolution of instrument $= 1\times\frac{1}{1000} = 10^{-3}$ mm

Example -m-le - A metallic strain gauge has a resistance of 120 Ω and a gauge factor of 2. It is installed on an aluminium structure which has a yield point stress of 0.2 GN/m² and Young's modulus of 68.7 GN/m². Determine the change in the resistance of the gauge that would be caused by loading the material to yield point.

Solution:

Given, $R = 120\ \Omega$, $G_f = 2$, stress = 0.2 GN/m², $Y = 68.7$ GN/m²

We know that, Young's modulus,

$$Y = \frac{\text{stress}}{\text{strain}}$$

or, $$\text{Strain} = \frac{\text{stress}}{Y} = \frac{0.2}{68.7} = 2.9\times10^{-3} = \frac{\Delta L}{L}$$

Also, Gauge factor, $$G_f = \frac{\Delta R/R}{\text{strain}} \quad \text{or} \quad \frac{\Delta R}{R} = G_f \times \text{strain}$$

or, $$\Delta R = G_f \times \text{strain} \times R$$
$$= 2\times2.9\times10^{-3}\times120 = 0.696\ \Omega = 0.7\ \Omega$$

∴ Charge in the resistance = 0.7 Ω

Exercise

1) A variable potential divider bas a total resistance of 2 kΩ and is fed from a 10 V supply. The output is connected across a load resistance of 5 kΩ. Determine the loading error for the slider positions corresponding to x_i/x_t = 0, 0.25, 0·5, 0·75 and 1.0. Use the results to plot a rough graph of loading error against the ratio x_i/x_t .

2) A compressive force is applied to a structural member. The strain is 5 micro-strain. Two separate strain gauges are attached to the structural member, one is a nickel wire strain gauge having a gauge factor of –12.1 and the other is nichrome wire strain gauge having a gauge factor of 2. Calculate the value of resistance of the gauges after they are strained. The resistance of strain gauges before being strained is 120 Ω.

3) A capacitive transducer is made up of two concentric cylindrical electrodes. The length of the electrodes is 25mm, the inner diameter of outer cylinder electrodes is 4.2 mm and the outer diameter of inner cylindrical electrode is 4mm. Determine the sensitivity of transducer. Determine also the dielectric stress when a voltage of 150V is applied across the electrodes. For a displacement of inner electrodes of 2.5 mm, determine the change in capacitance. Assume air as medium. Take the breakdown strength of air is 3kV/mm.

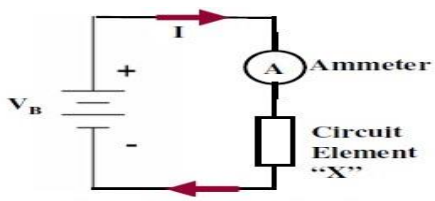
4) The output of LVDT is connected to a 5 V voltmeter through an amplifier whose amplification factor is 100. An output of 5 mV appears across the terminals of LVDT, when the core moves through a distance of 0.5 mm. Calculate the sensitivity of LVDT and that of whole setup. The milli-voltmeter scale has 100 divisions. The scale can be read to 1/5 of a division. Calculate the resolution of instrument in mm.

5) The resistance of thermistor at 27^{o}C is 1050 ohms with constant β = 3140. Calculate the value of temperature when the thermistor resistance becomes 2330 ohms in ^{o}C and kelvin scale.

Measurement of Voltage & Current (Moving Coil & Moving Iron Instruments)

Measuring Current: Ammeters

To measure current, the circuit must be broken at the point where we want that current to be measured, and the ammeter inserted at that point. In other words, an ammeter must be connected in series with the load under test.

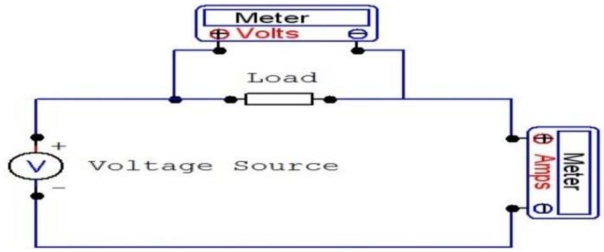


Current Measurement

It is very important that the insertion of the ammeter into a circuit has little effect the circuit's existing resistance and, thus, alter the current normally flowing in the circuit, ammeters are manufactured with very low values of internal resistance. Because ammeters have a very low internal resistance, it is vitally important that they are never inadvertently connected in parallel with any circuit component —and especially with the supply. Failure to do so will result in a short-circuit current flowing through the instrument which may damage the ammeter (although most ammeters are fused) or even result in personal injury.

Measuring Voltage: Voltmeters

To measure potential-difference, or voltage, a voltmeter must be connected between two points at different potentials. In other words, a voltmeter must always be connected in parallel with the part of the circuit under test.



In order to operate, a voltmeter must, of course, draw some current from the circuit under test, and this can lead to inaccurate results because it can interfere with the normal condition of the circuit. We call this the loading effect and, to minimize this loading effect' (and, therefore, improve the accuracy of a reading), this operating current must be as small as possible and, for this reason, voltmeters are manufactured with a very high value of internal resistance —usually many megohms

The classification of ammeter and voltmeter based on effect is as follows.

- Moving Coil Instruments
  Permanent Magnet Moving Coil [PMMC] instrument
  Electrodynamic or Dynamometer types instrument
- Moving Iron Instruments
  Attraction type M.I. instrument
  Repulsion type M.I. instrument

Moving-Coil Meters

Figure is an exploded view of a moving-coil movement. It can be seen that a coil free to rotate is suspended in the field of a permanent magnet. The coil ends are connected to a suspension system so that current can be passed through the coil.

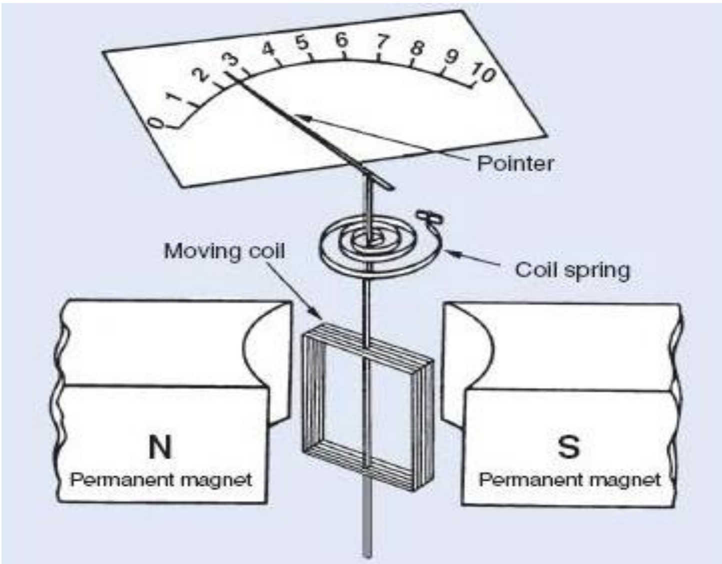


Figure: Exploded view of a moving-coil movement

The suspension system may consist of one of two methods:

1. A coiled spring as shown in **Figure**. Sometimes called a hair spring, the outer end is attached to an adjustable arm so that the pointer of the movement can be adjusted to align itself up with the zero on the meter scale.
2. The second method is called 'taut band suspension' and is considered a more robust method for suspending the moving coil. With this method the rigid coil pivot is replaced with two separate thin metal strands under tension. The hair springs are no longer necessary so are usually removed. Zero adjustment of the meter is achieved by a similar movable arm attached to one of the bands.

It must be noted that a current is passed through the coil—not a voltage. The current that flows through the coil is governed by the value of the applied voltage. The coil sets up its own field which reacts with that of the permanent magnet and causes the coil to rotate. A pointer attached to the coil gives a voltage reading against a scale.

The meter movement can only work satisfactorily on direct current. If AC is applied to the movement, it tries to turn the coil rapidly in the opposite directions with the result that the coil effectively remains stationary.

The meter can only operate on AC if the AC is rectified to DC before it flows through the meter. Because of these factors, the moving-coil meter always reads average values of current.

Moving-Iron Instruments

Figure shown is an exploded view of a moving-iron meter to illustrate its operating principle.

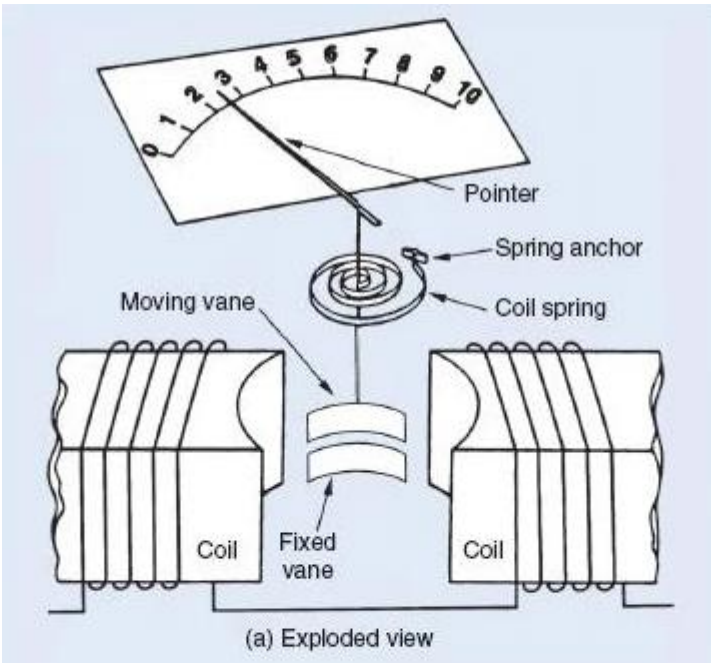


Figure: Moving-iron instrument/meter exploded view, construction, and non-linear scale

There are two magnetically soft iron vanes in the movement. One vane is fixed and the other pivoted and free to rotate. A pointer attached to the moving vane moves across a scale as an indicator.

When an electric current is passed through the coil, both the fixed and moving vanes are magnetized and have like poles at adjacent ends. Like poles repel each other and the movable vane moves away from the fixed vane. The attached pointer then indicates a value against a calibrated scale.

A restraining spring provides opposing torque so that the vane movement can be stabilized.

Like the moving-coil instrument, the moving-iron meter is current operated. The current that flows through the coil is governed by the applied voltage.

As a voltmeter, the coil impedance is very low when compared with the required series resistance. Consequently the meter movement can be considered as resistive only and the current through the meter is directly proportional to the applied voltage (**Ohm's law**).

The meter will operate on both DC and AC, although it might need to be calibrated differently. Because the two vanes are magnetized by the same current, the moving-iron meter operates on root-mean-square (RMS) values of current.

Measurement of Low, High & Medium Resistances

Depending upon the value of resistance they are classified into three categories,

Low Resistance - Resistance of the order of 1Ω and below are classified as low resistance.

Medium Resistance - Resistance ranging from 1Ω to 100Ω are classified as medium resistances

High Resistance - Resistance of the order of 100kΩ and above are classified as high resistances

Different techniques are applied for measurement of low, medium, and high values of resistances.

Measurement of Low Resistance (<1Ω) :

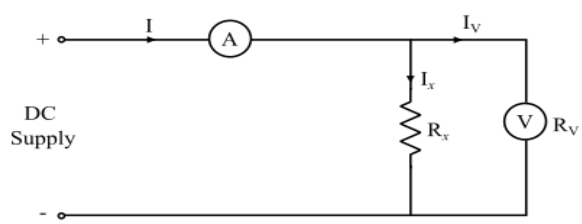
The various methods that can be employed for the measurement of low resistance are,

- Ammeter-voltmeter Method
- Kelvin's Double Bridge Method
- Potentiometer Method

Ammeter – Voltmeter Method

In this method, current through the unknown resistor (Rx) and the potential drop across it are simultaneously measured. The readings are obtained by ammeter and voltmeters respectively. There are two ways in ammeter and voltmeters may be connected for measurement as,

Case 1 – When voltmeter is directly connected across the resistor, then the ammeter measures current flowing through the unknown resistance (R_x) and the voltmeter.



Current through ammeter = Current through(R_x) + Current through voltmeter

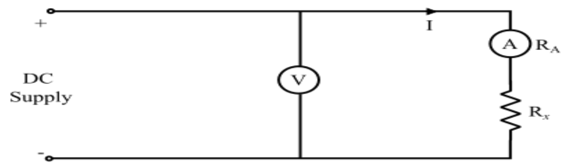
$$I = IR_x + IVI = IRx + IV$$

$$\Rightarrow IRx = I - IV$$

Therefore, the value of unknown resistance,

$$Rx = \frac{\mathbf{V}}{\mathbf{Ix}} = \frac{\mathbf{V}}{(\mathbf{I-IV})} = \frac{\mathbf{V}}{(\mathbf{I}-\frac{R}{Rv})} \quad ....1)$$

Case 2 – When the ammeter is connected such that it measures only the current flowing through the unknown resistor (R_x), then the voltmeter measures voltage drop across the ammeter and R_x.



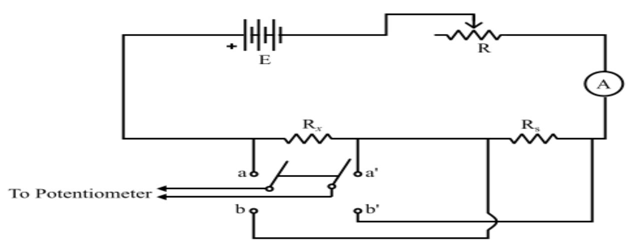
Therefore,

$$V = I\,R_A + I\,Rx = I(R_A + R_x)$$

$$\Rightarrow Rx = \frac{V}{I} - R_A ....(2)$$

Potentiometer Method

In the *potentiometer method*, the unknown resistance is compared with a standard resistance of the same order of magnitude.



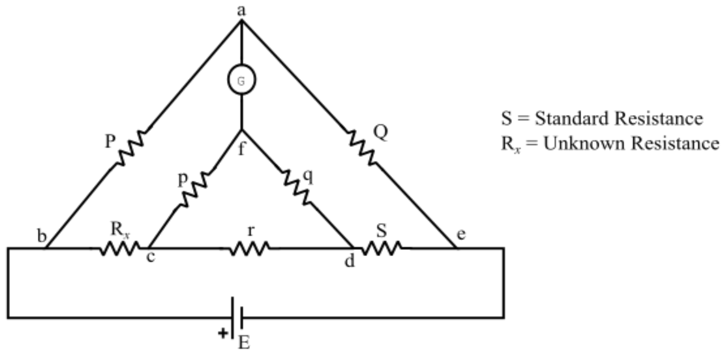
The circuit consists of an unknown resistance (R_x), a rheostat (R) and a standard resistance (R_s) all are connected in series across a low voltage, high current supply. The value of Rs should be known and of the same order of R_x. The current flowing in the circuit is adjusted,so that the potential difference across each resistor is about 1 V.

Now, the voltage drop across both the standard resistance (R_s) and unknown resistance (R_x) are measured by a potentiometer. The ratio of the two potentiometer readings gives the ratio of R_x and R_s, i.e.

$$\frac{\mathbf{Rx}}{\mathbf{Rs}} = \frac{\mathbf{VRx}}{\mathbf{VRs}} ....(3)$$

Kelvin Double Bridge Method

The *Kelvin double bridge* is a modified version of Wheatstone bridge and used to measure the low resistances with higher accuracy. This bridge is called double bridge since the circuit contains a second set of ratio arms (*p* and *q*). This second set of ratio arms connects the galvanometer (G) to a point f at the appropriate potential difference between c and d and this eliminates the effect of yoke resistance r. The galvanometer shows zero reading when potential at a equals to the potential at f, i.e. the bridge is balanced.



Therefore, the value of unknown resistance can be given by,

$$Rx = \frac{PS}{Q} + \frac{pr}{p+q+r}\left(\frac{P}{Q} - \frac{p}{q}\right)$$

Since, the ratio of resistances of arms p and q is the same as the ratio of P and Q. Thus,

$$p/q=P/Q$$

Substituting in the above expression, we get,

$$Rx=PS/Q\ldots\ldots(4)$$

The eq. (4) is the work equation of kelvin double bridge.

Measurement of Medium Resistances

To measure the medium resistances following methods are used −

- Ammeter-Voltmeter Method
- Substitution Method
- Wheatstone Bridge
- Carey-Foster Slide-Wire Bridge Method.

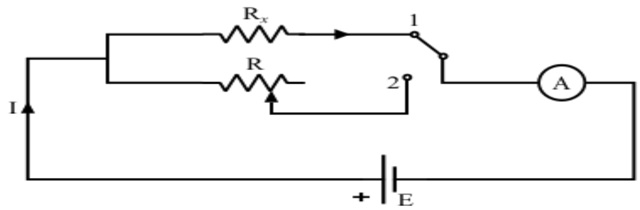
Ammeter Voltmeter Method

This is the most crude and simplest method of measuring resistance. It uses one ammeter to measure current, I and one voltmeter to measure voltage, V and we get the value of resistance as R= V/I

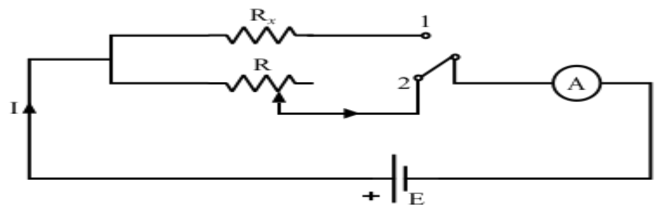
Two method to measured is already described above.

Substitution Method

Step 1 – In this method, first the unknown resistance (R_x) is put into the circuit and note the value of current.



Step 2 – Then the resistance R_x is removed and it is *substituted* by a known variable resistance R which is varied so that the value of current is same in both the cases. This value of R is equal to the value of unknown resistance.



Wheatstone Bridge

The *Wheatstone bridge* method is the most accurate method for the measurement of resistances.

The bridge consists of four resistive arms, source of emf and a galvanometer (null detector). The current through the galvanometer depends upon the potential difference between the points B and D. The bridge is said to be *balanced* when the potential difference across the galvanometer is zero so that there is no current flows through the galvanometer.

For the *balanced Wheatstone bridge*,

$$PS = QR$$

$$\Rightarrow R = PS/Q \quad ...(3)$$

Measurement of High Resistances

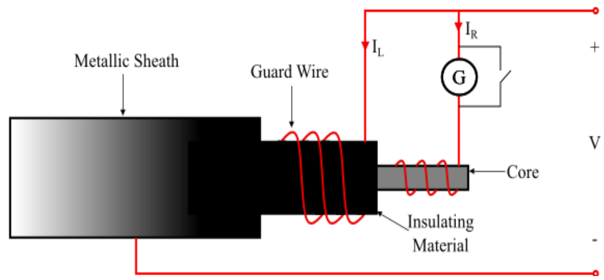
The following methods are employed for the measurement of high resistances −

- Direct Deflection Method
- Loss of Charge Method
- Megohm Bridge
- Megger

Direct Deflection Method

In this method, a very sensitive and high resistance (more than 1 kΩ) PMMC galvanometer is connected in series with the resistance to be measured and to a battery. The deflection of galvanometer gives the measure of unknown resistance. This method is mainly used for the measurement of insulation resistance.

Let us take an example of direction deflection method for measuring insulation resistance of a cable.

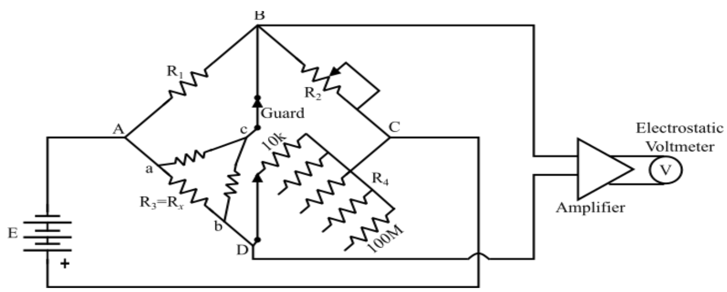


Refer the figure, the galvanometer (G) measures the current I_R between conductor core and metal sheath. The leakage current I_L over the surface of insulating material is carried by the guard wire wound on the insulation and does not flow through the galvanometer. Thus, the resistance of the cable is,

R=V/IR……..(1)

Megohm Bridge

The circuit of Megohm bridge consists of power supplies, resistances, amplifiers and indicating instruments.

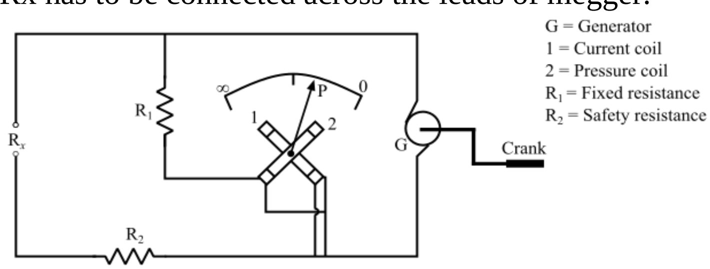


In this instrument, the dial on R_2 is calibrated 1-10-100-1000 MΩ and the R_4 gives five multipliers 0.1, 1, 10, 100 and 100. The junction of R_1 and R_2 is brought on the main panel and assigned a name as *Guard terminal*. The unknown resistance is given by,

R3= (R_1R_4) / R_2…….(4)

Megger

Megger (megohmmeter) is a device used for the measurement of high resistances, mainly insulation resistances of electric circuits with respect to earth or one another. A megger consists of a source of emf and a voltmeter whose scale is usually calibrated in mega-ohms. The unknown resistance Rx has to be connected across the leads of megger.



When the megger operates, the deflection of the moving system depends upon the ratio of the applied voltage and the current in the coils of the megger. The unknown resistance is read directly from the scale of the megger.

Unit II: Principle of Analog Instruments

Introduction

The analogue instrument is defined as the instrument whose output is the continuous function of time, and they have a constant relation to the input. The physicals quantity like voltage, current, power and energy are measured through the analogue instruments. Most of the analogue instrument use pointer or dial for indicating the magnitude of the measured quantity.

Analog instruments find extensive use in present day applications although digital instruments are increasing in number and applications. The areas of application which are common to both analog and digital instruments are fairly limited at present. Hence, it can safely be predicted that the analog instruments will remain in extensive use for a number of years and are not likely to be completely replaced by digital instruments for certain applications.

Types of Analog Instruments

- Electrical instruments may also be classified according to the kind of current that can be measured by them. Electrical instruments may be classified as instruments for:

1. Direct Current (DC)
2. Alternating Current (AC)
3. Direct and Alternating Current (DC/AC) or (Universal Instruments)

DC Instruments

• The instruments, whose deflections are proportional to the current or voltage under measurement are used for dc measurements only.

• If such an instrument is connected in an ac circuit, the pointer will deflect up-scale for one half cycle of the input waveform and down-scale for the next half cycle.

• At lower frequencies of 50 Hz, the pointer will not be able to follow the variations in direction and will quiver slightly around the zero mark, seeking the average value of ac i.e., zero.

• Example – PMMC instrument (Permanent Magnet Moving Coil)

AC Instruments

• The instruments utilizing the electromagnetic induced currents for their operation are used for ac measurements only.

• These instruments cannot be used for dc measurements because the electromagnetic induced currents are not generally available in dc circuit.

• Example – Moving Iron type instruments

DC / AC Instruments (Universal Instruments)

•The instruments having deflection proportional to the square of the current or voltage under measurement can be used for dc as well as ac measurements.

• Example – Dynamometer type moving coil, hot-wire, electrostatic instruments, moving iron (attraction as well as repulsion type).

- Instruments depend for their operation on one of the many effects produced by current and voltage and thus can be classified according to which of the effects is used for their working.

Effects	Instruments
Magnetic Effect	Ammeters, Voltmeters, Wattmeters, Integrating meters.
Heating Effect	Ammeters & Voltmeters
Electrostatic Effect	Voltmeters
Induction Effect	AC Ammeters, Voltmeters, Wattmeters, Integrating meters
Hall Effect	Flux Meters, Ammeters and Poynting vector wattmeter

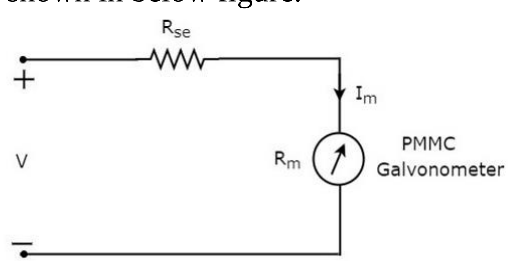
- The analog instruments are also classified as :
  1. Indicating Instruments
  2. Recording Instruments
  3. Integrating Instruments

- The analog instruments may also be classified on the basis of method used for comparing the unknown quantity (measurand) with the unit of measurement. The two categories of instruments based upon this classification are:
  1. Direct Measuring Instruments
  2. Comparison Instruments

DC Voltmeters

DC voltmeter is a measuring instrument, which is used to measure the DC voltage across any two points of electric circuit. If we place a resistor in series with the Permanent Magnet Moving Coil (PMMC) galvanometer, then the entire combination together acts as **DC voltmeter**.

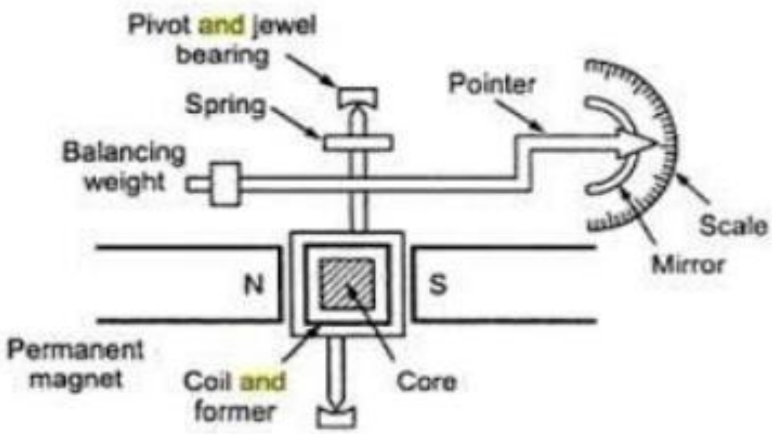
The series resistance, which is used in DC voltmeter is also called series multiplier resistance or simply, multiplier. It basically limits the amount of current that flows through galvanometer in order to prevent the meter current from exceeding the full scale deflection value. The **circuit diagram** of DC voltmeter is shown in below figure.



We have to place this DC voltmeter across the two points of an electric circuit, where the DC voltage is to be measured.

Review of DC/AC Voltmeter and Ammeter: The D' Arsonval Principle

The D'Arsonval principle is a fundamental principle behind the operation of DC/AC voltmeters and ammeters. The principle is based on the interaction between a magnetic field and an electric current. The D'Arsonval principle involves the use of a moving coil and a permanent magnet. Here's how it works:



Moving Coil: The voltmeter or ammeter consists of a coil of wire that is mounted on a pivoting spindle. This coil is free to move within the magnetic field.
Permanent Magnet: A permanent magnet is positioned near the coil, creating a static magnetic field.
Current Flow: When a current flows through the coil, it interacts with the magnetic field produced by the permanent magnet.
Force on the Coil: According to principle of electromagnetic induction, the interaction between magnetic field and electric current generates a force on the coil, which causes it to move.
Measurement Scale: The coil movement is proportional to the current passing through it or the voltage applied across it. This movement is calibrated and displayed on a measurement scale, allowing the user to read the value.

For a voltmeter
The coil is connected in parallel with a high-value resistor, which limits the current flow through the coil and ensures that the voltmeter has a high input impedance. When a voltage is applied across the voltmeter, the current passing through the coil is proportional to the voltage, resulting in a corresponding deflection of the coil.

For an ammeter,
The coil is connected in series with a low-value shunt resistor, which allows a small fraction of the total current to flow through the coil. The current passing through the coil is directly proportional to the total current, resulting in a deflection of the coil corresponding to the measured current.

The D'Arsonval principle is widely used in analog needle-type voltmeters and ammeters, providing accurate and reliable measurements of DC and AC currents and voltages. However, it should be noted that modern digital instruments have largely replaced analog meters in many applications, offering improved precision, versatility, and additional measurement features.

DC Ammeter:

The PMMC galvanometer constitutes the basic movement of a dc ammeter. Since the coil winding of a basic movement is small and light, it can carry only very small currents. When large currents are to be measured, it is necessary to bypass a major part of the current through a resistance called a shunt, as shown in Fig. The resistance of shunt can be calculated as,

Let, R_m = Internal Resistance of the Movement.

I_{sh} = Shunt Current

I_m = Full Scale Deflection Current of the Movement

I = Full Scale Current of the Ammeter + Shunt (i.e. Total Current)

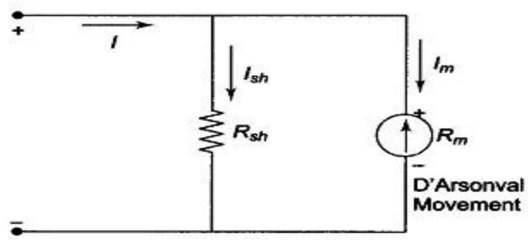


Fig: Basic DC Ammeter

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

Therefore ,
$$V_{sh} = V_m$$

$$\therefore \quad I_{sh} R_{sh} = I_m R_m, \qquad R_{sh} = \frac{I_m R_m}{I_{sh}}$$

But

$$I_{sh} = I - I_m$$

hence

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

For each required value of full scale meter current, we determine the value of shunt resistance.

Multirange Ammeters:

The current range of the dc ammeter may be further extended by a number of shunts, selected by a range switch. Such a meter is called a multirange ammeter, shown in Fig.

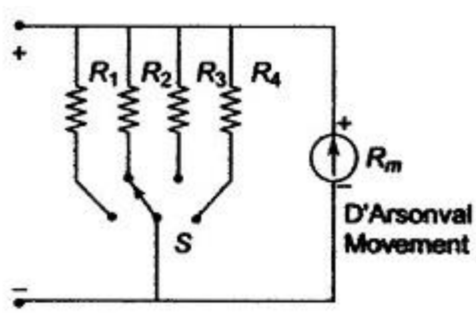


Fig: Multirange Ammeter

The circuit has four shunts R_1, R_2, R_3 and R_4, which can be placed in parallel with the movement to give four different current ranges. Switch **S** is a multiposition switch, (having low contact resistance and high current carrying capacity, since its contacts are in series with low resistance shunts). Make before break type switch is used for range changing. This switch protects the meter movement from being damaged without a shunt during range changing.
If we use an ordinary switch for range changing, the meter does not have any shunt in parallel while the range is being changed, and hence full current passes through the meter movement, damaging the movement. Hence a make before break type switch is used. The switch is so designed that when the switch position is changed, it makes contact with the next terminal (range) before breaking contact with the previous terminal. Therefore the meter movement is never left unprotected. Multirange ammeters are used for ranges up to 50A. When using a multirange ammeter, first use the highest current range, then decrease the range until good upscale reading is obtained. The resistance used for the various ranges are of very high precision values, hence the cost of the meter increases.

Extension of Range of PMMC Ammeter

The range of a permanent-magnet moving coil ammeter can be extended by connecting a low resistance, called *shunt in parallel with the moving coil of the instrument as shown in Fig. The shunt bypasses most of the line current and allows a small current through the meter which it can handle without burning.

Let R_m, = Meter Resistance

S = Shunt Resistance

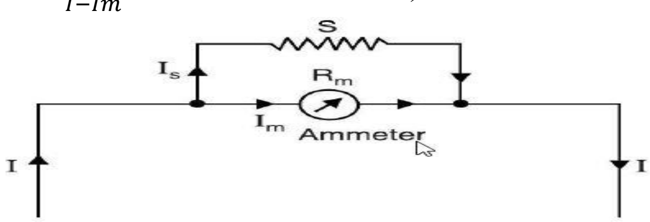
I_m = Full-Scale Deflection (F.S.D.) Current

I = Full Range Current of the Meter

Voltage across shunt = Voltage across the meter

Or, $(I - Im)\, S = Im\, Rm$

$$S = \frac{Im\,Rm}{I - Im} \text{ ....i)}$$



Multiplier power of shunt = $\frac{I}{Im}$ = $\frac{Rm + S}{S}$

Note that multiplying power of a shunt is the ratio of circuit current to be measured to the meter current. The multiplying power of a shunt is constant and indicates the factor by which the meter current must be multiplied to obtain the circuit current.

Q) A 1mA meter movement with an internal resistance of 100Ω is to be converted into a 0-100 mA. Calculate the value of shunt resistance required.

Soln,

$R_{sh} = \frac{Im\ Rm}{I - Im} = \frac{1mA*100}{100mA - 1mA} = 1.01$ ohms

Ayrton Shunt or Universal Shunt

In multi range ammeter, a make before break switch is must. The Ayrton shunt or universal shunt eliminates the possibility of having a meter without a shunt. The meter with Ayrton shunt is shown in the Fig

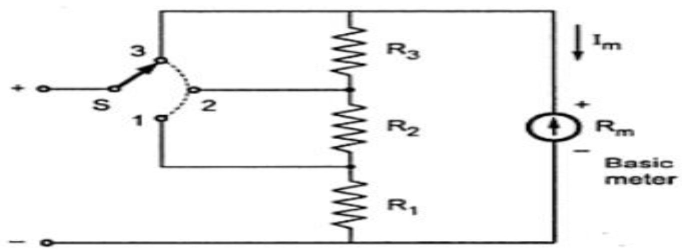


Fig. 1 Ammeter with Ayrton shunt

The selector switch S, selects the appropriate shunt required to change the range of the meter. When the position of the switch is '1' then the resistance R_1 is in parallel with the series combination of R_2 , R_3 and Rm. Hence current through the shunt is more than the current through the meter, thus protecting the basic meter. When the switch is in the position '2', then the series resistance of R1 and R2 is in parallel with the series combination of R_3 and Rm. The current through the meter is more than through the shunt in this position. In the position '3', the resistances R_1 , R_2 and R_3 are in series and acts as the shunt. In this position, the maximum current flows through the meter. This increases the sensitivity of the meter.
The voltage drop across the two parallel branches is always equal.

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

But in position 1, R_1 is in parallel with $R_2 + R_3 + R_m$

$$\therefore \quad I_1 [R_1] = I_m [R_2 + R_3 + R_m] \quad \ldots (1)$$

where I_1 is the first range required.

In position 2, $R_1 + R_2$ is in parallel with $R_3 + R_m$.

$$\therefore \quad I_2 (R_1 + R_2) = I_m (R_3 + R_m) \quad \ldots (2)$$

where I_2 is the second range required.

In position 3, $R_1 + R_2 + R_3$ is in parallel with R_m .

$$\therefore I_3 (R_1 + R_2 + R_3) = I_m R_m \quad \ldots (3)$$

where I_3 is the third range required.

The current range I_3 is the minimum while I_1 is maximum range possible. Solving the equations (1), (2) and (3) the required Ayrton shunt can be designed.

Example : *Design an Ayrton shunt to provide an ammeter with the current ranges 1 A, 5 A and 10 A. A basic meter resistance is 50 Ω and fullscale deflection current is 1 mA.*

Solution : The required meter with Ayrton shunt is shown in the Fig. 3.21.

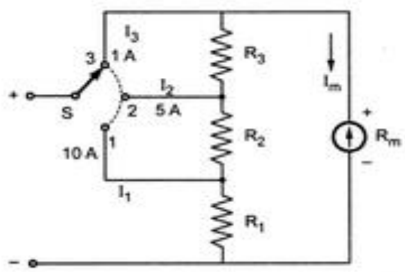


Fig. 3.21

In position 1, R_1 is shunt with $R_2 + R_3 + R_m$,

$\therefore \quad I_1 R_1 = I_m(R_2 + R_3 + R_m)$

where $\quad I_1 = 10$ A, $I_m = 1$ mA and $R_m = 50\ \Omega$

$\therefore \quad 10\,R_1 = 1\times10^{-3}(R_2 + R_3 + 50)$

$\therefore \quad R_1 = 10^{-4}(R_2 + R_3 + 50) \qquad \ldots(1)$

In position 2, $R_1 + R_2$ is shunt with $R_3 + R_m$,

$\therefore \quad I_2(R_1 + R_2) = I_m(R_3 + R_m)$

where $\quad I_2 = 5$ A

$\therefore \quad 5(R_1 + R_2) = 1\times10^{-3}(R_3 + 50)$

$\therefore \quad R_1 + R_2 = 2\times10^{-4}(R_3 + 50) \qquad \ldots(2)$

In position 3, $R_1 + R_2 + R_3$ is shunt with R_m,

$\therefore \quad I_3(R_1 + R_2 + R_3) = I_m R_m$

where $\quad I_3 = 1$ A

$\therefore \quad R_1 + R_2 + R_3 = 1\times10^{-3}\times 50$

$\therefore \quad R_1 + R_2 + R_3 = 0.05 \qquad \ldots(3)$

From equation (3), $R_1 + R_2 = 0.05 - R_3$

Substituting in equation (2) we get, $0.05 - R_3 = 2\times10^{-4}(R_3 + 50)$

$\therefore \quad 0.05 - R_3 = 2\times10^{-4}R_3 + 0.01$

$\therefore \quad 1.0002\,R_3 = 0.04$

$\therefore \quad R_3 = \mathbf{0.0399\ \Omega}$

$\therefore \quad R_1 + R_2 = 0.05 - 0.0399 = 0.01$

$\therefore \quad R_2 = 0.01 - R_1$

Substituting in equation (1), $R_1 = 10^{-4}[\,0.01 - R_1 + 0.0399 + 50]$

$\therefore \quad R_1 = 10^{-6} - 10^{-4}R_1 + 5\times10^{-3}$

$\therefore \quad 1.0001R_1 = 5.00139\times10^{-3}$

$\therefore \quad R_1 = \mathbf{0.005\ \Omega}$

$\therefore \quad R_2 = \mathbf{0.005\ \Omega}$

Thus the various sections of the Ayrton shunt are 0.005 Ω, 0.005 Ω and 0.0399 Ω.

DC Voltmeter:

A basic D' Arsonval movement can be converted into a dc voltmeter by adding a series resistor known as multiplier, as shown in Fig. The function of the multiplier is to limit the current through the movement so that the current does not exceed the full scale deflection value. A dc voltmeter measures the potential difference between two points in a dc circuit.

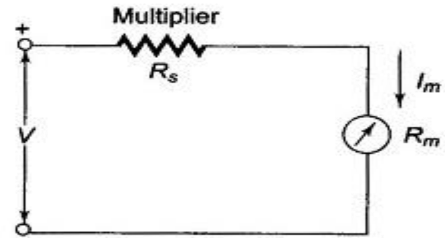


Fig: Basic dc voltmeter

To measure the potential difference between two points in a dc circuit or a circuit component, a dc voltmeter is always connected across them with the proper polarity. The value of the multiplier required is calculated as follows. Referring to Fig. above

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

R_m = internal resistance of movement

R_s = multiplier resistance

V = full range voltage of the instrument

From the circuit of Fig.

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

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

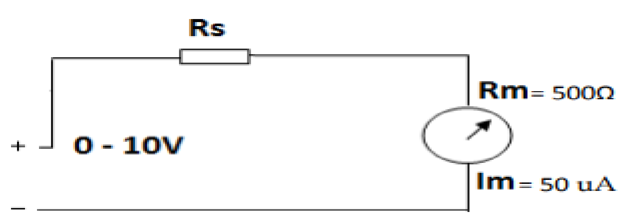
Therefore

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

The multiplier limits the current through the movement, so as to not exceed the value of the full scale deflection I_{fsd}. The above equation is also used to further extend the range in DC voltmeter.

Q) A basic D' Arsonval movement with a full-scale deflection of 50 µA and internal resistance of 500Ω is used as a DC voltmeter. Determine the value of the multiplier resistance needed to measure a voltage range of 0-10V.

Solution:



Rs = $\frac{V}{Im} - Rm$

Rs = $\frac{10}{50*10^{-3}} - 500$ = 199.5 KOhms

Multirange Voltmeter:

As in the case of an ammeter, to obtain a multirange ammeter, a number of shunts are connected across the movement with a multi-position switch. Similarly, a dc voltmeter can be converted into a multirange voltmeter by connecting a number of resistors (multipliers) along with a range switch to provide a greater number of workable ranges.

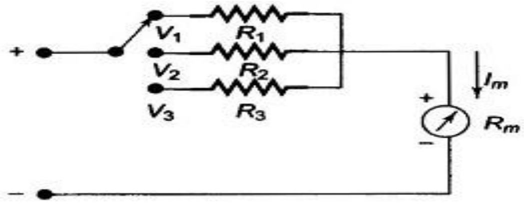


Fig. 4.2 ▬ Multirange Voltmeter

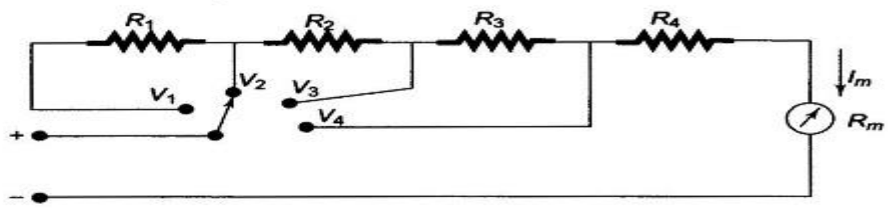


Fig. 4.3 ▬ Multipliers Connected in Series String

Figure 1st shows a multirange voltmeter using a three position switch and three multipliers R_1, R_2, and R_3 for voltage values V_1, V_2, and V_3. Figure 1st can be further modified to Fig. 2nd, which is a more practical arrangement of the multiplier resistors of a multirange voltmeter.

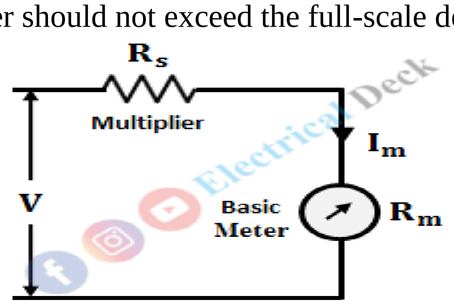
In this arrangement, the multipliers are connected in a series string, and the range selector selects the appropriate amount of resistance required in series with the movement.

This arrangement is advantageous compared to the previous one, because all multiplier resistances except the first have the standard resistance value and are also easily available in precision tolerances:

The first resistor or low range multiplier, R_4, is the only special resistor which has to be specially manufactured to meet the circuit requirements.

Extending Voltmeter Ranges:

A multiplier is basically a resistor connected in series with the voltmeter as shown below. The main function of the multiplier is to limit the flow of current through the voltmeter in such a way that the deflection of the pointer should not exceed the full-scale deflection.



It must ensure that the voltmeter should be connected in parallel or across two points, to measure the potential difference.

Let,

- R_m = Internal Resistance of the Meter
- R_s = Resistance of Multiplier
- I_m = Full-Scale Deflection Current of Meter
- V = Voltage being Measured
- V_m = Full Deflection Voltage of the Meter

From the above figure,

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

$$V = I_m R_m + I_m R_s$$

$$I_m R_s = V - I_m R_m$$

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

The multiplying factor of the multiplier is the ratio of extended voltage range to be measured V to the actual sustainable voltage by the voltmeter V_m. If the sustainable voltage drop of the meter $V_m = I_m R_m$. Then multiplying factor m is,

$$m = \frac{V}{V_m} = \frac{I_m(R_m + R_s)}{I_m R_m}$$

$$m = 1 + \frac{R_s}{R_m}$$

$$R_s = (m-1)R_m$$

Hence, to extend a voltmeter range for m times. The resistance of the multiplier required is (m-1) × resistance of the meter.

AC Voltmeters

The instrument, which is used to measure the AC voltage across any two points of electric circuit is called **AC voltmeter**. If DC voltmeter consists of rectifier, then it is said to be rectifier based AC voltmeter. The DC voltmeter measures only DC voltages. If we want to use it for measuring AC voltages, then we have to follow these two steps.

- **Step1** − Convert the AC voltage signal into a DC voltage signal by using a rectifier.
- **Step2** − Measure the DC or average value of the rectifier's output signal.

We get **Rectifier based AC voltmeter**, just by including the rectifier circuit to the basic DC voltmeter. This chapter deals about rectifier based AC voltmeters.

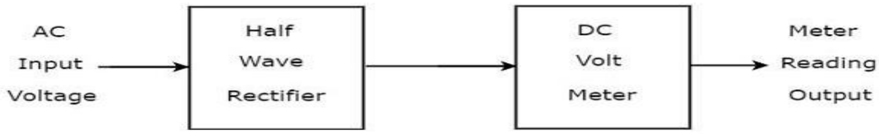
Types of Rectifier based AC Voltmeters

Following are the **two types** of rectifier based AC voltmeters.

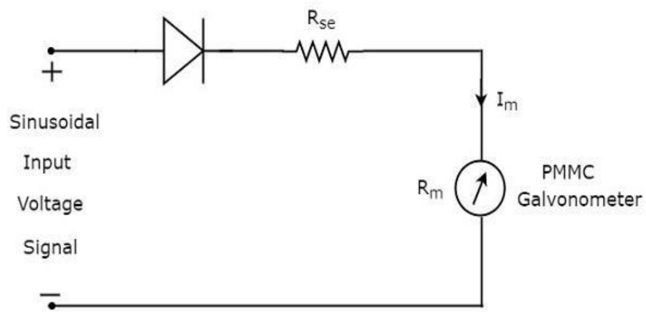
- AC Voltmeter using Half Wave Rectifier
- AC Voltmeter using Full Wave Rectifier

AC Voltmeter using Half Wave Rectifier

The **block diagram** of AC voltmeter using Half wave rectifier is shown in below figure.



The above block diagram consists of two blocks: half wave rectifier and DC voltmeter. We will get the corresponding circuit diagram, just by replacing each block with the respective component(s) in above block diagram.



The **rms value** of sinusoidal (AC) input voltage signal is

$$V_{rms} = V_m/\sqrt{2}$$

$$\Rightarrow V_m = \sqrt{2} * V_{rms}$$

$$\Rightarrow V_m = 1.414V_{rms}$$

Where, Vm is the maximum value of sinusoidal (AC) input voltage signal.

The **DC** or average value of the Half wave rectifier's output signal is

$$V_{dc} = V_m/\pi$$

Substitute, the value of Vm in above equation.

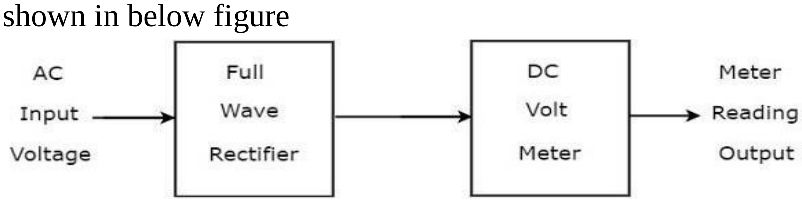
$$V_{dc} = 1.414V_{rms}/\pi$$

$$V_{dc} = 0.45V_{rms}$$

Therefore, the AC voltmeter produces an output voltage, which is equal to **0.45** times the rms value of the sinusoidal (AC) input voltage signal

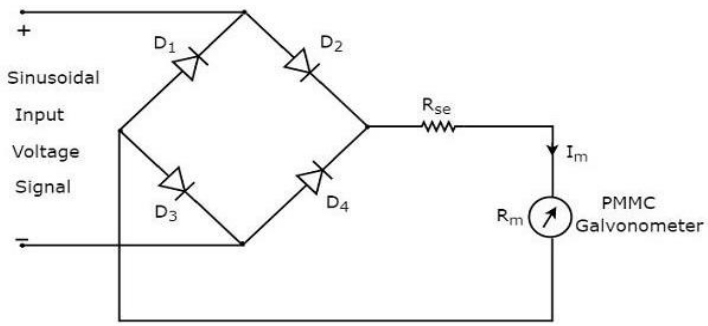
AC Voltmeter using Full Wave Rectifier

If a Full wave rectifier is connected ahead of DC voltmeter, then that entire combination together is called AC voltmeter using Full wave rectifier. The **block diagram** of AC voltmeter using Full wave rectifier is shown in below figure



The above block diagram consists of two blocks: full wave rectifier and DC voltmeter. We will get the corresponding circuit diagram just by replacing each block with the respective component(s) in above block diagram.

So, the **circuit diagram** of AC voltmeter using Full wave rectifier will look like as shown in below figure.



The **rms value** of sinusoidal (AC) input voltage signal is

$Vrms = Vm/\sqrt{2}$

$\Rightarrow Vm = \sqrt{2}*Vrms$

$\Rightarrow Vm = 1.414Vrms$

Where,

Vm is the maximum value of sinusoidal (AC) input voltage signal.

The **DC** or average value of the Full wave rectifier's output signal is

$Vdc = 2Vm/\pi$

Substitute, the value of Vm in above equation

$Vdc = 2\times1.414Vrms/\pi$

$Vdc = 0.9Vrms$

Therefore, the AC voltmeter produces an output voltage, which is equal to **0.9** times the rms value of the sinusoidal (AC) input voltage signal.

AC multi Range Voltmeter

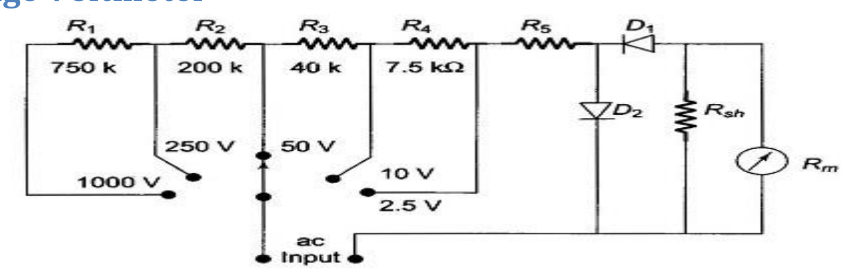


Fig: multirange ac voltmeter

Figure above is circuit for measuring ac voltages for different ranges. Resistances R_1, R_2, R_3 and R_4 form a chain of multipliers for voltage ranges of 1000 V, 250 V, 50 V, and 10 V respectively. On the 2.5 V range, resistance R_5 acts as a multiplier and corresponds to the multiplier R_s shown in Fig. below

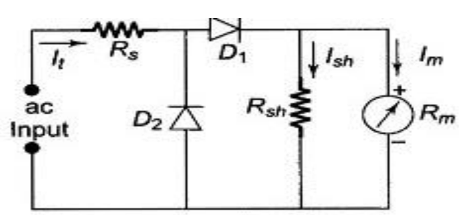


Fig: General rectifier type ac voltmeter

R_{sh} is the meter shunt and acts to improve the rectifier operation.

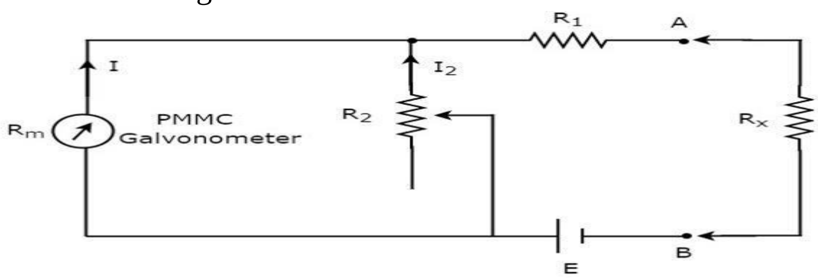
Ohm Meter and Multirange

The instrument, which is used to measure the value of resistance between any two points in an electric circuit, is called **ohmmeter**. There are two **types** of ohmmeters.

- Series Ohmmeter
- Shunt Ohmmeter

Series Ohmmeter

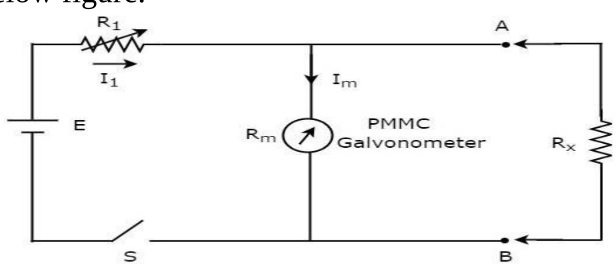
If the resistor's value is unknown and has to be measured by placing it in series with the ohmmeter, then that ohmmeter is called series ohmmeter. The **circuit diagram** of series ohmmeter is shown in below figure.



The part of the circuit, which is left side of the terminals A & B is **series ohmmeter**. So, we can measure the value of unknown resistance by placing it to the right side of terminals A & B

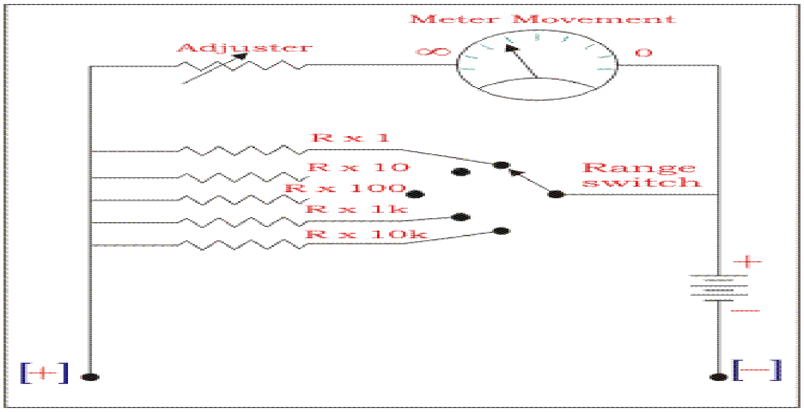
Shunt Ohmmeter

If the resistor's value is unknown and to be measured by placing it in parallel (shunt) with the ohmmeter, then that ohmmeter is called shunt ohmmeter. The **circuit diagram** of shunt ohmmeter is shown in below figure.



The part of the circuit, which is left side of the terminals A & B is **shunt ohmmeter**. So, we can measure the value of unknown resistance by placing it to the right side of terminals A & B.

Multi-Range Ohmmeter



This instrument provides the reading up to a very wide range. In this case, we have to select the range switch according to our requirements. An adjuster is provided so that we can adjust the initial reading to be zero.

The resistance to be measured is connected in parallel to the meter. The meter is adjusted so that it shows full-scale deflection when the terminals in which the resistance connected is full-scale range through the range switch.

When the resistance is zero or short circuit, there is no current flow through the meter and hence no deflection. Suppose we have to measure a resistance under 1 ohm, then the range switch is selected at the 1-ohm range at first.

Then that resistance is connected in parallel and the corresponding meter deflection is noted. For 1 ohm resistance, it shows full-scale deflection but for the resistance other than 1 ohm it shows a deflection which is less than the full load value, and hence resistance can be measured.

Electronic Multimeter

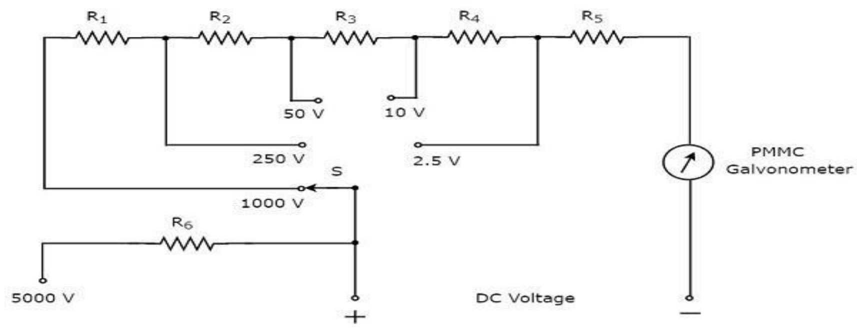
Electronic Multimeter is a device which is used for the measurement of various electrical and electronic quantities such as current, voltage, resistance etc. It is provided with inbuilt power supply necessary for the functioning of the device. Any component such as a resistor, battery can be connected to its outer probes for the measurement of the electronic quantity.

Measurements by using Multimeter

Multimeter is an instrument used to measure DC & AC voltages, DC & AC currents and resistances of several ranges. It is also called Electronic Multimeter or Voltage Ohm Meter (VOM).

DC voltage Measurement

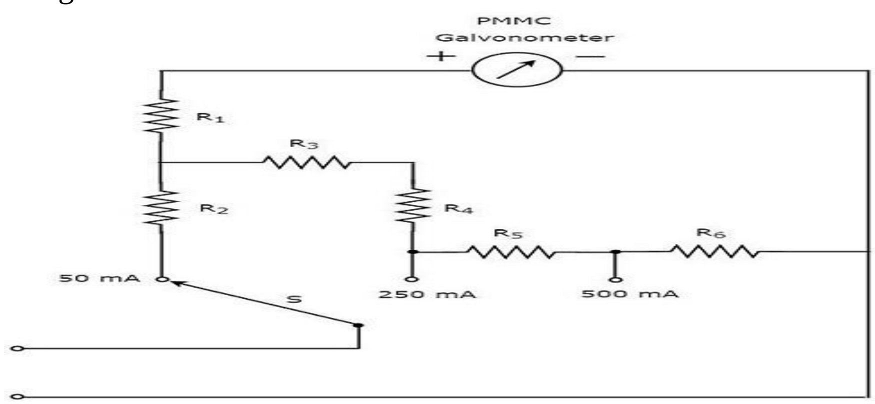
The part of the **circuit diagram** of Multimeter, which can be used to measure DC voltage is shown in below figure.



The above circuit looks like a multi range DC voltmeter. The combination of a resistor in series with PMMC galvanometer is a **DC voltmeter**. So, it can be used to measure DC voltages up to certain value

DC Current Measurement

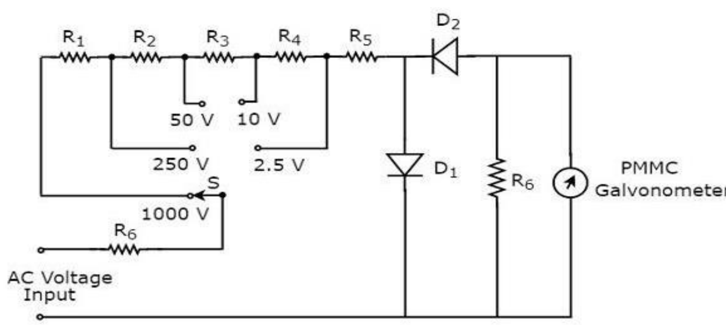
The part of the **circuit diagram** of Multimeter, which can be used to measure DC current is shown in below figure.



The above circuit looks like a multi range DC ammeter. the combination of a resistor in parallel with PMMC galvanometer is a **DC ammeter**. So, it can be used to measure DC currents up to certain value.

AC voltage Measurement

The part of the **circuit diagram** of Multimeter, which can be used to measure AC voltage is shown in below figure.

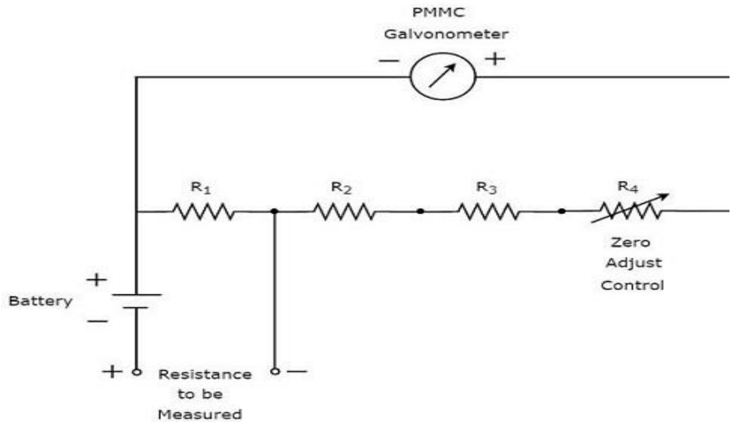


The above circuit looks like a **multi range AC voltmeter**. We know that, we will get AC voltmeter just by placing rectifier in series (cascade) with DC voltmeter. The above circuit was created just by placing the diodes combination and resistor, R6 in between resistor, R5 and PMMC galvanometer.

We can measure the AC voltage across any two points of an electric circuit, by connecting the switch, S to the desired voltage range.

Resistance Measurement

The part of the **circuit diagram** of Multimeter, which can be used to measure resistance is shown in below figure.



We have to do the following two tasks before taking any measurement.

- Short circuit the instrument
- Vary the zero adjust control until the meter shows full scale current. That means, meter indicates zero resistance value.

Now, the above circuit behaves as shunt ohmmeter and has the scale multiplication of 1, i.e. 10^0. We can also consider higher order powers of 10 as the scale multiplications for measuring high resistances.

Wattmeter: Types and Working principles

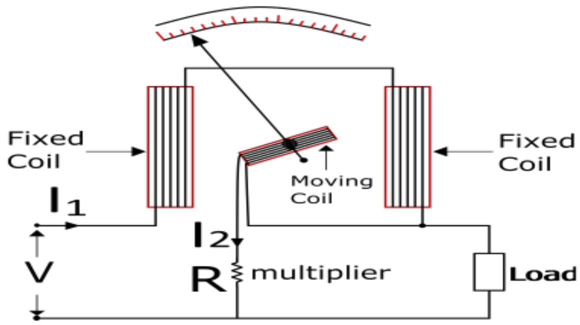
A wattmeter is an instrument which is used to measure electric power given to or developed by an electrical circuit. Generally, a wattmeter consists of a current coil and a potential coil.

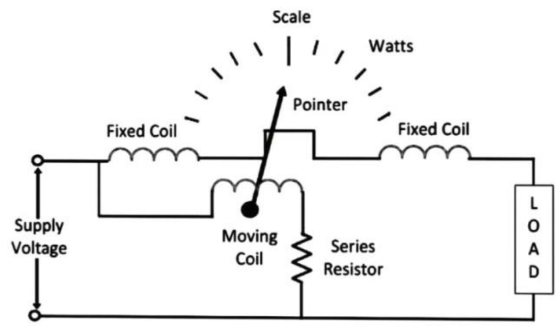
Types of Wattmeter

- Electrodynamometer Wattmeter – for both DC and AC Power Measurement
- Induction Wattmeter – for AC Power Measurement only

Working Principle of Electrodynamometer Wattmeter

The electrodynamometer wattmeter works on a **current-carrying conductor experiences a magnetic force when it is placed in a magnetic field.** Hence there will be a deflection of pointer that took place due to the mechanical force. It contains two coils such as fixed coil (current coil) and moving coil (pressure coil or voltage coil).





The fixed coil is connected in series with the circuit in order to measure power consumption. The supply voltage is applied to the moving coil**. Current across the moving coil is controlled with the help of a resistor**, which is connected in series with it. Moving coil on which pointer is fixed is placed in between fixed coils. **Two magnetic fields are generated due to the current and voltage in the fixed coil and moving coil. The pointer deflects as the two magnetic fields interact. The deflection is proportional to the power that is flowing through it.**

Advantages of Dynamometer Type Wattmeter

- These instruments are made to give very high accuracy and these are used as a standard for calibration purposes.
- These instruments provide full accuracy on **direct current** (DC).

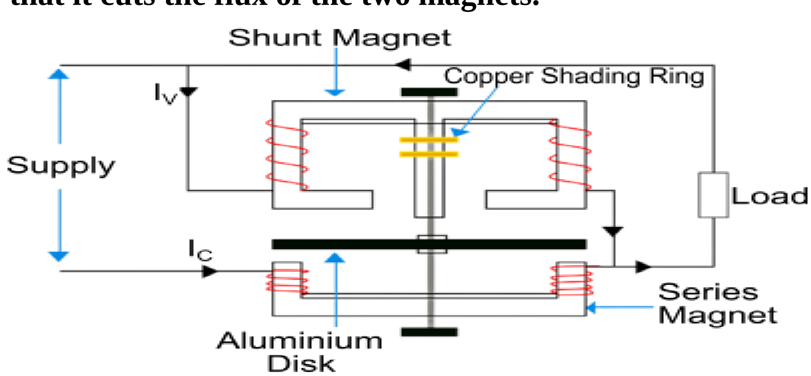
Disadvantages of Dynamometer Type Wattmeter

- These instruments cannot provide full accuracy on alternating Current (AC).
- These instruments cause errors at low power factor.

Working Principle of Induction Wattmeter

The induction type wattmeter can be used to measure AC power only.

The working of induction type wattmeter is based on the principle of electromagnetic induction. The induction wattmeter consists of two laminated electromagnets viz. ***Shunt Magnet and Series Magnet.*** The **shunt magnet is connected across the supply and carries a current proportional to the supply voltage.** The coil of shunt magnet is made highly inductive so that the current in it lags the supply voltage by 90°. **The series magnet is connected in series with the supply and carries the load current**. The coil of series magnet is made highly non-inductive. **A thin disc (made up of aluminum) mounted on a spindle is placed between the two magnets so that it cuts the flux of the two magnets.**



When the wattmeter is connected in an AC circuit, a current flows through the coil of the shunt magnet that is proportional to the supply voltage and the series magnet carries the load current. The fluxes produced by the two magnets induce eddy currents in the aluminium disc by the action of electromagnetic induction. Due to the interaction between the fluxes and eddy currents, a deflecting torque is produced on the disc, causing the disc to move and hence, the pointer connected to the disc moves over the scale. The pointer comes to rest when the deflecting torque becomes equal to the controlling torque.

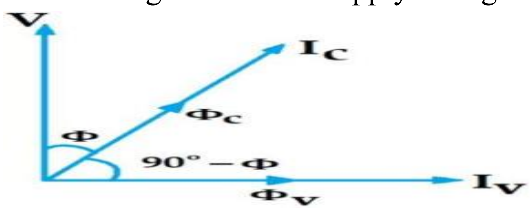
Let ***V = Supply voltage***

I_V = Current Carried by Shunt Magnet

I_C = Current Carried by Series Magnet

$\cos \Phi$ = Lagging Power Factor of the Load

You can see the phasor diagram in the picture below. The current I_V in the shunt magnet lags the supply voltage V by 90° and so does the flux Φ_V produced by it. The current I_C in the series magnet is the load current and hence lags behind the supply voltage V by Φ.



The flux Φ_C produced by this current (that is I_C) is in phase with it. It is clear that phase angle θ between the two fluxes is 90° – Φ that is θ = 90° – Φ

Therefore, Mean deflecting torque, $T_d \propto \Phi_V \Phi_C \sin \theta$

$\propto VI \sin (90° - \Phi)$

$[\because \Phi_V \propto V \text{ and } \Phi_C \propto I]$

$\propto V I \cos \Phi$

$\propto$ a. c. power

Since the instrument is spring controlled, $T_C \propto \theta$

For steady deflected position, $T_d = T_C$.

Therefore, $\theta \propto$ a. c. power

Hence such instruments have uniform scale. So let's now know about the energy meter, also known as the integrating meters.

Advantages of Induction Type Wattmeter:

- The scale is uniform.
- They provide good damping.
- There is no effect of stray fields.

Disadvantages of Induction Type Wattmeter:

- Can be used only for ac power measurements.
- Low accuracy due to heavy moving system and Power consumption is more
- Temperature changes can affect the readings by introducing errors.

Energy Meter: Types and Working Principle

Energy Meter or **Watt-Hour Meter** is an electrical instrument that measures the amount of electrical energy used by the consumers.

The energy meter has four main parts. They are the

1. Driving System
2. Moving System
3. Braking System
4. Registering System

Driving System – Electromagnet is the main component of driving system which is the temporary magnet and is excited by the current flow through their coil. The driving system has two electromagnets. The upper one is called the shunt electromagnet, and the lower one is called series electromagnet.

The series electromagnet is excited by the load current flow through the current coil. The coil of the shunt electromagnet is directly connected with the supply and hence carry the current proportional to the shunt voltage. This coil is called the pressure coil.

The centre limb of the magnet has the copper band. These bands are adjustable. The main function of the copper band is to align the flux produced by the shunt magnet in such a way that it is exactly perpendicular to the supplied voltage.

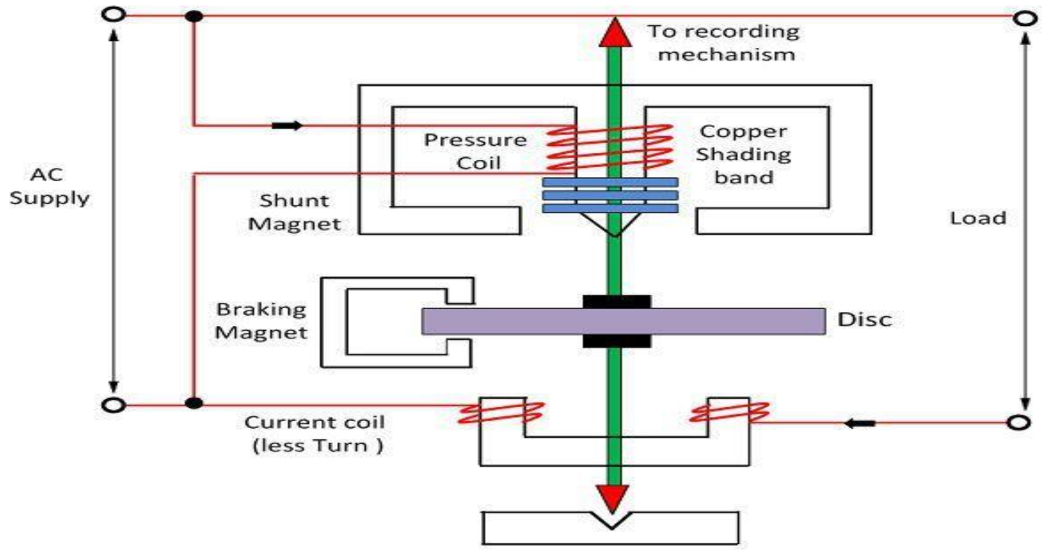
Moving System – The moving system is the aluminum disc mounted on the shaft of the alloy. The disc is placed in the air gap of the two electromagnets. The eddy current is induced in the disc because of the change of the magnetic field. This eddy current is cut by the magnetic flux. The interaction of the flux and the disc induces the deflecting torque.

When the devices consume power, the aluminum disc starts rotating, and after some number of rotations, the disc displays the unit used by the load. The number of rotations of the disc is counted at particular interval of time. Disc measured the power consumption in kilowatt hours.

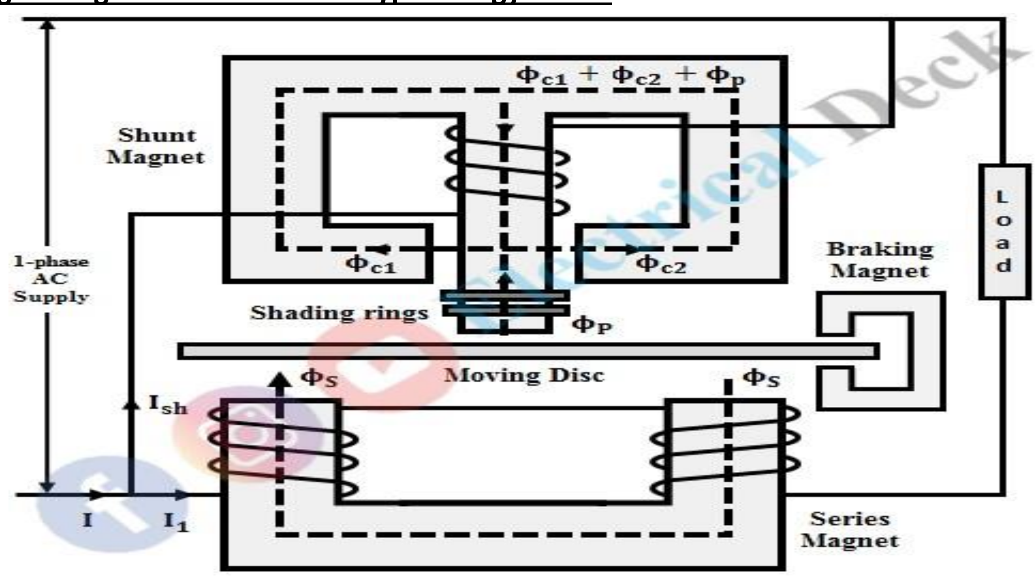
3. Braking System – The permanent magnet is used for reducing the rotation of the aluminum disc. The aluminum disc induces the eddy current because of their rotation. The eddy current cut the magnetic flux of the permanent magnet and hence produces the braking torque.

This braking torque opposes the movement of the disc, thus reduces their speed. The permanent magnet is adjustable due to which the braking torque is also adjusted by shifting the magnet to the other radial position.

4. Registration (Counting Mechanism) – The main function of the registration or counting mechanism is to record the number of rotations of the aluminum disc. Their rotation is directly proportional to the energy consumed by the loads in the kilowatt hour.



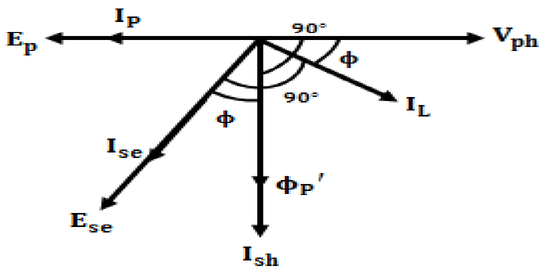
Working of Single Phase Induction Type Energy Meter



When the load is not connected, no flux is produced in the series magnet and only a shunt field is present. This alternating flux Φ_p links with the disc and induces an emf E_p in the disc, due to this emf an eddy current I_p flows in the disc, which produces an alternating field Φ_p' in the disc. But, no torque will be produced in the disc due to these two fluxes, because both the fluxes are 180° out of phase.

When the load current I_L flows through the current coil, the series magnet is magnetized and an alternating flux flows through it, and this flux links with the disc, which also produces an emf E_{se} resulting in the flow of eddy current I_{se}. I_{se} sets up a field Φ_{se}' in the disc which interacts with the field due to I_p and hence torque is produced in the disc due to this interaction of both the fields. The torque produced is proportional to the difference of the torques due to I_p and I_{se}.

The phasor diagram of the energy meter is shown below.



Therefore, average torque is given as,

$$T \propto \phi_p I_{se} \cos\phi - \phi_{se} I_p \cos(180° - \phi)$$

$$T \propto \phi_p I_{se} \cos\phi + \phi_{se} I_p \cos\phi$$

$$T \propto \cos\phi\, (\phi_p I_{se} + \phi_{se} I_p)$$

But,

$I_p \propto \Phi_p \propto V_{ph}$

$I_{se} \propto \varphi_{se} \propto I_L$

From this,

$$\phi_p I_{se} \propto V_{ph} I_L \Rightarrow \phi_p I_{se} = A V_{ph} I_L$$

$$and$$

$$\phi_{se} I_p \propto V_{ph} I_L \Rightarrow \phi_{se} I_p = B V_{ph} I_L$$

$$\therefore T \propto (A\, V_{ph} I_L + B\, V_{ph} I_L) \cos\phi$$

$$T \propto (A + B)\, V_{ph} I_L \cos\phi$$

Since A + B is a constant,

$T \propto V_{ph}\, I_L \cos\Phi$

From the above, the average torque produced in the disc is proportional to the actual power consumed in the load.

The above equation is derived assuming that Φ_p lags behind V_{ph} by exactly 90°. So, if Φ_p is not exactly in quadrature with V_{ph} the above relation fails. Hence the copper shading rings or bands must be provided to hold the above relation good. Let the torque produced by the braking magnet be T_B. T_B will be proportional to the speed of the disc (i.e., N).

$\therefore T_B \propto N$

$T_B = K_2\, N$

Since,

$$T \propto V_{ph} I_L \cos\phi$$

$$T = K_1\, V_{ph} I_L \cos\phi$$

At steady-state condition braking torque is equal to the driving torque.

$$\therefore T_B = T$$

$$K_2\, N = K_1\, V_{ph} I_L \cos\phi$$

$$N = \frac{K_1}{K_2}\, V_{ph} I_L \cos\phi$$

$$ie., N \propto True\ power\ of\ the\ ciruit$$

Total number of revolutions is,

$$= \int N\, dt$$

$$= \frac{K_1}{K_2} \int (V_{ph} I_L \cos \phi) dt$$

$$= \frac{K_1}{K_2} \int (True\ power) dt$$

Therefore, total number of revolutions is proportional to the integral of true power i.e., energy.

Power Factor Meter

The power factor of the transmission line is measured by dividing the product of voltage and current with the power. And the value of voltage current and power is easily determined by the voltmeter, ammeter and wattmeter respectively.

The power factor meter is of two types. They are

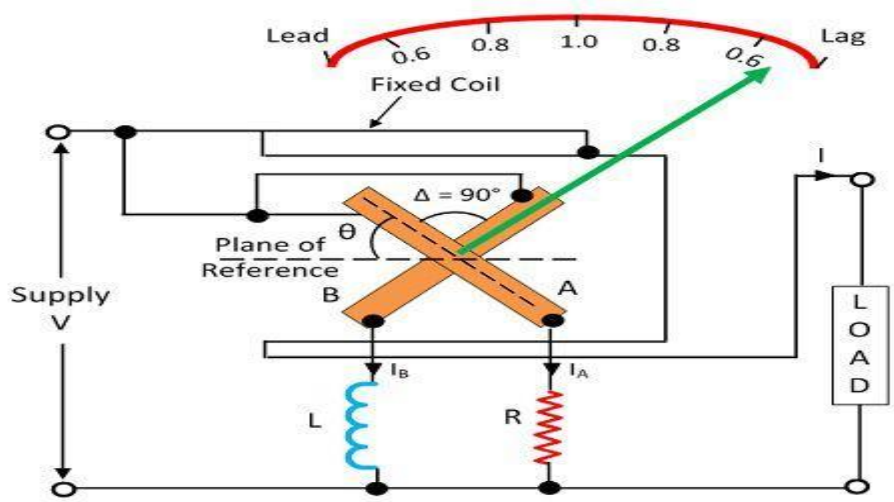
1. Electrodynamometer
   - Single Phase Electrodynamometer
   - Three Phases Electrodynamometer
2. Moving Iron Type Meter
   - Rotating Iron Magnetic Field
   - Number of Alternating Field

The different types of power factor meter are explained below in details.

Single Phase Electrodynamometer Power Factor Meter

The construction of the single phase electrodynamometer is shown in the figure below. The meter has fixed coil which acts as a current coil. This coil is split into two parts and carries the current under test. The magnetic field of the coil is directly proportional to the current flow through the coil.

The meter has two identical pressure coils A and B. Both the coils are pivoted on the spindle. The pressure coil A has no inductive resistance connected in series with the circuit, and the coil B has highly inductive coil connected in series with the circuit.



The current in the coil A is in phase with the circuit while the current in the coil B lag by the voltage nearly equal to 90º. The connection of the moving coil is made through silver or gold ligaments which minimize the controlling torque of the moving system.
The meter has two deflecting torque one acting on the coil A, and the other is on coil B. The windings are so arranged that they are opposite in directions. The pointer is in equilibrium when the torques are equal.
Deflecting torque acting on the coil A is given as

$$T_A = KVIMcos\emptyset sin\theta$$

θ – angular deflection from the plane of reference.

M_{max} – maximum value of mutual inductance between the coils.

The deflecting torque acting on coil B is expressed as

$$I_B = KVIM_{max}\,\mathrm{Cos}(90^{\circ} - \emptyset)\,Sin(90^{\circ} + \emptyset)$$

$$I_B = KVIM_{max}cos\emptyset sin\theta$$

The deflecting torque is acting on the clockwise direction.
The value of maximum mutual inductance is same between both the deflecting equations.

$$T_A = T_B$$

$$KVIMcos\emptyset sin\theta = KVIM_{max}cos\emptyset sin\theta$$

This torque acts on anti-clockwise direction. The above equation shows that the deflecting torque is equal to the phase angle of the circuit.

Instrument Transformer

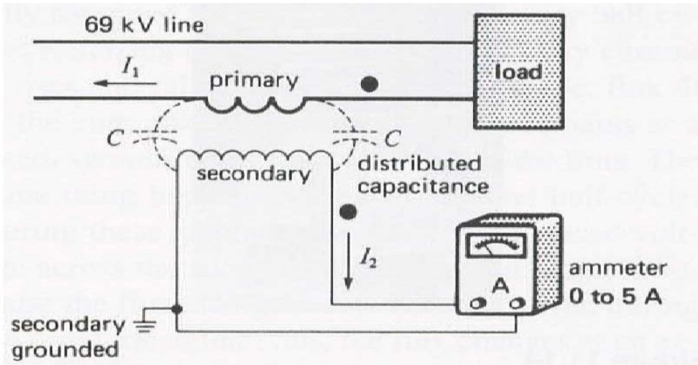
A transformer that is used to measure electrical quantities like current, voltage, power, frequency and power factor is known as an instrument transformer. These transformers are mainly used with relays to protect the power system.
The **Purpose of the instrument transformer** is to step down the voltage & current of the AC system because the level of voltage & current in a power system is extremely high. So designing the measuring instruments with high voltage & current is difficult as well as expensive. In general, these instruments are mainly designed for 5 A & 110 V.
Instrument transformers are classified into two types such as

- Current Transformer
- Potential Transformer

Current Transformer (CT)

- Current transformers are generally used to measure currents of high magnitude. These transformers step down the current to be measured, so that it can be measured with a normal range ammeter.

- A Current transformer has only one or very few numbers of primary turns. The primary winding may be just a conductor or a bus bar placed in a hollow core. The secondary winding has large number turns accurately wound for a specific turn's ratio. Thus, the current transformer steps up (increases) the voltage while stepping down (lowering) the current.



- Now, the secondary current is measured with the help of an AC ammeter. The turns ratio of a transformer is $K = N_s / N_p = I_p / I_s$

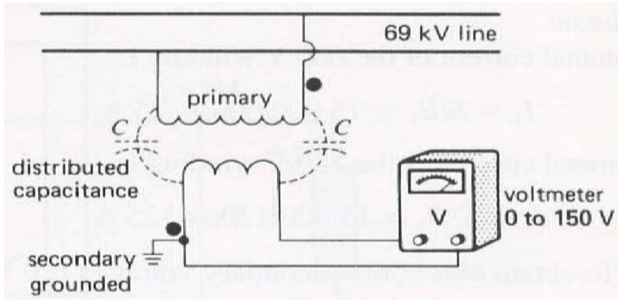
  I_1 (or, I_p) = K. Is (or I_2)

  If CT ratio 1000/5A i.e. k= 1000/5 = 200

  Secondary is connected directly to an ammeter. As the ammeter is having very small resistance. Hence, the secondary of current transformer operates almost in short circuited condition. **One terminal of secondary is earthed to avoid the large voltage on secondary with respect to earth.**
- Note: **The secondary winding of C.T shouldn't be left without ammeter**. If we did so secondary current I_2 will be zero and opposing flux in the iron core will be zero therefore magnetic flux in the core due to I_1 will be very high. Hence, high voltage will be induced in primary as well as secondary winding. Because of this high voltage the insulation of primary and secondary winding will get damage. Therefore, if we want to remove the ammeter the secondary winding must be short circuited by a thick wire.

Potential Transformer (PT)

- Potential transformers are also known as voltage transformers and they are basically step-down transformers with extremely accurate turns ratio.
- Potential transformers step down the voltage of high magnitude to a lower voltage which can be measured with standard measuring instrument. The range of this transformer is 110v. These transformers have large number of primary turns and smaller number of secondary turns.



- Secondary of P.T. is having few turns and connected directly to a voltmeter. As the voltmeter is having large resistance. Hence **the secondary of a P.T. operates almost in open circuited condition**. **One terminal of secondary of P.T. is earthed to maintain the secondary voltage with respect to earth, which assures the safety of operators.**
- If N_1 and N_2 are turn in primary & secondary, then turn ratio $=N_2/N_1$ which will be given on rating plate of PT.
- If V_2 is reading of voltmeter then, $V_1 = V_2/K$ can be calculated.

Numerical

1) **Design a multi range d.c. mille ammeter using a basic movement with an internal resistance Rm = 50Ω and a full scale deflection current Im =1mA . The ranges required are 0-10mA; 0-50mA; 0-100mA and 0-500mA.**

Solution:

Case-I 0-10mA

Multiplying power $m = \frac{I}{I_m} = \frac{10}{1} = 10$

$\therefore$ Shunt resistance $R_{sh1} = \frac{R_m}{m-1} = \frac{50}{10-1} = 5.55\Omega$

Case-II 0-50mA

$$m = \frac{50}{1} = 50$$

$$R_{sh2} = \frac{R_m}{m-1} = \frac{50}{50-1} = 1.03\Omega$$

Case-III 0-100mA, $m = \frac{100}{1} = 100\Omega$

$$R_{sh3} = \frac{R_m}{m-1} = \frac{50}{100-1} = 0.506\Omega$$

Case-IV 0-500mA, $m = \frac{500}{1} = 500\Omega$

$$R_{sh4} = \frac{R_m}{m-1} = \frac{50}{500-1} = 0.1\Omega$$

2) **A moving coil instrument gives a full scale deflection of 10mA, when the potential difference across its terminal is 100mV. Calculate (a) The shunt resistance for a full scale deflection corresponding to 100A (b) The resistance for full scale reading with 1000V. Calculate the power dissipation in each case?**

Soln,

Data given

$I_m = 10mA$
$V_m = 100mV$
$I = 100A$

$$I = I_m\left(1 + \frac{R_m}{R_{sh}}\right)$$

$$100 = 10\times10^{-3}\left(1 + \frac{10}{R_{sh}}\right)$$

$R_{sh} = 1.001\times10^{-3}\Omega$

$R_{se} = ??, V = 1000V$

$$R_m = \frac{V_m}{I_m} = \frac{100}{10} = 10\Omega$$

$$V = V_m\left(1 + \frac{R_{se}}{R_m}\right)$$

$$1000 = 100\times10^{-3}\left(1 + \frac{R_{se}}{10}\right)$$

$\therefore R_{se} = 99.99K\Omega$

3) The pointer of a moving coil instrument gives full scale deflection of 20mA. The potential difference across the meter when carrying 20mA is 400mV.The instrument to be used is 200A for full scale deflection. Find the shunt resistance required to achieve this, if the instrument to be used as a voltmeter for full scale reading with 1000V. Find the series resistance to be connected it?

Soln,

Case-1

V_m =400mV

$I_m = 20mA$

I=200A

$$R_m = \frac{V_m}{I_m} = \frac{400}{20} = 20\Omega$$

$$I = I_m\left(1 + \frac{R_m}{R_{sh}}\right)$$

$$200 = 20\times10^{-3}\left[1 + \frac{20}{R_{sh}}\right]$$

$R_{sh} = 2\times10^{-3}\Omega$

Case-II

V=1000V

$$V = V_m\left(1 + \frac{R_{se}}{R_m}\right)$$

$$4000 = 400\times10^{-3}\left(1 + \frac{R_{se}}{20}\right)$$

$R_{se} = 49.98k\Omega$

4) A 150 v moving iron voltmeter is intended for 50HZ, has a resistance of 3kΩ. Find the series resistance required to extent the range of instrument to 300v. If the 300V instrument is used to measure a d.c. voltage of 200V. Find the voltage across meter?

Solution:

Rm = 3kΩ,Vm =150V,V = 300V

$$V = V_m\left(1+\frac{R_{se}}{R_m}\right)$$

$$300 = 150\left(1+\frac{R_{se}}{3}\right) \Rightarrow R_{se} = 3k\Omega$$

Case-II $\quad V = V_m\left(1+\frac{R_{se}}{R_m}\right)$

$$200 = V_m\left(1+\frac{3}{3}\right)$$

$\therefore V_m = 100V$ Ans

5) Design an Aryton shunt to provide an ammeter with current ranges of 1A,5A,10A and 20A. A basic meter with an internal resistance of 50 ohm and a full scale deflection current of 1mA is to be used.

Solution: Data given

$$\begin{array}{l|l|l} I_m = 1\times10^{-3}A & I_1 = 1A & m_1 = \frac{I_1}{I_m} = 1000A \\ R_m = 50\Omega & I_2 = 5A & m_2 = \frac{I_2}{I_m} = 5000A \\ & I_3 = 10A & m_3 = \frac{I_3}{I_m} = 10000A \\ & I_4 = 20A & m_4 = \frac{I_4}{I_m} = 20000A \end{array}$$

$$R_{sh1} = \frac{R_m}{m_1-1} = \frac{50}{1000-1} = 0.05\Omega$$

$$R_{sh2} = \frac{R_m}{m_2-1} = \frac{50}{5000-1} = 0.01\Omega$$

$$R_{sh3} = \frac{R_m}{m_3-1} = \frac{50}{10000-1} = 0.005\Omega$$

$$R_{sh4} = \frac{R_m}{m_4-1} = \frac{50}{20000-1} = 0.0025\Omega$$

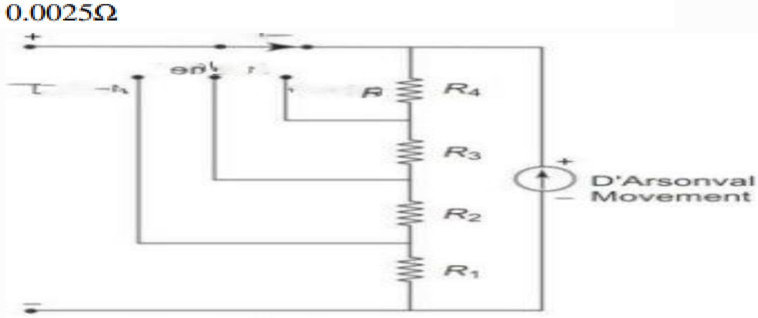
$\therefore$ The resistances of the various section of the universal shunt are

$$R_1 = R_{sh1} - R_{sh2} = 0.05 - 0.01 = 0.04\Omega$$

$$R_2 = R_{sh2} - R_{sh3} = 0.01 - 0.005 = 0.005\Omega$$

$$R_3 = R_{sh3} - R_{sh4} = 0.005 - 0.025 = 0.0025\Omega$$

$$R_4 = R_{sh4} = 0.0025\Omega$$



6) A basic d' Arsonval meter movement with an internal resistance Rm =100Ω and a full scale current of Im =1mA is to be converted in to a multi range D.C. voltmeter with ranges of 0-10V, 0- 50V, 0-250V, 0-500V. Find the values of various resistances using the potential divider arrangement.

Solution:

$$R_m = 100\Omega$$
$$I_m = 1mA$$
$$V_m = I_m \times R_m$$
$$V_m = 100 \times 1 \times 10^{-3}$$
$$V_m = 100mV$$

$$m_1 = \frac{V_1}{V_m} = \frac{10}{100\times10^{-3}} = 100$$
$$m_2 = \frac{V_2}{V_m} = \frac{50}{100\times10^{-3}} = 500$$
$$m_3 = \frac{V_3}{V_m} = \frac{250}{100\times10^{-3}} = 2500$$
$$m_4 = \frac{V_4}{V_m} = \frac{500}{100\times10^{-3}} = 5000$$

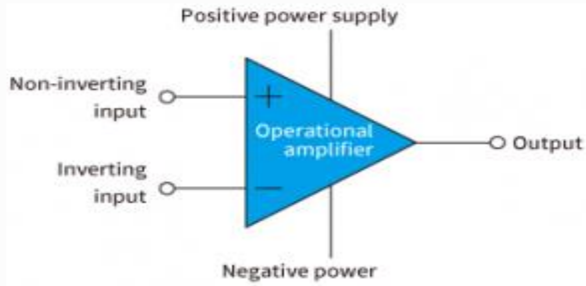
$$R_1 = (m_1 - 1)R_m = (100-1)\times100 = 9900\Omega$$
$$R_2 = (m_2 - m_1)R_m = (500-100)\times100 = 40K\Omega$$
$$R_3 = (m_3 - m_2)R_m = (2500-500)\times100 = 200K\Omega$$
$$R_4 = (m_4 - m_3)R_m = (5000-2500)\times100 = 250K\Omega$$

7)

Unit III: Electrical Signal Processing and Data Acquisition

OP-Amp

An operational amplifier is an integrated circuit that can amplify weak electric signals. An operational amplifier has two input pins and one output pin. Its basic role is to amplify and output the voltage difference between the two input pins.



Op-amps are linear devices that are ideal for DC amplification and are used often in signal conditioning, filtering or other mathematical operations (add, subtract, integration and differentiation).

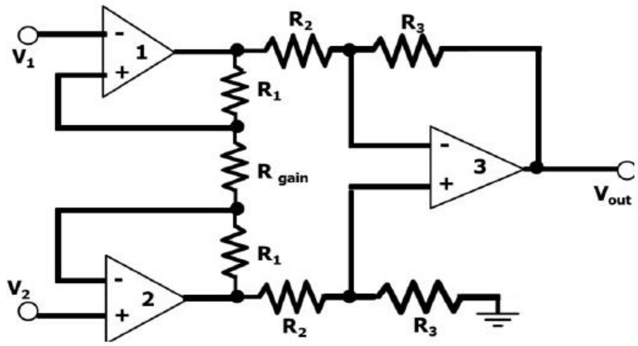
Ideal Op Amp Characteristics

- Open loop voltage gain is Infinite
- Input impedance is zero i.e. without any leakage of current from the supply to the inputs.
- Output impedance is infinite i.e. supply full current to the load connected to the output.
- Zero offset voltage i.e. output will be zero when the voltage difference between the inverting and the non-inverting inputs is zero
- Infinite bandwidth i.e. so that it can amplify any frequency from DC signals to the highest AC frequencies
- Infinite CMRR.
- Infinite slew rate i.e. changes in the output voltage occur simultaneously with the changes in the input voltage i.e. ensures zero common mode gain. Due to this common mode noise output voltage is zero for an ideal op-amp.
- Zero power supply rejection ratio i.e. reflects how well the op amp can reject noise in its power supply from propagating to the output

Instrumentation Amplifier

An instrumentation amplifier allows an engineer to adjust the gain of an amplifier circuit without having to change more than one resistor value. Compare this to the differential amplifier, which requires the adjustment of multiple resistor values.

Working of Instrumentation Amplifier

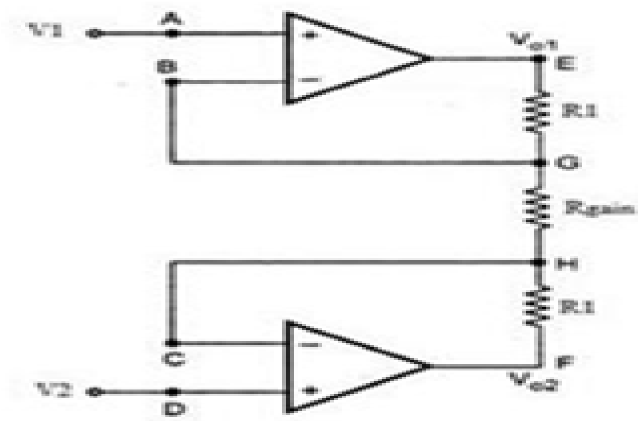


The output voltage V_{out} of the difference amplifier is actually the output stage of the instrumentation amplifier. This output voltage Vout is then the difference between the input signals applied at the input terminals.

Let us consider V_{o1} and V_{o2} the output voltages of the two op-amps 1 and 2 respectively. Then the value of voltage V_{out} of difference amplifier is

$$\mathbf{V_{out} = (R_3/R_2)\ (V_{o1}-V_{o2})}$$

The value of voltages V_{o1} and V_{o2} is in terms of the input voltages and resistances. The input stage of the instrumentation amplifier is also shown below.



Consider the value of input voltage as V_1 at node A. From the virtual ground concept, the value of the voltage at node B will be V_1. At node G the potential will also be equal to V_1.

Consider the value of input voltage as V_2 at node D. From the virtual ground concept the value of the voltage at node C will be V_2. At node H the potential will also be equal to V_2.

The value of current at input stage is zero because we consider the ideal case. Therefore, the value of current remains same in all the resistors R_1, R_{gain} and R_1

At node E and F from Ohm's Law, we can write

$$\mathbf{I = (V_{o1}-V_{o2})/(R_1+R_{gain}+R_1)} \quad \text{———————} \quad 1$$

$$\mathbf{I = (V_{o1}-V_{o2})/(2R_1+R_{gain})}$$

As there is no input current at the input stage hence, value of current between node G and H will be

$$I = (V_G - V_H)/R_{gain} = (V_1 - V_2)/R_{gain} \text{ ——————— } 2$$

Equating both equations 1 and 2,

$$(V_{o1} - V_{o2})/(2R_1 + R_{gain}) = (V1 - V_2)/R_{gain}$$

$$(V_{o1} - V_{o2}) = (2R_1 + R_{gain})\ (V_1 - V_2)/R_{gain} \text{ ——————— } 3$$

The output of the difference amplifier is

$$V_{out} = (R_3/R_2)\ (V_{o1} - V_{o2})$$

Therefore,

$$(V_{o1} - V_{o2}) = (R_2/R_3)\ V_{out}$$

In equation 3 we substitute $(V_{o1} - V_{o2})$ value

$$(R_2/R_3)\ V_{out} = (2R_1 + R_{gain})\ (V1 - V_2)/R_{gain}$$

$$V_{out} = (R_3/R2)\ \{(2R_1 + R_{gain})/R_{gain}\}\ (V1 - V_2)$$

The output voltage of an instrumentation amplifier is in the above equation. The value of the overall gain of the amplifier is $(R_3/R_2)\ \{(2R_1+R_{gain})/R_{gain}\}$.

Advantages of Instrumentation Amplifier

The **advantages of the instrumentation amplifier** include the following.

- The gain of a three op-amp **instrumentation amplifier circuit** can be easily varied by adjusting the value of only one resistor Rgain.
- Gain of the amplifier depends only on the external resistors used.
- Input impedance is very high due to the emitter follower configurations of amplifiers 1 and 2
- Output impedance of the instrumentation amplifier is very low due to difference amplifier3.
- CMRR of the **op-amp** 3 is very high and almost all of the common mode signal will be rejected.

Q. Write difference between OP-Amp and instrumentation amplifier.

Signal Amplification, Attenuation, Integration, Differentiation, Network Isolation, Wave Shaping

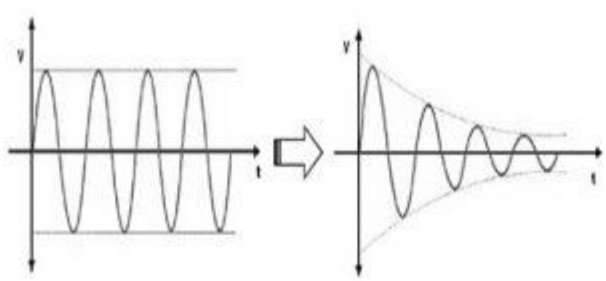
Signal Amplification

- A signal amplifier is a circuit that uses electrical power to increase the amplitude of an incoming signal voltage or current signal, and output this higher amplitude version at its output terminals.
- The ideal signal amplifier creates an exact replica of the original signal that is larger but identical in every other way. In practice, a "perfect" amplifier is not possible, because no circuit can perfectly and proportionately scales up all aspects of a signal past a certain point.

- Signal amplifiers are an essential component of thousands of devices, including landline and cellular telephone systems, music and public address systems, data acquisition (DAQ) systems, radio frequency transmitters, servo motor controllers, and countless more.
- Signal amplifiers are an essential component of thousands of devices, including landline and cellular telephone systems, music and public address systems, data acquisition (DAQ) systems, radio frequency transmitters, servo motor controllers, and countless more.
- In data acquisition (DAQ) systems, signal amplifiers are needed to increase the amplitudes from sensors that output small signals, up to the level where they can be sent to an A/D converter (ADC) for digitization. The typical analog-to-digital converter has an input aperture of ±5 V. Therefore, signals from thermocouples, shunts, strain gages, et al that are far lower than ±5V must be amplified significantly before they are sent to the ADC
- Some common signal amplifiers found in today's data acquisition systems:
  - **Differential Amplifiers**
  - **Isolated Amplifiers**
  - **Voltage Amplifiers: Low Voltage Amplifier, High Voltage Amplifier, DC Voltage Amplifier, AC Voltage Amplifier**
  - **Current Amplifiers**
  - **Charge Amplifiers**
  - **Thermocouple Amplifiers**
  - **Strain Gauge Amplifiers: Bridge Amplifier, Full-Bridge Amplifier, Half-Bridge Amplifier, Quarter-Bridge Amplifier)**

Attenuation

Attenuation, 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.



Attenuation is one of the techniques used in signal conditioning to scale down the amplitude or voltage level of a signal to match the input range or requirements of downstream components or systems. Attenuation can be achieved using passive or active components within a signal conditioning circuit.

Passive Attenuation techniques typically involve the use of voltage dividers or attenuator circuits that passively divide the input signal voltage by a fixed ratio. These circuits consist of resistors arranged in a specific configuration to achieve the desired attenuation. The voltage divider circuit is a common example of passive attenuation, where the output voltage is a fraction of the input voltage determined by the resistor values.

Active Attenuation involves the use of active components such as operational amplifiers (op-amps) to actively amplify or attenuate the signal. In the case of attenuation, an op-amp can be configured as an inverting amplifier or a voltage follower with appropriate gain settings to achieve the desired signal reduction. Active attenuation techniques offer more flexibility and precision in controlling the attenuation level and can be adjusted dynamically based on system requirements.

Attenuation in signal conditioning is often used to protect sensitive components from excessive signal levels, prevent signal clipping or saturation, or match signal levels between different stages of a system. For example, in analog-to-digital converters (ADCs), where the input voltage range is limited, attenuation can be applied to scale down the input signal to fit within the ADC's range without losing important information.

Network Isolation:

Network isolation refers to the separation or protection of one part of a network from another to prevent unwanted interactions or disturbances. It can involve techniques like using isolation transformers, optocouplers, or galvanic isolation methods to electrically separate different parts of a circuit or network.

Network isolation is an important aspect of signal conditioning because it helps ensure the integrity and accuracy of the conditioned signal.

Here are a few reasons why network isolation is important in signal conditioning:

Grounding and Ground Loops: Network isolation helps address grounding issues and ground loops, which can introduce unwanted noise or voltage differences between different parts of a network. By isolating the signal path, you can prevent these ground-related problems and maintain a clean signal.

Noise and Interference Rejection: Signals in a network can be susceptible to various sources of noise and interference, such as electromagnetic interference (EMI) or radio frequency interference (RFI). Network isolation techniques, such as using isolation transformers or optocouplers, can help block or attenuate these unwanted signals and provide a cleaner signal for further conditioning.

Voltage Level Differences: In some cases, signal conditioning circuit may operate at a different voltage level than the surrounding network. Network isolation allows for the conversion or adaptation of voltage levels while maintaining the separation between the circuit and the network.

Protection: Isolation can provide protection against voltage spikes, transients, or other electrical disturbances that may occur in the network.

Overall, network isolation in signal conditioning helps ensure the accuracy, reliability, and integrity of the conditioned signal by separating it from unwanted noise, interference, and disturbances present in the network.

Wave Shaping

- **Wave shaping circuits** are the electronic circuits, which produce the desired shape at the output from the applied input wave form. These circuits perform two functions −
  - Attenate the applied wave
  - Alter the dc level of the applied wave.
- Wave shaping technique include clipping and clamping.

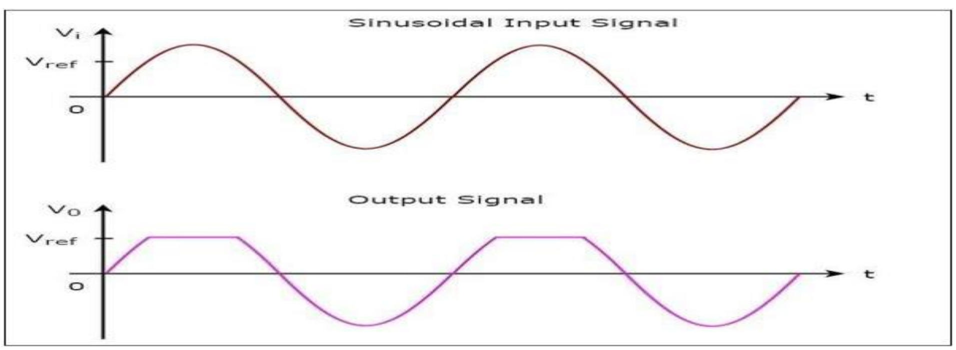
In op-amp clipper circuits a rectifier diode may be used to clip off a certain portion of the input signal to obtain a desired o/p waveform.

Clippers

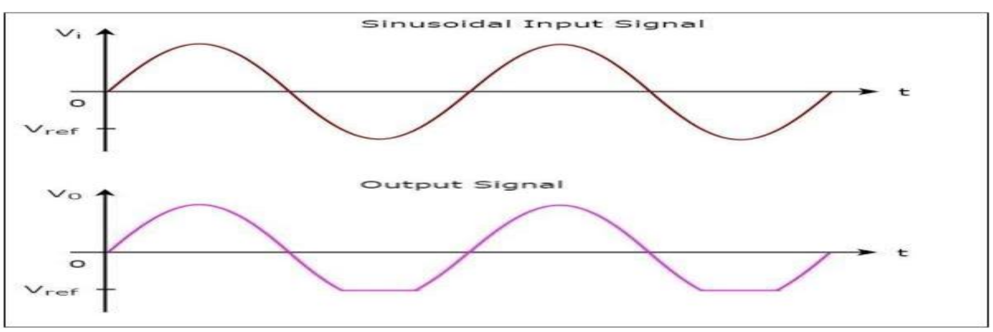
A **clipper** is an electronic circuit that produces an output by removing a part of the input above or below a reference value. Clippers can be classified into the following two types based on the clipping portion of the input.

- Positive Clipper
- Negative Clipper

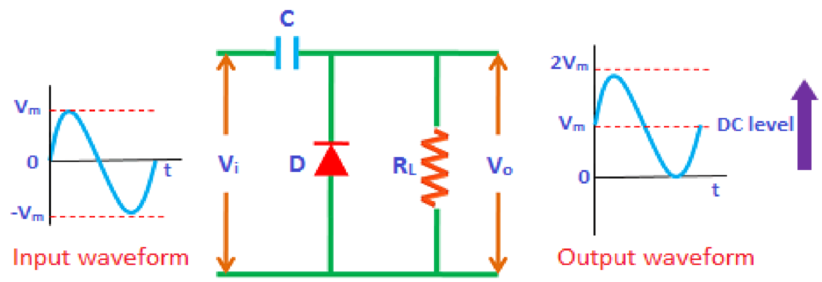
Positive Clipper: A **positive clipper** is a clipper that clips only the positive portion(s) of the input signal.



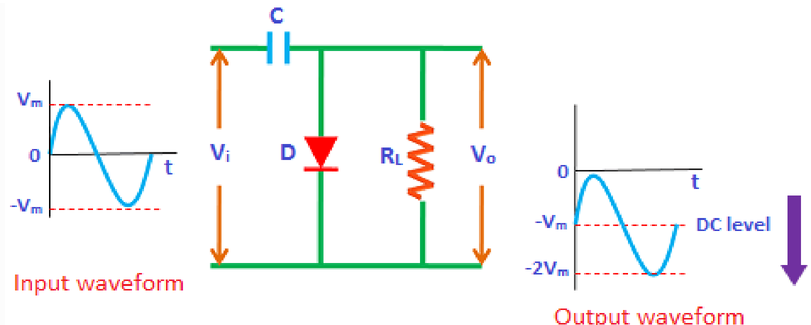
Negative Clipper: A **negative clipper** is a clipper that clips only the negative portion(s) of the input signal.



Clamper Circuit: A Clamper Circuit is a circuit that adds a DC level to an AC signal. Actually, the positive and negative peaks of the signals can be placed at desired levels using the clamping circuits. As the DC level gets shifted, a clamper circuit is called as a **Level Shifter**.



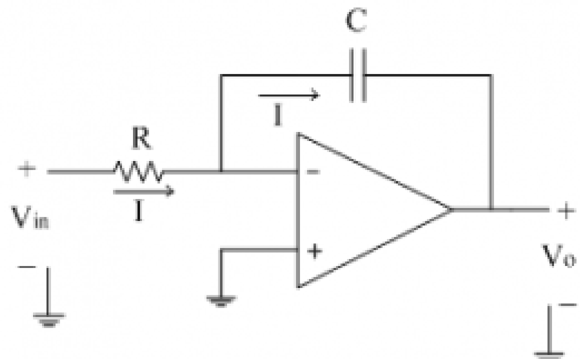
Positive clamper



Negative clamper

Integration: Integration is a mathematical operation applied to a signal that calculates the cumulative sum of the signal over time. It essentially measures the area under the signal curve. Integration is commonly used in applications such as measuring accumulated quantities or determining average values.

The following circuit shows a basic/ideal integrator using op-amp,



The non-inverting input terminal is at ground potential and hence, the inverting terminal is appearing to be at ground potential. The current 'I' through the resistance R is given as,

$$I = \frac{V_{in} - O}{R}$$

The input current to op-amp is zero so same current 'I' flows through the capacitor 'C' in feedback path also and is given as,

$$I = C\frac{d}{dt}(0 - V_0)$$

Comparing the above two equations for current 'I' we get,

$$\frac{V_{in} - O}{R} = C\frac{d}{dt}(O - V_O)$$

$$\frac{V_{in}}{R} = -C\frac{dV_O}{dt}$$

$$\therefore \; dV_o = -\frac{V_{in}dt}{RC}$$

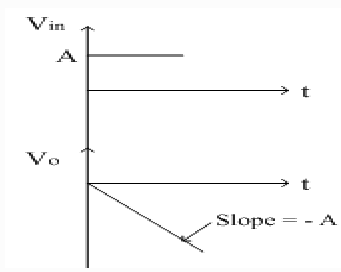
Integrating both the sides, we get,

$$V_o = -\frac{1}{RC}\int V_{in}dt$$

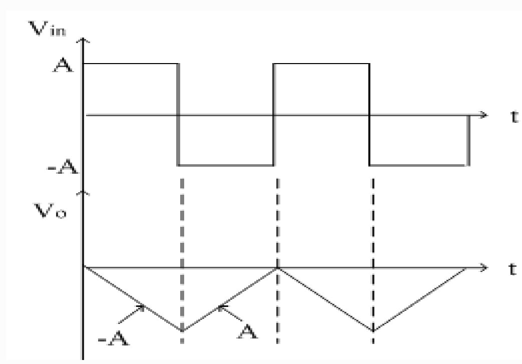
where – 1/RC=≫Gain / scale factor of an integrator.
Thus output voltage is nothing but time integration of the input signal and hence acting as an integrator.

Now let us see what is the response of the integrator to the different types of input signals.

1) Vin = Step signal

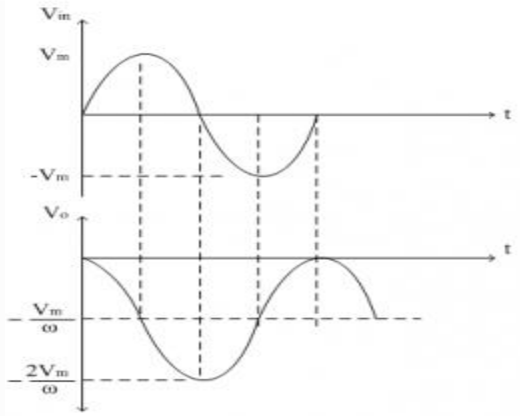


2) Vin = Square Wave

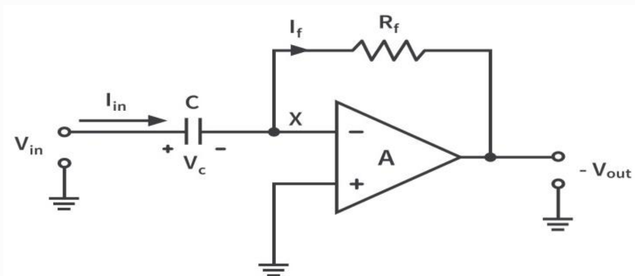


3) Vin = Sine Wave

Let Vin=Vm sinωt



Differentiation: Differentiation is the mathematical operation that calculates the rate of change or slope of a signal with respect to time. It provides information about the instantaneous change in the signal. Differentiation is frequently used in applications such as finding the velocity or acceleration from position data.



Let current I_f flows through the resistor Rf.

$$If = \frac{0 - Vout}{Rf}$$

The input capacitor current (I_{in}) is given as

$$Iin = C\,\frac{d\,Vc}{dt}$$

Apply kcl

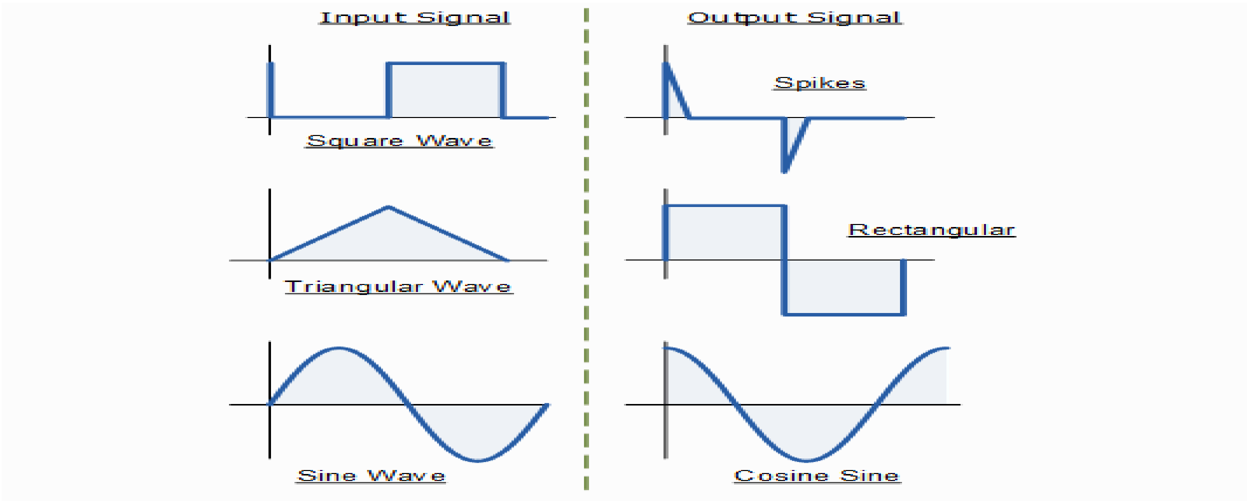
If = Iin

$\frac{0-Vout}{Rf} = C\,\frac{d\,Vin}{dt}$

So. Vout = $-R_f C\,\frac{d\,Vin}{dt}$

The negative sign in the output signifies that there is a 180° phase difference between output and the applied input.

Now let us see what is the response of the differentiator for the different types of input signals.



Effect of Noise, Analog Filtering, Digital Filtering

Noise refers to unwanted or random signals that can interfere with the desired signal. In signal conditioning, noise can degrade the quality of the signal and make it more difficult to extract useful information. It can arise from various sources, such as electromagnetic interference, thermal noise, or even limitations of electronic components.

The effect of noise can be mitigated through filtering techniques, both analog and digital. Filtering helps to reduce the impact of noise on the signal and improve its quality for further processing or transmission.

Analog Filtering:

Analog filtering involves the use of analog circuits, such as resistors, capacitors, and inductors, to modify the characteristics of the signal. Analog filters are commonly used in signal conditioning to attenuate unwanted frequencies, remove noise, or shape the frequency response of the signal.

Analog filters can be designed as low-pass, high-pass, band-pass, or band-reject filters to selectively allow or block certain frequency components of the signal. By employing analog filters, the undesired frequency components, including noise, can be attenuated, improving the signal quality for subsequent processing stages.

Digital Filtering:

Digital filtering involves processing the signal in the digital domain using digital signal processing (DSP) techniques. Digital filters are implemented through algorithms and computations performed by microprocessors, digital signal processors (DSPs), or dedicated hardware.

Digital filters offer several advantages in signal conditioning.

- They provide flexibility in terms of filter characteristics and can be easily reconfigured or modified.
- Digital filters can implement a wide range of filter types, including finite impulse response (FIR) filters and infinite impulse response (IIR) filters.

- Digital filtering allows precise control over filter parameters, such as cutoff frequencies, stop band attenuation, and filter order.
- It enables efficient noise removal, signal enhancement, and frequency response shaping.
- Digital filters can also be adaptive, adjusting their characteristics based on changing signal conditions or specific requirements.

Overall, noise, analog filtering, and digital filtering all contribute to signal conditioning by reducing noise, improving signal quality, and shaping the frequency response as needed. The choice of filtering techniques depends on the specific application, requirements, and available resources.

Data Acquisition System

A data acquisition system (DAQ) is an information system that collects, stores and distributes information. It is used in industrial and commercial electronics, and environmental and scientific equipment to capture electrical signals or environmental conditions on a computer device. A data acquisition system is also known as a data logger.

These data acquisition systems will perform the tasks such as conversion of data, storage of data, transmission of data and processing of data for the purpose of monitoring, analyzing, and/or controlling systems and processes. Data acquisition systems and instruments are either the combination of a number of data acquisition components that make up a complete system or a self-contained instrument. A data acquisition system is a system that acquires data, generally by digitizing analog channels and storing the data in digital form.

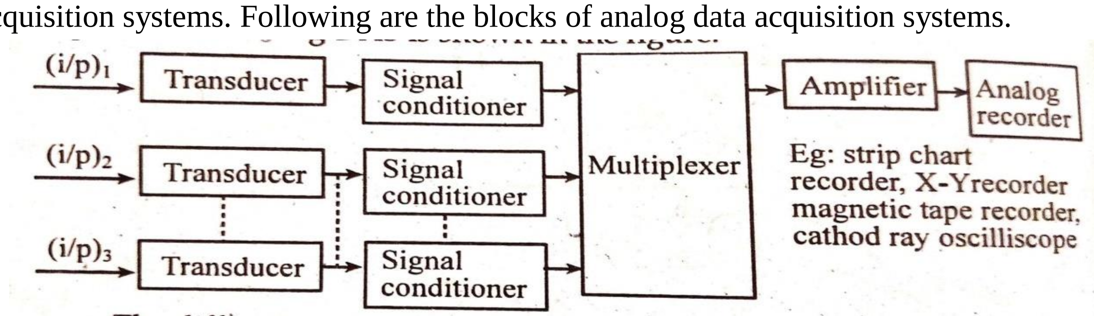
Types of Data Acquisition Systems

Data acquisition system is measurement system by which data is acquired economically and efficiently in desired form. The data can be acquired either in analog or digital form hence data acquisition systems can be classified into the following two types on the basic of data how it is acquired.

1) Analog Data Acquisition Systems
2) Digital Data Acquisition Systems

Analog Data Acquisition Systems

The data acquisition systems, which can be operated with analog signals are known as analog data acquisition systems. Following are the blocks of analog data acquisition systems.



The component of analog data acquisition system are:

Transducer − It converts physical quantities into electrical signals. The most common transducers convert physical quantities to electrical quantities, such as voltage or current. Transducer characteristics define many of the signal conditioning requirements of a DAQ system.

Signal Conditioner −It takes the output of the transducer and makes it into a suitable form of condition so that rest the rest of the DAQ process. It performs the functions like amplification and selection of desired portion of the signal.

Multiplexer − Multiplexer is the process of showing single channel with more than one input and multiplier accept multiple analog input and connects then sequentially to one measuring output. Multiplexing uses same transmission channel for transmitting more than one quantity and it becomes necessary if distance between transmitting and receiving point is large and many quantities are to be transmitted by separate channel.

Amplifier − An amplifier is increase the power of a signal (a time-varying voltage or current). It uses electric power from a power supply to increase the amplitude of a signal applied to its input terminals, producing a proportionally greater amplitude signal at its output. The amount of amplification provided by an amplifier is measured by its gain: the ratio of output voltage, current, or power to input. An amplifier is a circuit that has a power gain greater than one

Display Device/Analog Recorder − It displays the input signals for monitoring purpose.

Graphic recording instruments − These can be used to make the record of input data permanently.

Magnetic Tape Instrumentation − It is used for acquiring, storing & reproducing of input data.

Digital Data Acquisition Systems

The data acquisition systems, which can be operated with digital signals are known as digital data acquisition systems. So, they use digital components for storing or displaying the information.

Mainly, the following operations take place in digital data acquisition.

- Acquisition of analog signals
- Conversion of analog signals into digital signals or digital data
- Processing of digital signals or digital data

Following are the blocks of Digital data acquisition systems.

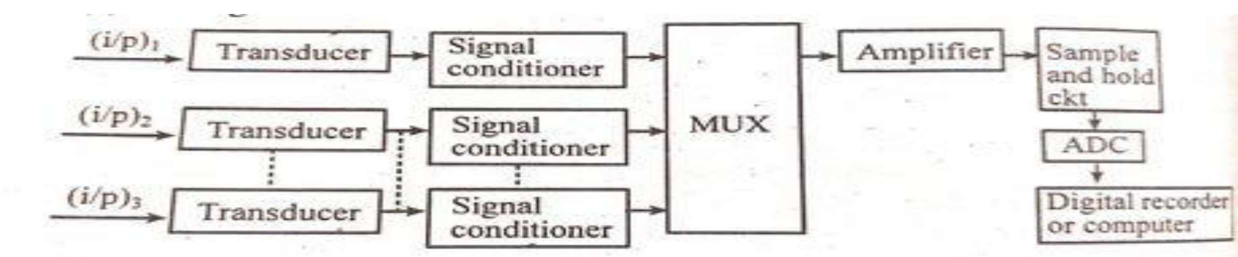


Fig: Digital data acquisition system

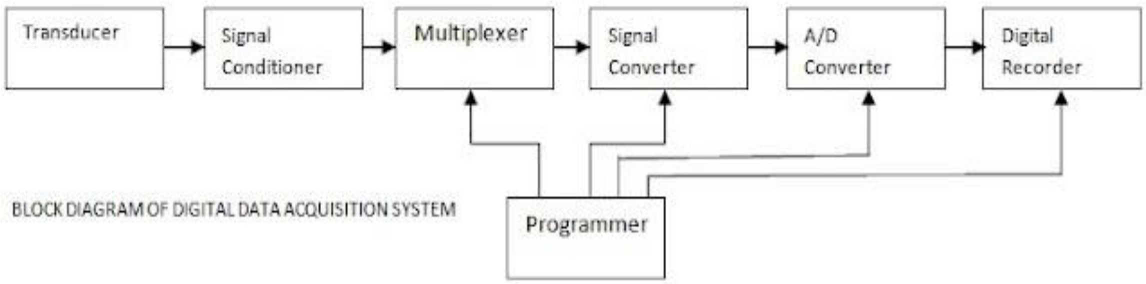


Fig: Modern Digital data acquisition system

Transducer − It converts physical quantities into electrical signals.

Signal Conditioner − It performs the functions like amplification and selection of desired portion of the signal.

Multiplexer − connects one of the multiple inputs to output. So, it acts as parallel to serial converter.

Sample and Hold Circuit − It is usually used with an Analog to Digital Converter to sample the input analog signal and hold the sampled signal, hence the name 'Sample and Hold'. In the S/H Circuit, the analog signal is sampled for a short interval of time, usually in the range of 10μS to 1μS. After this, the sampled value is hold until the arrival of next input signal to be sampled. The duration for holding the sample will be usually between few milliseconds to few seconds. Basically the sample and hold circuit, samples the analog signal and the capacitor present holds these samples. This sampled value when provided to the ADC, it generates a discrete signal from an analog one.

Analog to Digital Converter − It converts the analog input into its equivalent digital output.

Display Device − It displays the data in digital format.

Digital Recorder − It is used to record the data in digital format.

Single Channel Data Acquisition System:

A Single Channel Data Acquisition System consists of a signal conditioner followed by an analog to digital (A/D) converter, performing repetitive conversions at a free running, internally determined rate. The outputs are in digital code words including over range indication, polarity information and a status output to indicate when the output digits are valid.

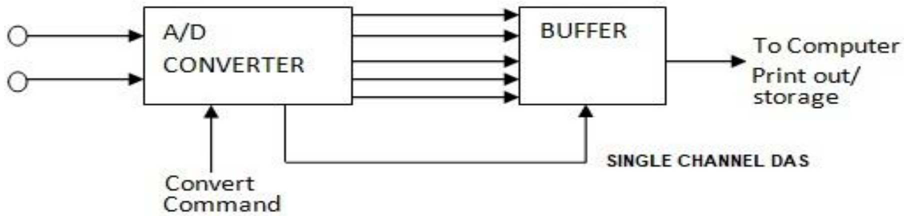


Fig: **Block Diagram of Single Channel DAS**

A Single Channel Data Acquisition System is shown in Fig. The digital outputs are further fed to a storage or printout device, or to a digital computer device, or to a digital computer for analysis.

The popular Digital panel Meter (DPM) is a well-known example of this. However, there are two major drawbacks in using it as a DAS.

1. It is slow and the BCD has to be changed into binary coding, if the output is to be processed by digital equipment.
2. While it is free running, the data from the A/D converter is transferred to the interface register at a rate determined by the DPM itself, rather than commands beginning from the external interface.

Multi-Channel Data Acquisition System

There will be many subsystems in a data acquisition system. They can be time shared by two or more input sources. The numbers of techniques are used for time shared measurements depending on the desired properties of the multiplexed system. It has a single A/D converter preceded by a multiplexer.

There can be number of inputs. Each signal is given to individual amplifiers. The output of the amplifiers is given to Signal condition circuits. From the output of the signal conditioning circuits the signals go to the multiplexer'. The multiplexer output is converted into digital signals by the A/D converters sequentially.

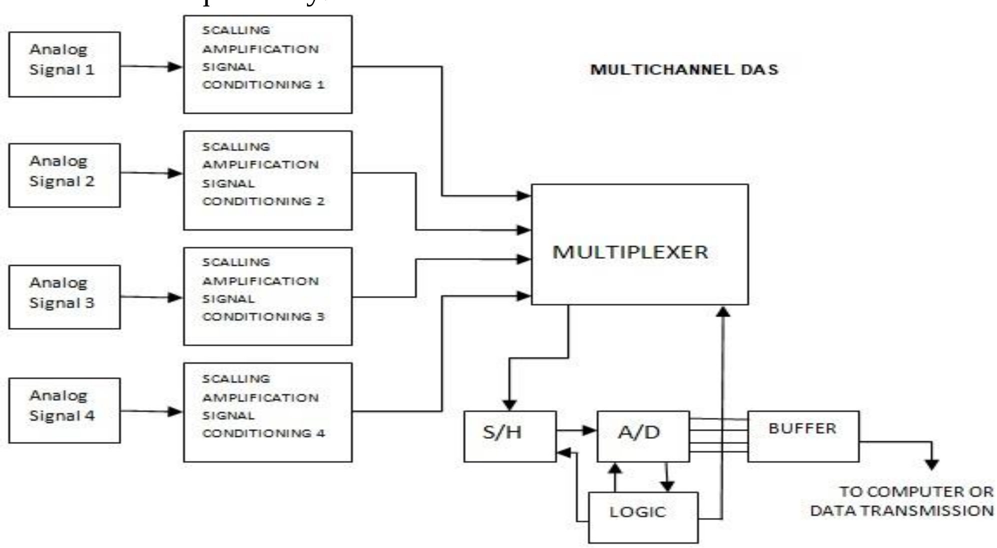


Fig: Multi Channel Data Acquisition System

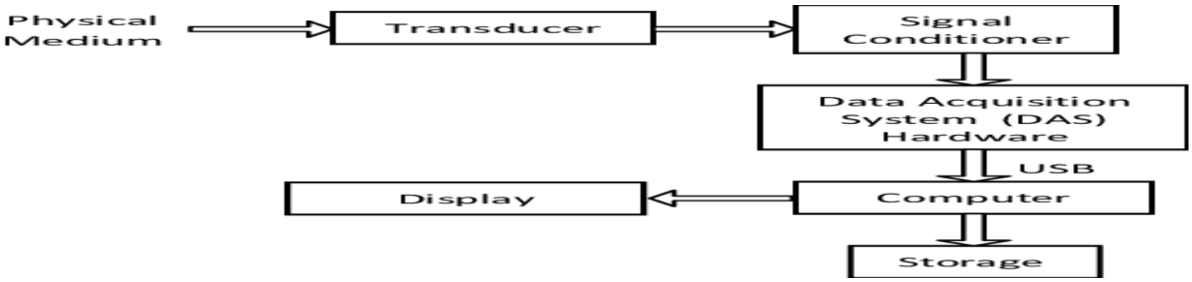
The multiplexer stores the data say of the first channel in the sample hold circuit. It then seeks the second channel. During this interval the data of the first channel will be converted into digital form. This permits utilization of time more efficiently.

When once the conversion is complete, the status line from the converter causes the sample/hold circuit to return to the sample mode. It then accepts the signal of the next channel. After acquisition of-data either immediately or on a command the sample hold circuit will be switched to the hold mode. Now conversion begins and the multiplexer selects the next channel.

This method is slow. Sample hold circuits or A/D converters are multiplexed for faster operation. However this method is less costly as majority of subsystems are shared. If the signal variations are very slow satisfactory accuracy can be obtained even without the sample hold circuit.

PC Based Data Acquisition System

The most visible trends can be seen as the effects of transition to PC-based DAQ. Now, all that processing is being done inside computers, so the instruments are interfaced to a computer with analysis being done through computer software. Thus we see a more software-defined approach to DAQ, as well as the emergence of high-speed USB-enabled DAQs.



PC-based DAQ (Data Acquisition) refers to a system where data acquisition hardware is connected to a computer for the purpose of acquiring and processing analog or digital signals.

Here's an overview of PC-based DAQ systems:

Data Acquisition Hardware: The data acquisition hardware serves as the interface between the physical signals and the computer. It typically consists of analog-to-digital converters (ADCs) for converting analog signals into digital data, digital-to-analog converters (DACs) for converting digital data into analog signals, and various input/output (I/O) channels for handling different types of signals (analog, digital, counter/timer, etc.).
The hardware may also include signal conditioning components like amplifiers, filters, and isolation circuits to enhance the quality and reliability of the acquired signals. Some PC-based DAQ systems offer modular designs, allowing users to customize and expand the system by adding or removing modules as needed.

PC Interface: The data acquisition hardware is connected to a computer via a suitable interface, such as USB (Universal Serial Bus), PCIe (Peripheral Component Interconnect Express), Ethernet, or wireless connections. The interface enables the transfer of acquired data between the hardware and the computer.

Driver and Software: To communicate with the data acquisition hardware, the computer requires device drivers and appropriate software. The device drivers establish the necessary communication protocols and provide an interface for accessing and controlling the hardware from the software applications.
The software typically includes development tools and libraries that facilitate data acquisition, signal processing, visualization, and analysis. These tools allow users to configure acquisition parameters, implement real-time processing algorithms, and visualize the acquired data in various formats.

Benefits of PC-Based DAQ:

Versatility: PC-based DAQ systems offer flexibility and adaptability due to the ability to utilize a wide range of software and hardware options.

Processing Power: PCs provide ample computing power for real-time signal processing, analysis, and visualization.

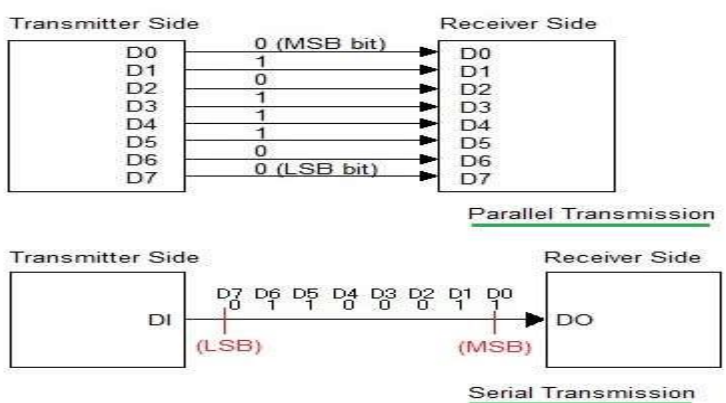
Integration: PC-based DAQ systems can easily integrate with other software and hardware components, making them suitable for complex measurement and control systems.

Cost-Effectiveness: PC-based DAQ systems are often more cost-effective compared to dedicated standalone data acquisition systems.

Series and Parallel Transmission:

The process of sending data between two or more digital devices is known as *data transmission*. Data is transmitted between digital devices using one of the two methods − serial transmission *or* parallel transmission.

Serial Transmission: In Serial Transmission, data-bit flows from one computer to another computer in bi-direction. In this transmission, one bit flows at one clock pulse. In Serial Transmission, 8 bits are transferred at a time having a start and stop bit.



Parallel Transmission: In Parallel Transmission, many bits are flow together simultaneously from one computer to another computer. Parallel Transmission is faster than serial transmission to transmit the bits. Parallel transmission is used for short distance.

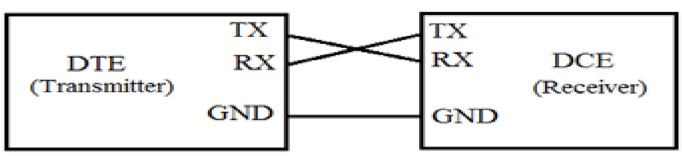
Difference between Serial and Parallel Transmission

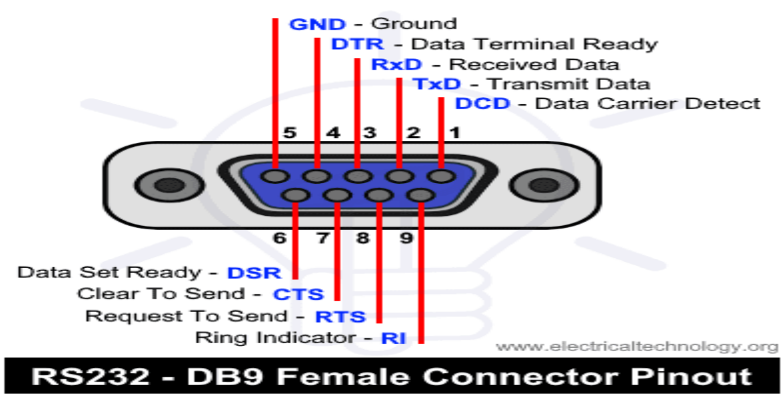
Key	Serial Transmission	Parallel Transmission
Definition	Serial Transmission is the type of transmission in which a single communication link is used to transfer the data from one end to another.	Parallel Transmission is the mode of transmission in which multiple parallel links are used that transmits each bit of data simultaneously.
Bit Transmission	In case of Serial Transmission, only one bit is transferred at one clock pulse.	In case of Parallel Transmission, 8-bits transferred at one clock pulse.

Key	Serial Transmission	Parallel Transmission
Cost Efficiency	As single link is used in Serial Transmission, it can be implemented easily without having to spend a huge amount. It is cost efficient.	Multiple links need to be implemented in case of Parallel Transmission, hence it is not cost efficient.
Performance	As single bit gets transmitted per clock in case of Serial Transmission, its performance is comparatively lower as compared to Parallel Transmission.	8-bits get transferred per clock in case of Parallel transmission, hence it is more efficient in performance.
Preference	Serial Transmission is preferred for long distance transmission.	Parallel Transmission is preferred only for short distance.
Complexity	Serial Transmission is less complex as compared to Parallel Transmission.	Parallel Transmission is more complex as compared to Serial Transmission.

Features and Application of RS232 cable

The term RS232 stands for "Recommended Standard 232" and it is a type of serial communication used for transmission of data normally in medium distances, it is used for connecting computer and its peripheral devices to allow serial data exchange between them. As it obtains the voltage for the path used for the data exchange between the devices. It is used in serial communication up to 50 feet with the rate of 1.492kbps. As EIA defines, the RS232 is used for connecting **Data Transmission Equipment (DTE)** and **Data Communication Equipment (DCE)**.





RS232 Features

1. RS232 uses Asynchronous communication so no clock is shared between PC and MODEM.
2. Logic '1' on pin is stated by voltage of range '-15V to -3V' and Logic '0' on pin is stated by voltage of range '+3V to +15V'. The logic has wide voltage range giving convenience for user.
3. MAX232 IC can be installed easily to establish **RS232 interface with microcontrollers**.
4. Full duplex interface of RS232 is very convenient.
5. Two pin simplex RS232 interface can also be established easily if required.
6. A maximum data transfer speed of 19 Kbps(Kilobits per second) is possible through RS232
7. A maximum current of 500mA can be drawn from pins of RS232
8. The interface can be established up to a distance of 50 feet.

Applications of RS232 Cables

- Serial Communication between Computers and Peripherals such as modems, printers, barcode scanners, and industrial control devices. This enables data exchange and control between the computer and the peripheral device.
- Configuration and Programming of Devices including routers, switches, network devices, and embedded systems. It allows users to access the device's command-line interface or configuration menu.
- Industrial Automation and Control to enables communication between programmable logic controllers (PLCs), human-machine interfaces (HMIs), and other control devices.
- Point-of-Sale Systems for connecting cash drawers, barcode scanners, and receipt printers to the main terminal. This allows the exchange of transaction data between different components of the system.
- Data Acquisition and Instrumentation used for connecting data acquisition devices, such as sensors, data loggers, and measuring instruments, to a computer or control system. This enables the collection and analysis of data from various sensors and instruments.

Features and application of IEEE 1248 B

IEEE 1248-2020 is titled "Standard for Analog-to-Digital Converter (ADC) Testing - Methods and Metrics." This standard provides guidelines and methods for testing the performance of analog-to-digital converters (ADCs) used in various applications.

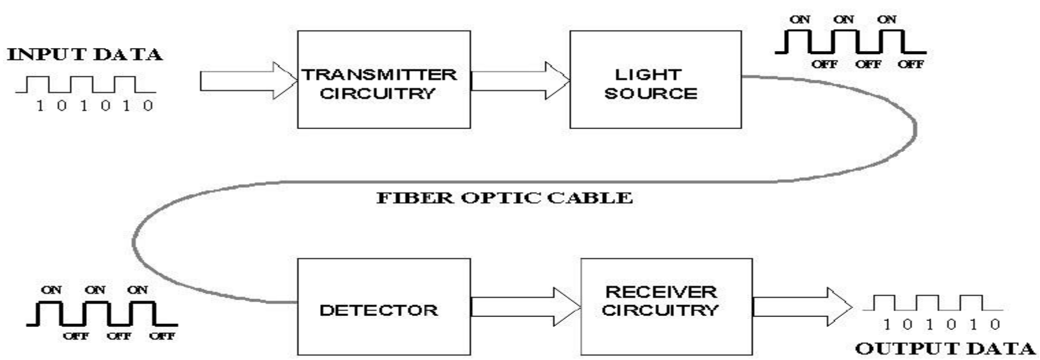
Key Features of IEEE 1248-2020

- ADC Testing Methods: The standard outlines various methods for evaluating the performance of ADCs. This includes testing the accuracy, linearity, resolution, dynamic range, and other important parameters of the ADC.
- Performance Metrics: IEEE 1248-2020 defines several performance metrics for characterizing the quality and reliability of ADCs. These metrics help in assessing the ADC's ability to convert analog signals into digital representation accurately.
- Test Procedures: The standard provides recommended test procedures for conducting the tests specified in the standard. It covers aspects such as test setup, test signals, measurement techniques, and data analysis.
- Reporting Requirements: IEEE 1248-2020 specifies the information that should be included in test reports to ensure clear and consistent documentation of ADC performance.

Optical Communication, Fiber Optics, Electro-Optic Conversion Devices

Optical Communication

Optical Fiber Communication is the method of communication in which signal is transmitted in the form of light and optical fiber is used as a medium of transmitting those light signal from one place to another. The signal transmitted in optical fiber is converted from the electrical signal into light and at the receiving end; it is converted back into the electrical signal from the light. The data sent can be in the form of audio, video or telemetry data that is to be sent over long distances or over Local Area Networks.



Transmitter side: On the transmitter side, first if the data is analog, it is sent to a coder or converter circuit which converts the analog signal into digital pulses of 0,1,0,1…(depending on how the data is) and passed through a **light source transmitter circuit**. And if the input is digital then it is directly sent through the light source transmitter circuit which converts the signal in the form of light waves.

Optical Fiber Cable: The light waves received from the transmitter circuit to the fiber optic cable is now transmitted from the source location to destination & received at the receiver block.

Receiver Side: Now on the receiver side the **photocell**, also known as the light detector, receives the light waves from the optical fiber cable, amplifies it using the amplifier and converts it into the proper digital signal. Now if the output source is digital then the signal is not changed further

and if the output source needs analog signal then the digital pulses are then converted back to an analog signal using the decoder circuit.
The whole process of transmitting an electrical signal from one point to other by converting it into light using Fiber optic-cable as transmission source is called **Optical Fiber Communication**.

<u>Fiber Optics:</u>
Fiber optics involves the transmission of light signals through optical fibers, which are typically made of glass or plastic. These fibers have the ability to guide light through multiple reflections, allowing for efficient and high-speed transmission of data over long distances. The Fiber optic cable is made of high-quality extruded glass (si) or plastic, and it is flexible. The diameter of the fiber optic cable is in between 0.25 to 0.5mm (slightly thicker than a human hair).

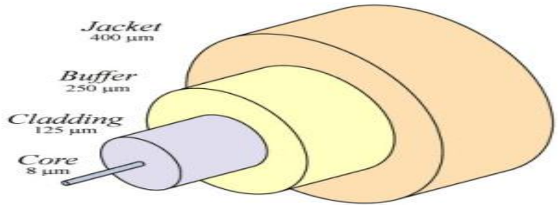


Fig: Fiber Optic Cable

Key features of fiber optics include:

- **Low Loss** enabling data to be transmitted over long distances without significant degradation.
- **Large Transmission capacity**
- **Easy Amplification**
- **High Bandwidth** allowing for the transmission of large amounts of data simultaneously.
- **Immunity to Electromagnetic Interference** making them suitable for use in environments with high electrical noise.
- **Lightweight and Flexible** making them easy to install and for various applications.

<u>Electro-optic Conversion Devices</u>:
Electro-optic conversion devices, also known as optoelectronic devices, are essential components in optical communication systems. These devices facilitate the conversion of electrical signals to optical signals and vice versa. Some commonly used electro-optic conversion devices include:

- **Light Emitting Diodes (LEDs):** LEDs are used as light sources in optical communication systems. They convert electrical signals into light signals, typically in infrared or visible spectrum.
- **Laser Diodes**: Laser diodes are another type of light source used in optical communication. They produce coherent & highly focused light, making them suitable for long-distance transmission.

- **Photodiodes**: Photodiodes are used to convert optical signals back into electrical signals. They detect and convert light intensity variations into electrical current, allowing for signal detection and processing.
- **Modulators**: Modulators are devices that modulate the intensity, phase, or frequency of an optical signal in response to an electrical signal. They are used to encode information onto the optical carrier signal for transmission.

These electro-optic conversion devices enable the transmission, reception, and processing of data in optical communication systems. They are integrated into transmitters, receivers, and other system components to ensure efficient and reliable communication.

Overall, fiber optics and electro-optic conversion devices are crucial components in optical communication systems, enabling high-speed, long-distance, and secure data transmission in various applications.

Unit IV: Data Converter and Connectors

Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC): Principle and Specification

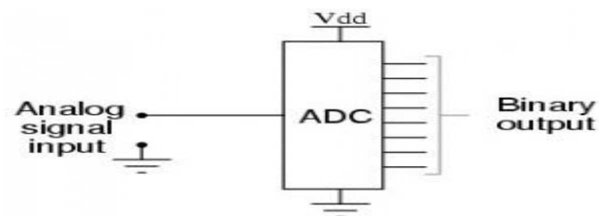
All the real world quantities are analog in nature. Therefore, this system needs an intermediate device to convert the analog temperature data into digital data in order to communicate with digital processors like microcontrollers and microprocessors. Analog to Digital Converter (ADC) is an electronic integrated circuit used to convert the analog signals such as voltages to digital or binary form consisting of 1s and 0s. Most of the ADCs take a voltage input as 0 to 10V, -5V to +5V, etc., and correspondingly produces digital output as some sort of a binary number.

There are two **types of data converters** −

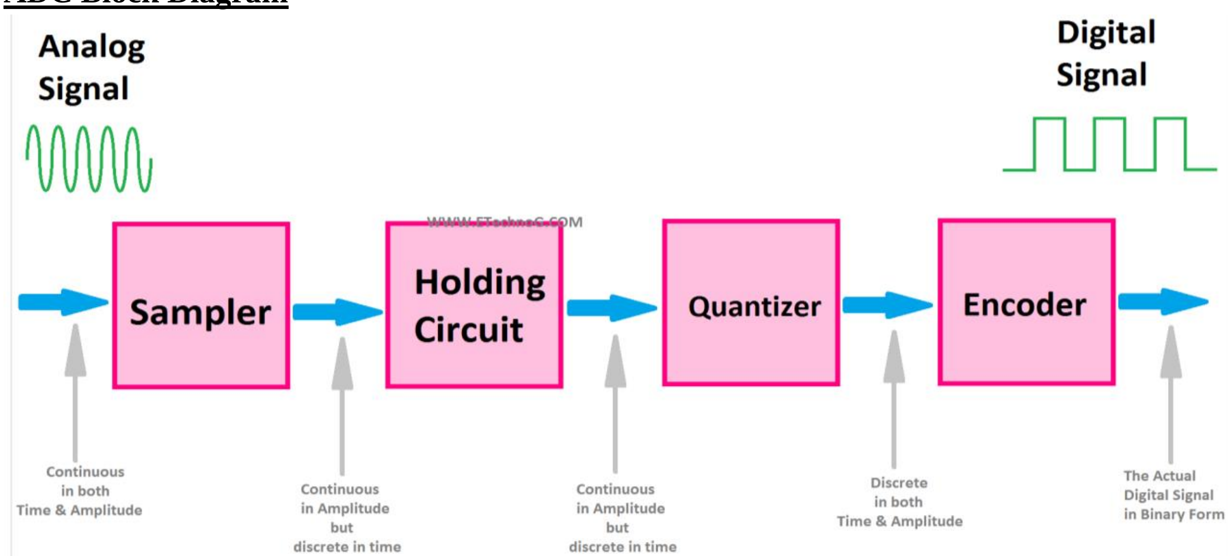
- Analog to Digital Converter
- Digital to Analog Converter

Analog to Digital Converter

A converter that is used to change the analog signal to digital is known as an analog to digital converter or ADC converter. This converter is one kind of integrated circuit or IC that converts the signal directly from continuous form to discrete form.



<u>ADC Block Diagram</u>



The analog signal is first applied to the '**sample**' block where it is sampled at a specific sampling frequency. The sample amplitude value is maintained and held in the '**hold**' block. It is an analog value. The hold sample is quantized into discrete value by the '**quantize**' block. At last, the '**encoder**' converts the discrete amplitude into a binary number.

Analog To Digital Conversion Steps

The conversion from analog signal to a digital signal in an analog to digital converter is explained below using the block diagram given above.

Sampler: Sampler is a circuit that takes samples from the continuous analog signal according to its sample frequency. The sampling frequency is set according to the requirement. Basically, the sampler converts the continuous-time-continuous amplitude signal into a continuous amplitude-discrete time signal.

Holding Circuit: Holding circuit does not convert anything it just holds the samples generated by the sampler circuit. It holds the first sample until the next sample comes from the sampler. Once the new sample comes from the sampler to the holding circuit it releases the old sample to its next block.

Quantizer: Quantizer quantized the signal which means it converts the continuous amplitude-discrete time signal into discrete time-discrete amplitude signal. It breaks or splits the samples into small parts.

Encoder: Encoder is the circuit that actually generates the digital signal into binary form. The output from encoder is fed to the next circuitry. Here, is the end of the analog to a digital circuit.

As we know that the digital devices operate on binary signals so it is necessary to convert the digital signal into the binary form using the Encoder. This is the whole process of converting an Analog signal into digital form using an **Analog to Digital Converter**. This whole conversion occurs in a microsecond.

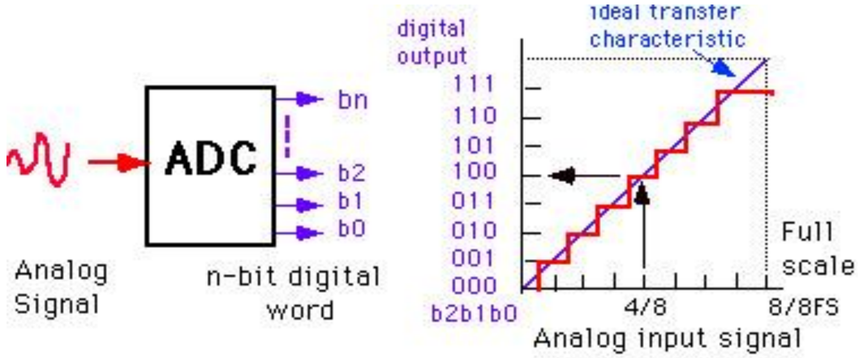


Fig: Analog to Digital Conversion Process

Characteristics of ADC (Analog to Digital converter)

Some of the important characteristics of ADC are:

1. Resolution:

- Resolution is defined as the maximum number of digital output codes. This is the same as that of a DAC.

$$Resolution = 2^n$$

- Alternatively, resolution can be defined as the ratio of the change in the value of the input analog voltage V_A, required to change the digital output by 1 LSB.

$$Resolution = \frac{VF}{2^n - 1}$$

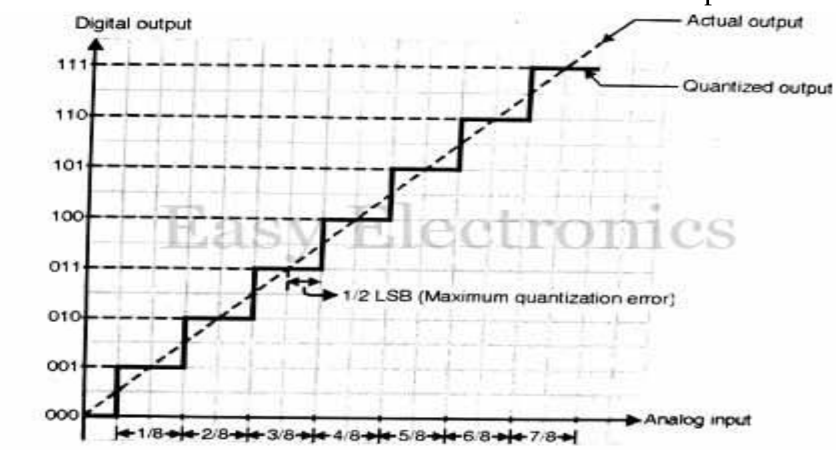
2. Conversion Time:

- It is the total time required to convert analog signal into a corresponding digital output.
- As we know, the conversion time depends on the conversion technique used for an ADC.

- The conversion time also depends on the propagation delay introduced by the circuit components.
- Conversion time should ideally be zero and practically as small as possible.

3. Quantization Error:

- Quantization error is a type of error that occurs during the process of digitizing analog signals. It arises due to the discrete nature of digital representation, where the continuous range of analog values is converted into a finite set of discrete digital values.
- As shown in the figure, the digital output is not always an accurate representation of the analog input.
- For example, any input voltage between 1/8 and 2/8 of full scale will be converted to a digital word of "001". This approximation process is called quantization and the error due to quantization is called quantization error.
- The maximum value of **quantization error is ±1/2 LSB**.
- The quantization error should be as small as possible. It can be reduced by increasing the number of bits. The increase in the number of bits will also improve resolution.



A graph of input and output voltages for an ADC

And it is given as,

$$QE = \frac{ViFS}{2(2n - 1)}$$

Where 'ViFS' is the full-scale input voltage

'n' is the number of output bits.

Maximum the number of bits selected, finer the resolution and smaller the quantization error.

Sampling Theorem

The sampling theorem states that a continuous-time signal needs to be uniformly sampled at a minimum rate in order to recover or reconstruct the original signal.

In sampling theorem, the input signal is in an analog form of signal and the second input signal is a sampling signal, which is a pulse train signal and each pulse is equidistance with a period of "Ts". This sampling signal frequency should be more than twice of the input analog signal frequency. If this condition satisfies, analog signal perfectly represented in discrete form else analog signal may be losing its amplitude values for certain time intervals.

The sampling theorem can be defined as the conversion of an analog signal into a discrete form by taking the sampling frequency as twice the input analog signal frequency. Input signal frequency denoted by Fm and sampling signal frequency denoted by Fs.

$$\mathbf{Fs \geq 2Fm}$$

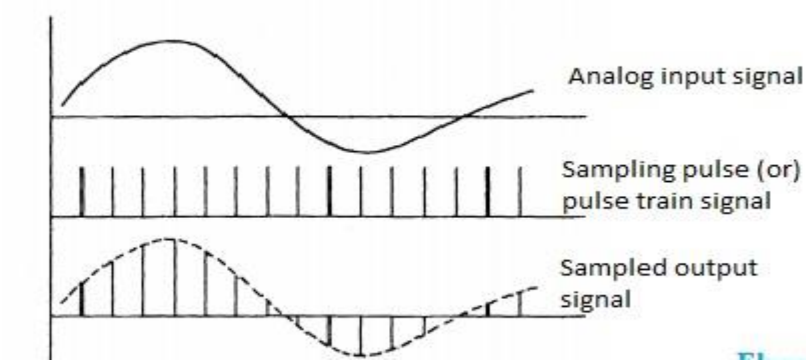
Nyquist Rate: If the sampling frequency (Fs) equals twice the input signal frequency (Fm), then such a condition is called the Nyquist Criteria for sampling. When sampling frequency equals twice the input signal frequency is known as “Nyquist rate”.

$$\mathbf{Fs = 2Fm}$$

Aliasing Effect: If the sampling frequency (Fs) is less than twice the input signal frequency, such criteria called an Aliasing effect.

$$\mathbf{Fs < 2Fm}$$

So, there are three conditions that are possible from the sampling frequency criteria. They are sampling, Nyquist and aliasing states. Now we will see the Nyquist sampling theorem.



Types of ADC

ADCs all perform the same function, but with different converter circuit architectures and capabilities. Two of the primary capabilities where these types of ADCs differ are in their sample rate and resolution, which arises due to the different conversion circuitry used in these components.

a) Flash Type/Parallel ADC

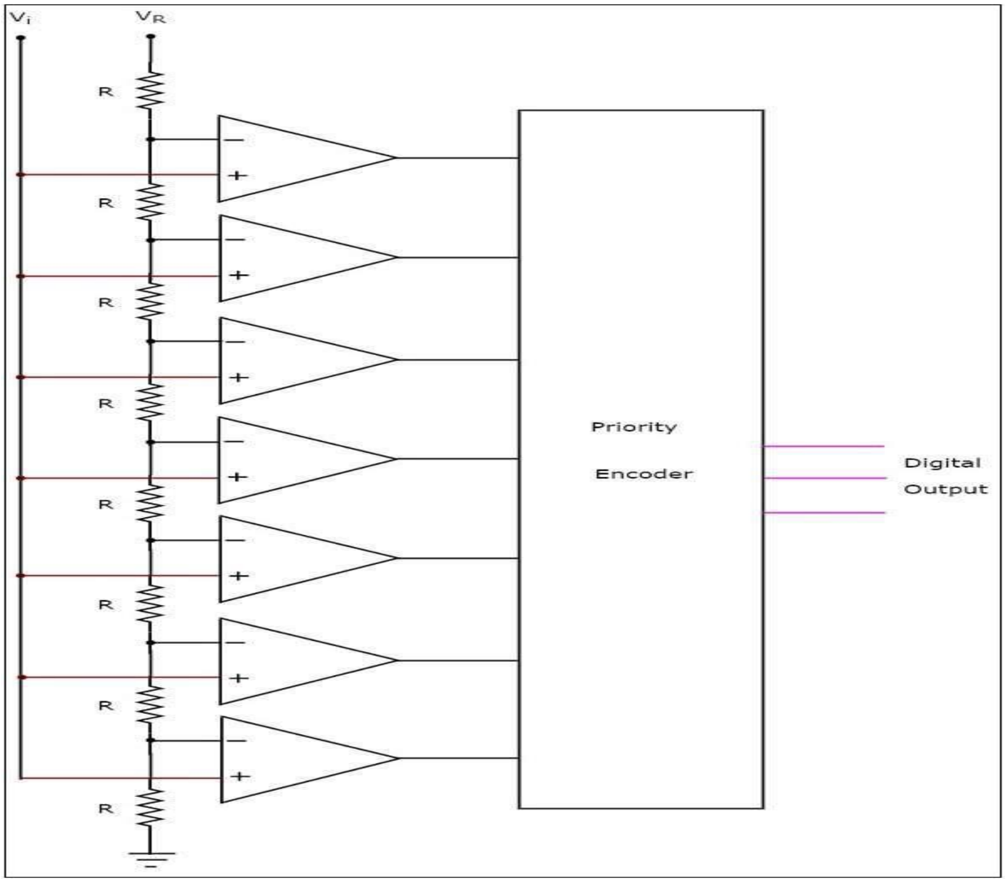
Flash ADCs are, perhaps, the simplest in concept of the ADCs and are **very fast**, but they tend to be **large and expensive**. They derive their name from the parallel configuration of ‘comparator’ reference voltages used in the conversion process. A **flash type ADC** produces an equivalent digital output for a corresponding analog input in no time. So, flash type ADC is fastest ADC.

Basic operation:

- The analog input voltage is compared with a set of (known) fixed reference voltages operating in parallel—the more reference voltages used, the better the resolution
- To generate an *n*-bit result, $2^n - 1$ reference voltage comparators are required—e.g., 4-bit resolution requires 15 reference voltages, 8-bit resolution requires 255 reference voltages comparators, and so on.

- One end of the comparator array is connected to the analog voltage, while the other end is connected to a series of resistors set up as voltage dividers.

The **circuit diagram** of a 3-bit flash type ADC is shown in the following figure



The **working** of a 3-bit flash type ADC is as follows.

- The **voltage divider network** contains 8 equal resistors. A reference voltage V_R is applied across that entire network with respect to the ground. The voltage drop across each resistor from bottom to top with respect to ground will be the integer multiples (from 1 to 8) of $V_{R8.}$
- The external **input voltage** Vi is applied to the non-inverting terminal of all comparators. The voltage drop across each resistor from bottom to top with respect to ground is applied to the inverting terminal of comparators from bottom to top.
- At a time, all the comparators compare the external input voltage with the voltage drops present at the respective other input terminal. That means, the comparison operations take place by each comparator **parallelly**.
- The **output of the comparator** will be '1' as long as Vi is greater than the voltage drop present at the respective other input terminal. Similarly, the output of comparator will be '0', when, Vi is less than or equal to the voltage drop present at the respective other input terminal.

- All the outputs of comparators are connected as the inputs of **priority encoder**. This priority encoder produces a binary code (digital output), which is corresponding to the high priority input that has ‘1’.
- Therefore, the output of priority encoder is nothing but the binary equivalent **(digital output)** of external analog input voltage, Vi.

Pros:

- Fastest ADC method, capable of sampling rates in the gigahertz range

Cons:

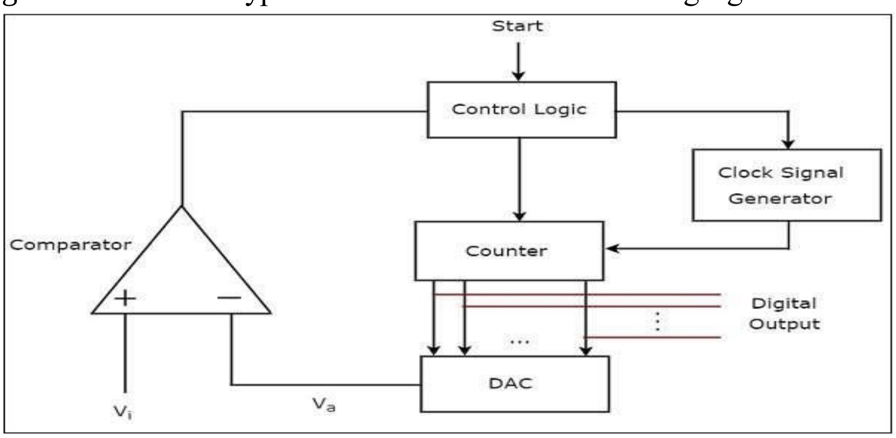
- The higher the resolution, the larger the flash ADC needs to be, requiring more power and limiting the sample rate—an 8-bit resolution tends to achieve a sensible balance between power and precision and is a popular configuration
- Larger and more expensive than other ADC configurations

Q) Design a 2-bit flash type ADC with its working principle if the reference voltage is 10V and input voltage is 5V.

b) Ramp/Counter type ADC

A counter type ADC produces a digital output, which is approximately equal to the analog input by using counter operation internally.

The block diagram of a counter type ADC is shown in the following figure −



The counter type ADC mainly consists of 5 blocks: Clock signal generator, Counter, DAC, Comparator and Control logic.

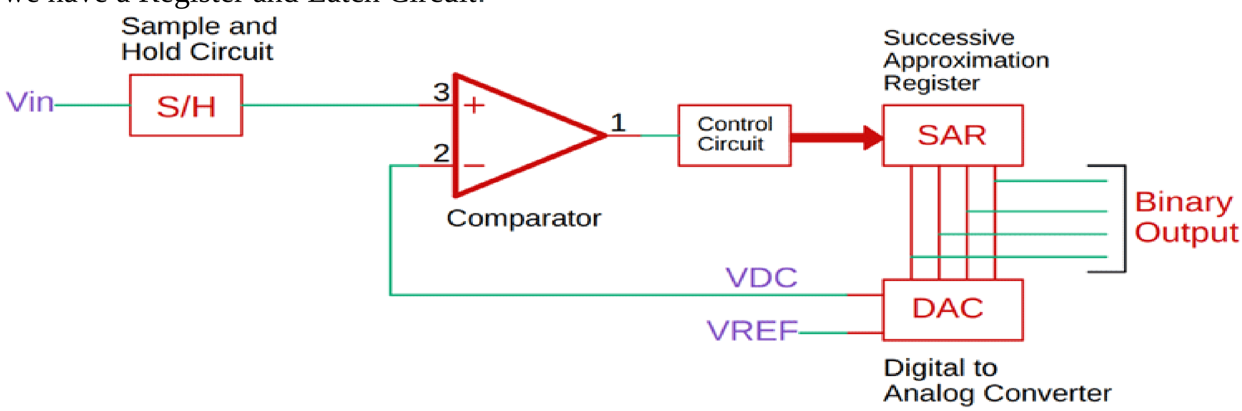
The working of a counter type ADC is as follows −

- The **control logic** resets the counter and enables the clock signal generator in order to send the clock pulses to the counter, when it received the start commanding signal.
- The **counter** gets incremented by one for every clock pulse and its value will be in binary (digital) format. This output of the counter is applied as an input of DAC.
- **DAC** converts the received binary (digital) input, which is the output of counter, into an analog output. Comparator compares this analog value,Va with the external analog input value Vi.

- The **output of comparator** will be **'1'** as long as Vi is greater than. The operations mentioned in above two steps will be continued as long as the control logic receives '1' from the output of comparator.
- The **output of comparator** will be **'0'** when Vi is less than or equal to Va. So, the control logic receives '0' from the output of comparator. Then, the control logic disables the clock signal generator so that it doesn't send any clock pulse to the counter.
- At this instant, the output of the counter will be displayed as the **digital output**. It is almost equivalent to the corresponding external analog input value Vi.

c) Successive Approximation Type ADC

The Successive Approximation Register (SAR) type ADC is an **extremely popular implementation for a long time**. SAR is a very popular ADC configuration since it offers a good balance between speed, resolution, and fidelity for a wide variety of signal types. They are slower than flash ADCs, however, since they must pause and reset after each trial. The block diagram of SAR ADC, it is similar to the Counter ADC except that in place of the main Counter, we have a Register and Latch Circuit.



The **working** of a successive approximation ADC is as follows −

- The **control logic** resets all the bits of SAR and enables the clock signal generator in order to send the clock pulses to SAR, when it received the start commanding signal.
- The binary (digital) data present in **SAR** will be updated for every clock pulse based on the output of comparator. The output of SAR is applied as an input of DAC.
- **DAC** converts the received digital input, which is the output of SAR, into an analog output. The comparator compares this analog value Va with the external analog input value Vi.
- The **output of a comparator** will be '1' as long as Vi is greater than Va. Similarly, the output of comparator will be '0', when Vi is less than or equal to Va.
- The operations mentioned in above steps will be continued until the digital output is a valid one.

The digital output will be a valid one, when it is almost equivalent to the corresponding external analog input value Vi.

Pros:

- Relatively simple circuit design (only one comparator required)
- Offers a good balance between speed and resolution
- Versatile for different signal types (wave shapes)

Cons:

- Only intermediate speeds can be achieved (slower than flash but faster than delta-sigma ADCs)
- Limited bit resolution—typically 8 to 18 bits—which is lower than delta-sigma ADCs
- Not good at handling spikes in the analog input voltage
- Requires separate (external) anti-aliasing filtering
- Susceptible to high-frequency quantization noise

Steps.

(1) The MSB is initially set to 1 with the remaining three bits set as 000. The digital equivalent voltage is compared with the unknown analog input voltage.

(2) If the analog input voltage is higher than the digital equivalent voltage, the MSB is retained as 1 and the second MSB is set to 1. Otherwise, the MSB is set to 0 and the second MSB is set to 1. Comparison is made as given in step (1) to decide whether to retain or reset the second MSB.

Let us assume that the 4-bit ADC is used and the analog input voltage is V_A = 11 V and reference voltage is 16V.

Step 1:

When the conversion starts, the MSB bit is set to 1. i.e. i/p = 1000

Let, input to DAC = 1000 =$d_3\ d_2\ d_1\ d_0$

Vout = $\frac{16}{16}$ { 8 + 0 + 0 + 0 }

= 8 V < Input Voltage (V)

Since the unknown analog input voltage V_A is higher than the equivalent digital voltage V_D, as discussed in step (2), the MSB is retained as 1 and the next MSB bit is set to 1 as follows

Step: 2

So, Let, input to DAC = 1100 =$d_3\ d_2\ d_1\ d_0$

Vout = $\frac{16}{16}$ { 8 + 4 + 0 + 0 }

= 12 V > input voltage

Here now, the unknown analog input voltage V_A is lower than the equivalent digital voltage V_D. As discussed in step (2), the second MSB is set to 0 and next MSB set to 1 as

Step: 3

Let, input to DAC = 1010 =$d_3\ d_2\ d_1\ d_0$

So, Vout = $\frac{16}{16}$ { 8 + 0 + 2 + 0 }

= 10V < input voltage

Again as discussed in step (2) VA>VD, hence the third MSB is retained to 1 and the last bit is set to 1.

Step: 4

Let, input to DAC = 1011 =$d_3\ d_2\ d_1\ d_0$

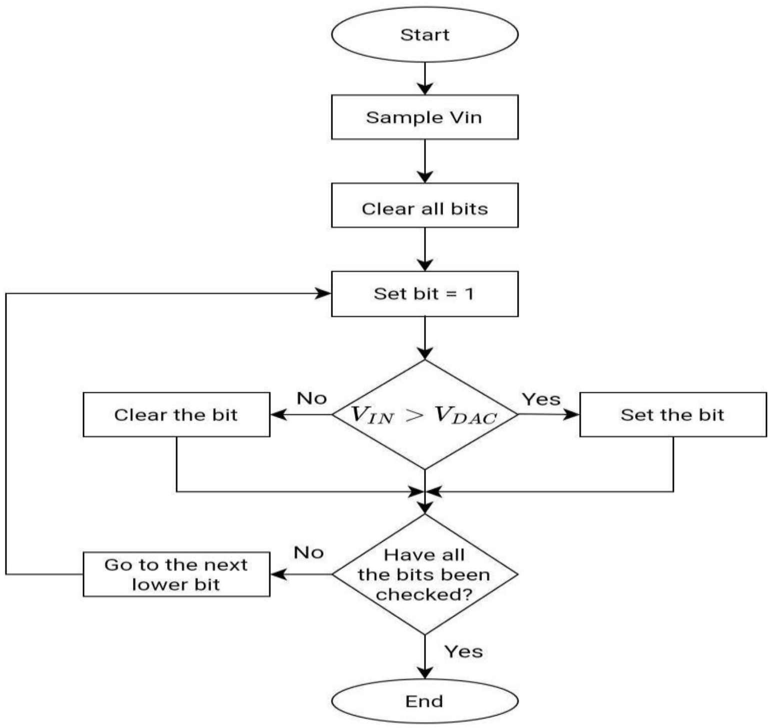
Vout = $\frac{16}{16}$ { 8 + 0 + 2 + 1 }

= 11V = input voltage

Now finally $V_A = V_D$, and the conversion stops.

So, The nearest digital input is 1011.

Flowchart of SAR



Q) **Find digital output of 4 bit SAR if input is 3.2V and reference voltage is 5 V.**

Solution:

We have , Formula of DAC

Vout = $\frac{Vref}{2^n}$ { $d_{n-1}2^{n-1} + d_{n-2}2^{n-2} + d_{n-3}2^{n-3} + \ldots\ldots\ldots\ldots\ldots + d_1 2^1 + d_0 2^0$ }

For 4 bit,

Vout = $\frac{Vref}{4}$ { $d_3 2^3 + d_2 2^2 + d_1 2^1 + d_0 2^0$ }

Step: 1

Let, input to DAC = 1000 =$d_3\ d_2\ d_1\ d_0$

Vout = $\frac{5}{16}$ { 8 + 0 + 0 + 0 }

= 2.5V < input Voltage (3.2V)

So, set d_3 and set d_2

Step: 2

So, Let, input to DAC = 1100 =$d_3\ d_2\ d_1\ d_0$

Vout = $\frac{5}{16}$ { 8 + 4 + 0 + 0 }

= 3.75V < input voltage (3.2V)

So, reset d_2 and set d_1

Step: 3

Let, input to DAC = 1010 =d_3 d_2 d_1 d_0

So, Vout = $\frac{5}{16}$ { 8 + 0 + 2 + 0 }

= 3.125V < input voltage (3.2V)

So, set d_1 and set d_0

Step: 4

Let, input to DAC = 1011 =d_3 d_2 d_1 d_0

Vout = $\frac{5}{16}$ { 8 + 0 + 2 + 1 }

= 3.4375V < input voltage (3.2V)

So, reset d_0.

Step: 5

Let, input to DAC = 1010 =d_3 d_2 d_1 d_0

So, Vout = $\frac{5}{16}$ { 8 + 0 + 2 + 0 }

= 3.125V < input voltage (3.2V)

Repeted,

So, The nearest digital input is 1010.

Q) Find the digital output from the SAR if the input voltage is 11.1 V.

d) Dual Slope ADC/integrating ADC

In this type of ADC converter, comparison voltage is generated by using an integrator circuit which is formed by a resistor, capacitor, and operational amplifier combination. By the set value of Vref, this integrator generates a saw tooth waveform on its output from zero to the value Vref. When the integrator waveform is started correspondingly counter starts counting from 0 to 2^{n-1} where n is the number of bits of ADC.

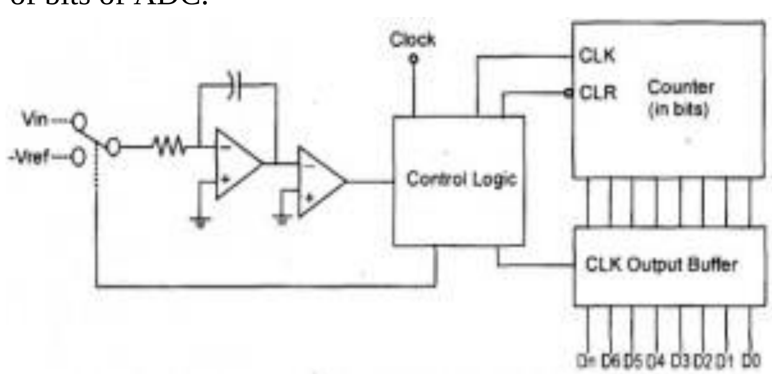


Fig: Dual Slope Analog to Digital Converter

When the input voltage Vin equal to the voltage of the waveform, then the control circuit captures the counter value which is the digital value of the corresponding analog input value. This **Dual slope ADC is a relatively medium cost and slow speed device.**

e) Introduction to Delta-Sigma ADC

A newer ADC design is the delta-sigma ADC (or delta converter), which takes advantage of DSP technology in order to improve amplitude axis resolution and reduce the high-frequency quantization noise inherent in SAR designs.

The **complex and powerful design** of delta-sigma ADCs makes them ideal for dynamic applications that require as much amplitude axis resolution as possible. This is why they are commonly found in audio, sound, and vibration, and a wide range of high-end data acquisition applications. They are also **used extensively in precision industrial measurement applications**.

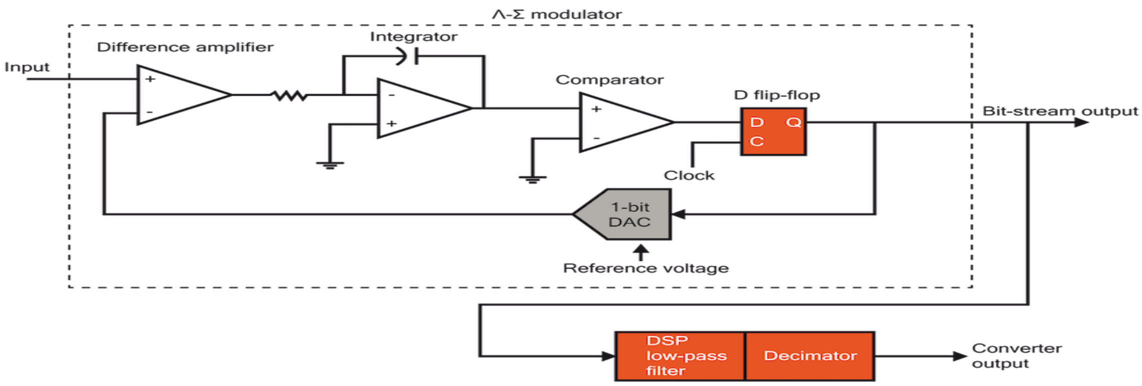


Fig: Typical Delta-Sigma ADC block diagram

A low-pass filter implemented in a DSP eliminates virtually quantization noise, resulting in excellent signal-to-noise performance.

Delta-sigma ADCs work by over-sampling the signals far higher than the selected sample rate. The DSP then creates a high-resolution data stream from this over-sampled data at the rate that the user has selected. This over-sampling can be up to hundreds of times higher than the selected sample rate. This approach creates a very high-resolution data stream (24-bits is common) and has the advantage of allowing multistage anti-aliasing filtering (AAF), making it virtually impossible to digitize false signals. However, it does impose a kind of speed limit, so delta-sigma ADCs are typically not as fast as SAR ADCs, for example.

Pros

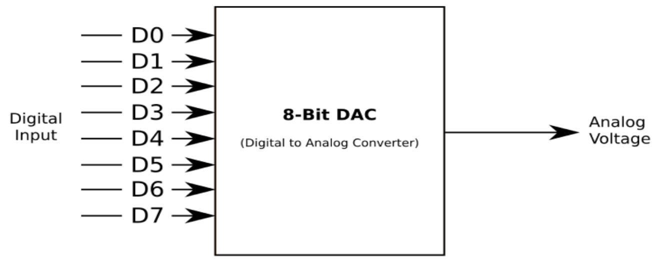
- High-resolution output (24-bits)
- Over-sampling reduces quantization noise
- Inherent Anti-aliasing filtering

Cons

- Limited to around 200 kS/s sample rate
- Do not handle unnatural shape waveforms as well as SAR

Digital to Analog Converter

Digital to Analog Converter (DAC) is an integrated circuit that converts digital signal to analog voltage/current which is necessary for further Analog Signal Processing. DAC basically converts digital code that represents digital value to analog current or voltage. Fig. shows a block diagram of DAC circuit which shows 8-bit digital inputs converted to Analog Signal.



Working of DAC

The digital binary data exists in the form of bits. Each bit is either 1 or 0 & they represent its weight corresponding to its position. The weight is 2^n where the n is the position of the bit from right hand side & it start from 0.

$$\text{Bit Weight} = 2^n$$

$$\text{Bit weight of } 4^{th} \text{ bit from left} = 2^n = 2^3 = 8$$

The bit weight is multiplied by the bit value. Since the bit could be either 0 or 1, it means;

$$\text{Bit value of 1 x bit weight} = 1 \times 2^n = 2^n$$

$$\text{Bit value of 0 x bit weight} = 0 \times 2^{(n-1)} = 0$$

Let,

Consider n bit digital number = a b c d = $d_3\ d_2\ d_1\ d_0$

d_3 = MSB

d_1 = LSB

Its respective analog value = $d_0 2^0 + d_1 2^1 + d_2 2^2 + \ldots\ldots\ldots\ldots + d_{n-1} 2^{n-1}$

Suppose a four bit system having full range E_R volts, then for different combination of digital input, analog voltage is given by

Digital Input	Analog Value
1000	$E_R/2$ i.e. range of MSB= $E_R/2$
0100	$E_R/2^2$
0010	$E_R/2^3$
1000	$E_R/2^4$ i.e. range of LSB= $E_R/2^n$

Full scale o/p voltage is given by

$$E_0 = \frac{ER}{2} + \frac{ER}{2^2} + \frac{ER}{2^3} + \frac{ER}{2^4}$$

$$E_0 = E_R \{ 1*2^{-1} + 1*2^{-2} + 1*2^{-3} + 1*2^{-4} \}$$

$$E_0 = E_R \{ d_3*2^{-1} + d_2*2^{-2} + d_1*2^{-3} + d_0*2^{-4} \}$$

$$E_0 = \frac{ER}{16} \{ d_3*2^3 + d_2*2^2 + d_1*2^1 + d_0*2^0 \}$$

Thus, for n bit

$$E_0 = \frac{ER}{2^n} \{ d_{n-1}*2^{n-1} + d_{n-2}*2^{n-2} + \ldots\ldots\ldots\ldots + d_1*2^1 + d_0*2^0 \}$$

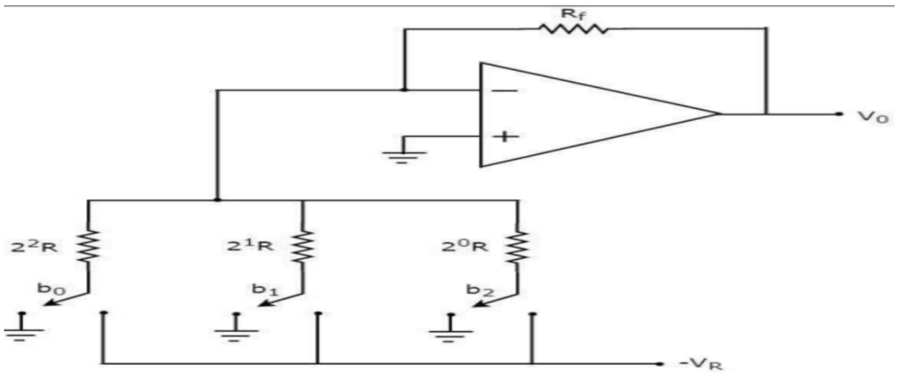
This is how the digital to analog converter DAC works by adding the weights of all corresponding bits with its value to generate the analog value at its output.

Types of Digital to Analog Converter

- Binary Weighted Resistor D/A Converter Circuit
- Binary ladder or R–2R ladder D/A Converter Circuit
- Segmented DAC
- Delta-Sigma DAC

a) Weighted Resistor DAC

DAC converts binary or non-binary numbers and codes into analog ones with its output voltage (or current) being proportional to the value of its digital input number.



The **circuit diagram** of a 3-bit binary weighted resistor DAC is shown in the following figure

The **digital switches** shown in the above figure will be connected to ground, when the corresponding input bits are equal to '0'. Similarly, the digital switches shown in the above figure will be connected to the negative reference voltage, −VR when the corresponding input bits are equal to '1'.

In the above circuit, the non-inverting input terminal of an op-amp is connected to ground. That means zero volts is applied at the non-inverting input terminal of op-amp.

$V+ = 0$

According to the **Virtual Short Concept**,

$V- = 0$

Apply kcl,

Or,$-\{ \frac{VR-V-}{2^0R} + \frac{VR-V-}{2^1R} + \frac{VR-V-}{2^2R} \} = \frac{V- -Vo}{Rf}$

Or, $-\{ \frac{VR-0}{2^0R} + \frac{VR-0}{2^1R} + \frac{VR-0}{2^2R} \} = \frac{0-V0}{Rf}$

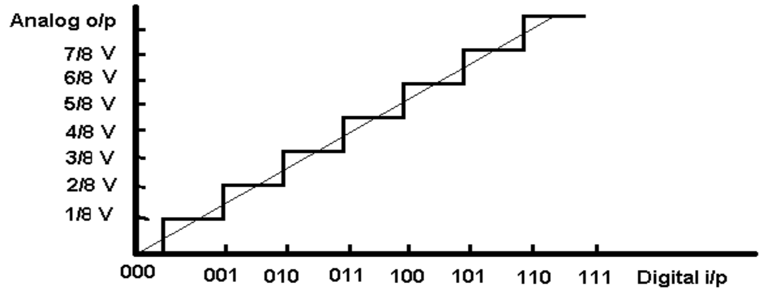
Or, $\frac{VR}{2^2R} \{ 1*2^2 + 1*2^1 + 1*2^1 \} = \frac{V0}{Rf}$

So, $Vo = \frac{VR*Rf}{2^2R} \{ 1*2^2 + 1*2^1 + 1*2^1 \}$

So, for n bit converter the output is given as

$Vo = \frac{VR*Rf}{2^{n-1}R} \{ d_{n-1}2^{n-1} + d_{n-2}2^{n-2} + d_{n-3}2^{n-3} + \ldots\ldots\ldots\ldots\ldots + d_1 2^1 + d_0 2^0 \}$

Diagram of Weighted Resistor Digital to Analog Converter for 3 bit



<u>Drawbacks</u>

- The binary-weighted DAC has quite a large gap between LSB and MSB resistors values and requires a very precise value of resistors.
- It becomes impractical for higher-order DACs and is suitable for less resolution DACs.
- The stability of the device is resistor-dependent and is difficult to maintain an accurate resistance ratio with temperature variations.

Numerical

1) Find the analog output if the reference voltage is 10V and digital input is given as

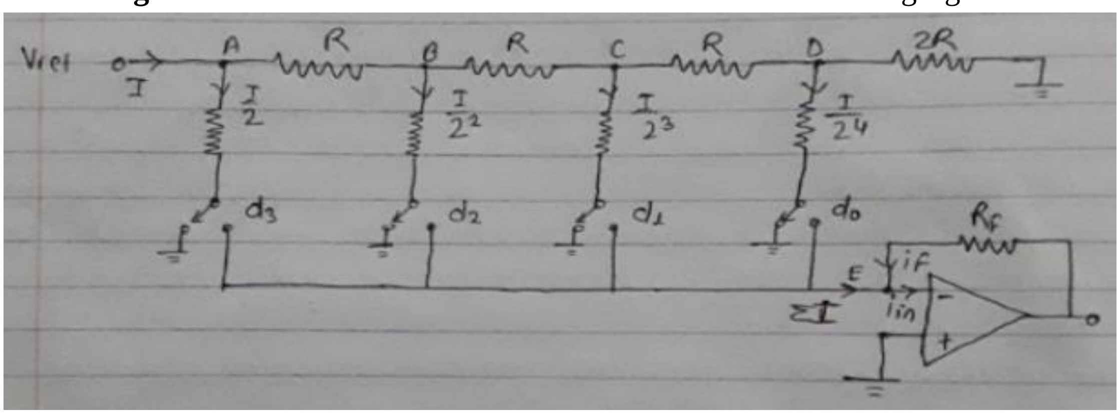
a) 1000 b) 0101 c) 1011

Using the weighted binary resistor network DAC

b) R-2R Ladder DAC

The R-2R Ladder DAC overcomes the disadvantages of a binary weighted resistor DAC. As the name suggests, R-2R Ladder DAC produces an analog output, which is almost equal to the digital (binary) input by using a **R-2R ladder network** in the inverting adder circuit.

The **circuit diagram** of a 4-bit R-2R Ladder DAC is shown in the following figure



We know that the bits of a binary number can have only one of the two values i.e., either 0 or 1. Let the **4-bit binary input** is $d_3d_2d_1d_0$. Here, the bits d_3 and d_0 denote the Most Significant Bit (MSB) and Least Significant Bit (LSB) respectively.

Let us assume all the bits are high then,

Apply kcl we get

$$\frac{I}{2}+\frac{I}{2^2}+\frac{I}{2^3}+\frac{I}{2^4} = \frac{0-Vo}{Rf}$$

$$\frac{-Vo}{Rf} = I\left\{\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3}+\frac{1}{2^4}\right\}$$

$$\frac{-Vo}{Rf} = \frac{-Vref}{R}\left\{\frac{1}{2}+\frac{1}{2^2}+\frac{1}{2^3}+\frac{1}{2^4}\right\}$$

$$\frac{-Vo}{Rf} = \frac{-Vref}{R\,2^4}\{1*2^3+1*2^2+1*2^1+1*2^0\}$$

$$Vo = \frac{Vref}{2^4}*\frac{Rf}{R}\{1*2^3+1*2^2+1*2^1+1*2^0\}$$

For n bit converter

$$Vo = \frac{Vref}{2^n}*\frac{Rf}{R}\{d_{n-1}2^{n-1}+d_{n-2}2^{n-2}+d_{n-3}2^{n-3}+\ldots\ldots\ldots\ldots\ldots+d_1 2^1+d_0 2^0\}$$

Advantages:

• Only two resistor values are used in R-2R ladder type.

• It does not need as precision resistors as Binary weighted DACs.

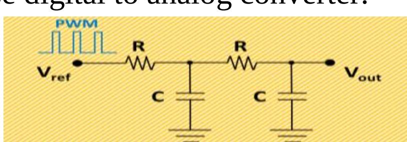
• It is cheap and easy to manufacture.

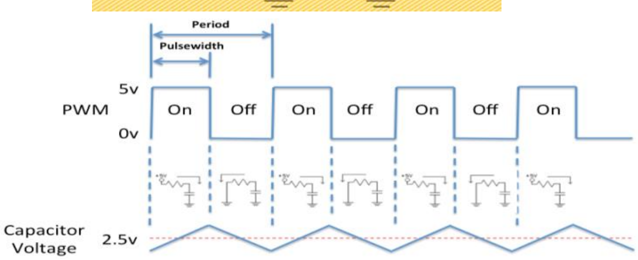
Disadvantages:

• It has slower conversion rate.

c) PWM Type DAC

- It is another method used in DAC converter & microcontrollers such as Arduino can be easily programed to utilize its PWM function to generate an analog output.
- Pulse Width Modulation or PWM is a method of varying the average power of a signal by varying its duty cycle. The duty is the % turn on time of the signal, the % amount of time for which the signal remains high. Like 40% duty cycle signal means it stays high for 40% of time & stays low for 60%.
- We can use a binary number to generate such type signal whose duty cycle depends on the binary digit. The PWM wave is the filtered using a low pass filter to remove the fluctuations & provide a smooth analog voltage.
- The low pass filter used can be a first order. 2^{nd} order low pass filter would be a great choice for a PWM base digital to analog converter.





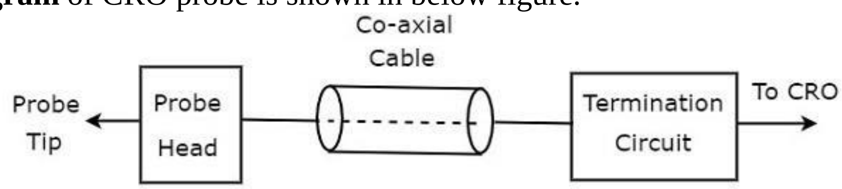
<u>Question</u>

Mention the preference of R-2R Resistance over binary weighted resistor DAC. Design a suitable 7-bit R-2R ladder network considering of suitable value of resistor and voltage. Calculate maximum output obtained in your own design.

Probes and Connectors

Probes and Connectors are essential tools used in various fields, including electronics, electrical engineering, and telecommunications, to facilitate accurate measurements, signal transmission, and device connectivity. . A probe is a device that makes a physical and electrical connection between the oscilloscope and test point. Probes are vital to oscilloscope measurements.

The **block diagram** of CRO probe is shown in below figure.



As shown in the figure, CRO probe mainly consists of three blocks. Those are probe head, co-axial cable and termination circuit. Co-axial cable simply connects the probe head and termination circuit.

Types of CRO Probes

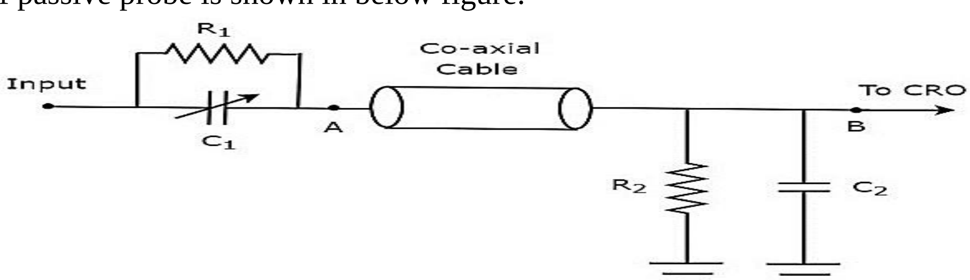
CRO probes can be classified into the following **two types**.

- Passive Probes
- Active Probes

Now, let us discuss about these two types of probes one by one.

Passive Probes

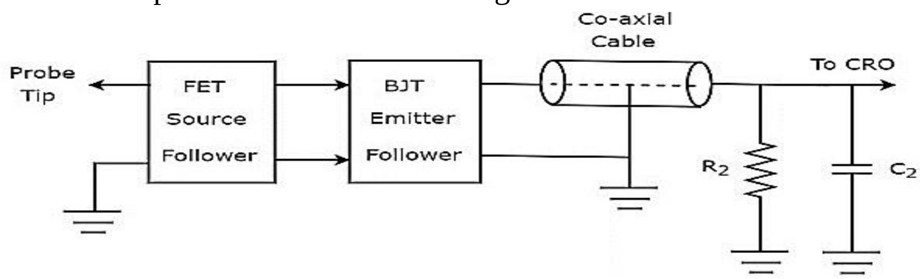
If the probe head consists of passive elements, then it is called **passive probe**. The circuit diagram of passive probe is shown in below figure.



As shown in the figure, the probe head consists of a parallel combination of resistor, R1 and a variable capacitor, C1. Similarly, the termination circuit consists of a parallel combination of resistor, R2 and capacitor, C2.

Active Probes

If the probe head consists of active electronic components, then it is called active probe. The block diagram of active probe is shown in below figure.



As shown in the figure, the probe head consists of a FET source follower in cascade with BJT emitter follower. The FET source follower provides high input impedance and low output impedance. Whereas, the purpose of BJT emitter follower is that it avoids or eliminates the impedance mismatching.

Depending on your measurement needs, this connection can be made with something as simple as a length of wire or with something as sophisticated as an active differential probe.

a) **Test Leads**: (Twisted pair unshielded test leads): Twisted pair unshielded test leads are commonly used in electrical testing and measurements. They consist of two insulated wires twisted together to reduce electromagnetic interference. These test leads are suitable for low voltage measurements and are often used in general-purpose applications.

b) **Shielded Cables**: Shielded cables are designed to minimize electromagnetic interference (EMI) and radio frequency interference (RFI). They have an additional metallic layer, called a shield, surrounding the inner conductors. The shield helps to protect the signals from external interference, ensuring accurate and reliable measurements. Shielded cables are commonly used in high-frequency applications or environments with high levels of electrical noise.

c) **Connectors**: Connectors are used to establish a physical and electrical connection between different components or devices. In the context of probes and measurements, connectors play a crucial role in connecting the test leads or cables to the measuring instrument or the device under test. Common types of connectors used in this context include banana plugs, BNC (Bayonet Neill–Concelman) connectors, and coaxial connectors.

d) **Low Capacitive Probes**: Low capacitive probes are designed to minimize the capacitance between the probe and the circuit under test. Capacitance can affect high-frequency measurements by introducing additional impedance or altering the frequency response. Low capacitive probes are used in applications where accurate and high-frequency measurements are required.

e) **High Voltage Probes**: High voltage probes are specifically designed to measure high voltages safely. They feature special insulation and shielding to protect the user and the measuring instrument from potential electrical hazards. High voltage probes typically have a higher voltage rating and larger physical size compared to regular probes, enabling them to handle higher voltage levels without compromising safety.

f) **Current Probes**: Current probes, also known as current clamps or current transformers, are used to measure electric current without the need for breaking the circuit or inserting a series resistor. They work based on the principle of electromagnetic induction. Current probes are typically designed to measure AC or DC currents and come in various forms, such as clamp-on probes or flexible Rogowski coils. They are commonly used in power measurements, motor control, and troubleshooting electrical systems.

Numerical

1) A 5 bit converter is used for a voltage range of 0-10 V. Find the weight of MSB and LSB. Also the exact range of the converter and the error. Find the error a 10 bit converter is used.

Solution

Range of MSB = ½ * range of converter=1/2 x 10 =5 V.

Range of LSB: $(1/2^5)$ * range of the converter= $(1/2^5)$ x 10=0.3125 V,

The exact range of converter

$Eo = 10 * (1x2^{-1} + 1*2^{-2} + 1\ x2^{-3} + 1*2^{-4} + 1x2^{-5}) = 9.6875$ V

Error = 10 - 9.6875 = 0.3125 V

% error V = (0.3125/10) x 100 = 3.125%

The exact range of the converter when 1O bits are used is :

$Eo = 10*(1x2^{-1} + 1*2^{-2} + 1x2^{-3}+ 1*2^{-4} + 1x2^{-5} + 1x2^{-6} + 1 *2^{-7} + 1\ x2^{-8}+ 1*2^{-9} + 1x2^{-10}) = 9.99$ V

Error = 10 - 9.99 = 0.01

% Error V = (0.01/10) x 100 = 0.1%

Thus if a large number of bits are used, the error reduces considerably. But the use of a converter with a large number of bits results in higher cost of the converter itself and also of the system where it is used. Also, a higher number of bits add to the complexity of the system.

2) An 8-bit digital system is used to convert an analog signal to digital signal for a data acquisition system. The voltage range for the conversion is 0-10 V. Find the resolution of the system and the value of the least significant bit.

Solution

n=8 so signal converted to 2^8 = 256 different levels.

% Resolution = $\frac{1}{2^n-1} = \frac{1}{2^8-1}$ = 0.392%

$V_{LSB} = 10/2^8 = 0.039V$

3) An 8 bits DAC has reference voltage of 12V. find the minimum value of resistance R such that o/p current doesnot exceeds 10mA if it is use.

i) WRN DAC

ii) R:2R ladder network DAC

Also, find the smallest value of quantized current in both case.

Soln,

n=8

Vref=12V

I_{max}=10mA=10*10^{-3}

i) **WRN network**

for n bit converter the output is given as

$$Io = \frac{VR}{2^{n-1}R} \{ d_{n-1}2^{n-1} + d_{n-2}2^{n-2} + d_{n-3}2^{n-3} + \ldots\ldots\ldots\ldots\ldots + d_1 2^1 + d_0 2^0 \}$$

For 8 bit

$$Io = \frac{VR}{2^7 R} \{ d_7 2^7 + d_6 2^6 + \ldots\ldots\ldots + d_1 2^1 + d_0 2^0 \}$$

If i/p = 11111111 then, I=Imax

$$10*10^{-3} = \frac{12}{2^7 R} \{ 1*2^7 + 1*2^6 + \ldots\ldots\ldots + 1*2^1 + 1*2^0 \}$$

So, Ro=20.39 kiloohms

Smallest value of quantized current $= \frac{VR}{2^{n-1}R} \{ d_0 2^0\} = \frac{12}{2^7 * 2390} * 1*2^0 = 39.22*10^{-6}$ A

ii) **R:2R ladder network DAC**

for n bit converter the output is given as

$$Io = \frac{VR}{2^n R} \{ d_{n-1}2^{n-1} + d_{n-2}2^{n-2} + d_{n-3}2^{n-3} + \ldots\ldots\ldots\ldots\ldots + d_1 2^1 + d_0 2^0 \}$$

For 8 bit

$$Io = \frac{VR}{2^8 R} \{ d_7 2^7 + d_6 2^6 + \ldots\ldots\ldots + d_1 2^1 + d_0 2^0 \}$$

- If i/p = 11111111 then, I=Imax
- $10*10^{-3} = \frac{12}{2^8 R} \{ 1*2^7 + 1*2^6 + \ldots\ldots\ldots + 1*2^1 + 1*2^0 \}$
- So, Ro = 1195.31 ohms
- Smallest value of quantized current $= \frac{VR}{2^{n-1}R} \{ d_0 2^0\} = \frac{12}{2^8 * 1195.31} * 1*2^0 = 39.22*10^{-6}$ A

4) Consider a 6 bit DAC with a resistance of 320 kilo-ohms in LSB position the converter is designed with weighted resistance network. The reference voltage is 10V the output of resistance network is connected to an op-Amp with a feedback resistance of 5 kilo-ohms. What is the analog o/p for a binary i/p of 111010?

Soln,

N=6

Resistance of LSB=320*10^3 = 2^{n-1} R

Or, 2^{6-1} R=320

R= 10kilo-ohm

Vref=10V

Rf=5kil;o-ohms

If i/p=111010

For WRN DAC

$$Vo = \frac{10*5}{2^5 R} \{ 1*2^5 + 1*2^4 + 1*2^3 + 0*2^2 + 1*2^1 + 0*2^0 \}$$

$$Vo = \frac{10*5}{320} \{ 32 + 16 + 8 + 0 + 2 + 0 \}$$

Vo = 9V

And, Resistance of MSB = 1*2^0 R = 1*10kilo-ohm = 10 kilo-ohm

5) An 8 bits DAC has reference voltage of 10V. it uses R-2R ladder Network. find the minimum value of resistance R such that the analog voltage of op-Amp having feed-back resistance 10 kilo-ohms does not exceed 9.5V.

Soln,

For R:2R ladder network DAC

for n bit converter the output is given as

Vo = $\frac{VR*Rf}{2^n R}$ { $d_{n-1}2^{n-1}$ + $d_{n-2}2^{n-2}$ + $d_{n-3}2^{n-3}$ + ……………+ $d_1 2^1$ + $d_0 2^0$ }

For 8 bit

Vo = $\frac{VR*Rf}{2^8 R}$ { $d_7 2^7$ + $d_6 2^6$ +…… ..+ $d_1 2^1$ + $d_0 2^0$ }

If i/p = 11111111 then, I=Imax

$9.5 = \frac{10*10*10^3}{2^8 R}$ { $1*2^7$ + $1*2^6$ +…… ..+ $1*2^1$ + $1*2^0$ }

R = 10485.197 ohms

6) An analog voltage signal whose highest significant frequency is 1kHz is to be definatly code with a resolution of 0.01% converting a voltage range of 0-10V. find i) Minimum number of bits between the digital code ii) Analog value of LSB iii) Minimum sampling rate iv) Aperture time required

Soln,

We have

Resolution = $1/2^n$ = 0.01%

0.01*(1/100) = $1/2^n$

2^n = 1000

since, 2^{13} = 8192 and, 2^{14} = 16384

since 8192 is less than 10000, so we cannot choose n = 13.

Thus, Minimum number of bits = 14

Similarly,

Weight of LSB = Vref/2^n =10/2^{14} = 0.61 * 10^{-3} V

And,

Minimum sampling rate = 2*fs = 2*1kHz = 2KHz

Also,

In order to preserve the signal the sampling frequency should not be less than 5 times the highest6 frequency.

Thus, minimum sampling frequency = 5KHZ

And,

Aperture time = $\frac{\wedge E}{2\,\pi\, f\, Em}$

But, $\frac{\wedge E}{Em}$ = 1/16384

Ta = $\frac{1}{(2\,\pi * 1 * 10^3)}$* 1/16384

Ta = 9.71*10^{-9} Sec

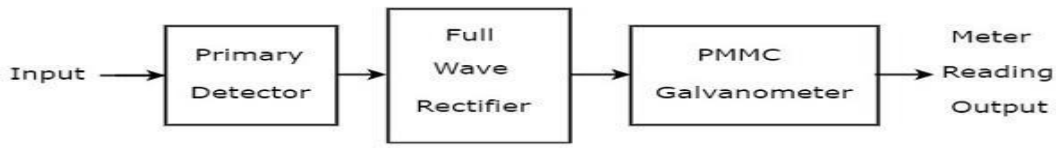
Unit V: Wave Analyzers and Digital Instruments (8 hrs)

Wave Analyzer

A wave analyzer is an instrument designed to measure the relative amplitude of signal-frequency components in a complex or distorted waveform. They provide a graphical representation of signal amplitudes versus frequency, known as a spectrum. It is also called signal analyzer, since the terms signal and wave can be interchangeably used frequently.

Basic Wave Analyzer

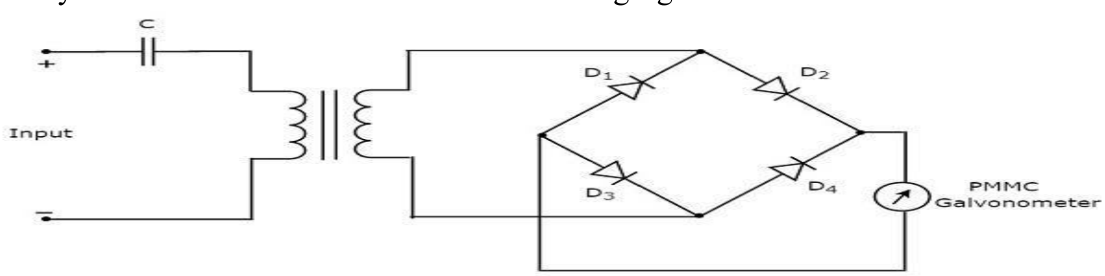
Basic wave analyzer mainly consists of three blocks − the primary detector, full wave rectifier, and PMMC galvanometer. The **block diagram** of basic wave analyzer is shown in below figure



The **function** of each block present in basic wave analyzer is mentioned below.

- **Primary Detector** − It consists of an LC circuit. We can adjust the values of inductor, L and capacitor, C in such a way that it allows only the desired harmonic frequency component that is to be measured.
- **Full Wave Rectifier** − It converts the AC input into a DC output.
- **PMMC Galvanometer** − It shows the peak value of the signal, which is obtained at the output of Full wave rectifier.

We will get the corresponding circuit diagram, just by replacing each block with the respective component(s) in above block diagram of basic wave analyzer. So, the **circuit diagram** of basic wave analyzer will look like as shown in the following figure −



This basic wave analyzer can be used for analyzing each and every harmonic frequency component of a periodic signal.

Types of Wave Analyzers

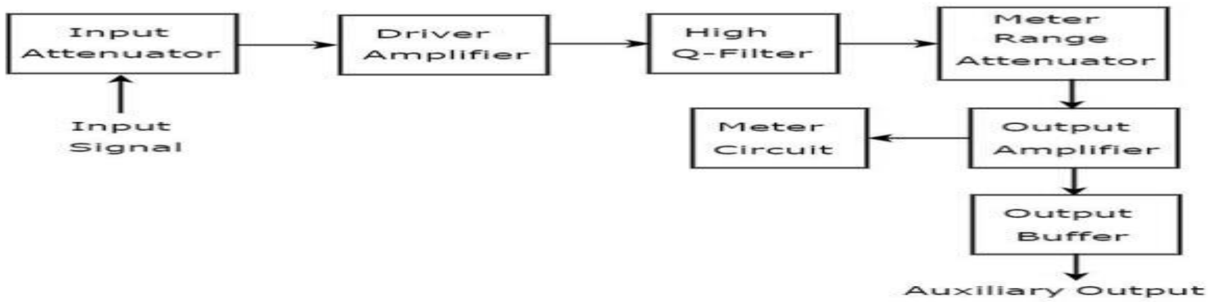
Wave analyzers can be classified into the following **two types**.

- Frequency Selective Wave Analyzer
- Super heterodyne Wave Analyzer

Now, let us discuss about these two wave analyzers one by one.

a) Frequency Selective Wave Analyzer

The wave analyzer, used for analyzing the signals are of **AF range (**audible frequency range 20Hz to 20 KHz) is called frequency selective wave analyzer. The block diagram of frequency selective wave analyzer is shown in below.

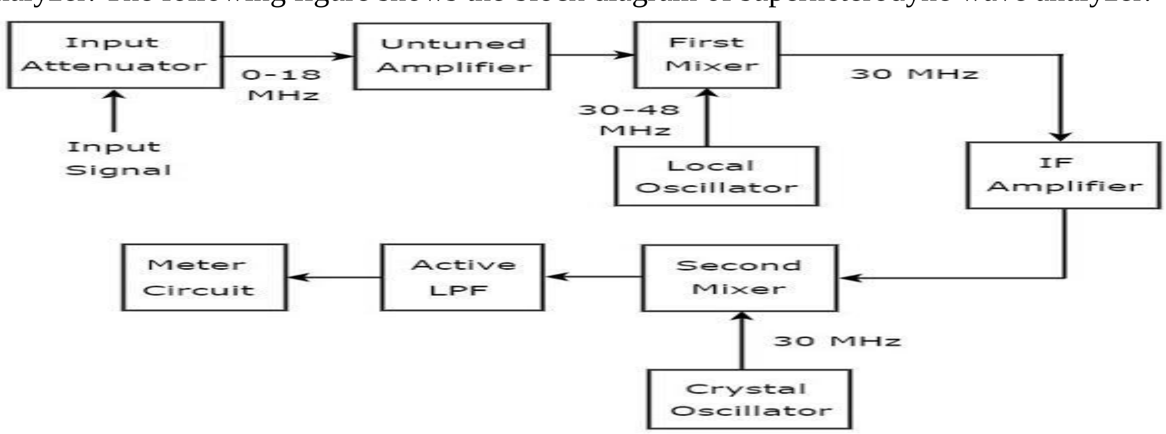


Frequency selective wave analyzer consists a set of blocks whose **function** is mentioned below.

- **Input Attenuator**: The AF signal, which is to be analyzed is applied to input attenuator. If the signal amplitude is too large, then it can be attenuated by input attenuator.
- **Driver Amplifier**: It amplifies the received signal whenever necessary.
- **High Q-filter**: It is used to select the desired frequency and reject unwanted frequencies. It consists of two RC sections and two filter amplifiers & all these are cascaded with each other. We can vary the capacitance values for changing the range of frequencies in powers of 10. Similarly, we can vary the resistance values in order to change the frequency within a selected range.
- **Meter Range Attenuator**: It gets the selected AF signal as an input & produces an attenuated output, whenever required.
- **Output Amplifier**: It amplifies the selected AF signal if necessary.
- **Output Buffer**: It is used to provide the selected AF signal to output devices.
- **Meter Circuit**: It displays the reading of selected AF signal. We can choose the meter reading in volt range or decibel range.

b) Superheterodyne Wave Analyzer

The wave analyzer, used to analyze the signals of **RF range** is called superheterodyne wave analyzer. The following figure shows the block diagram of superheterodyne wave analyzer.



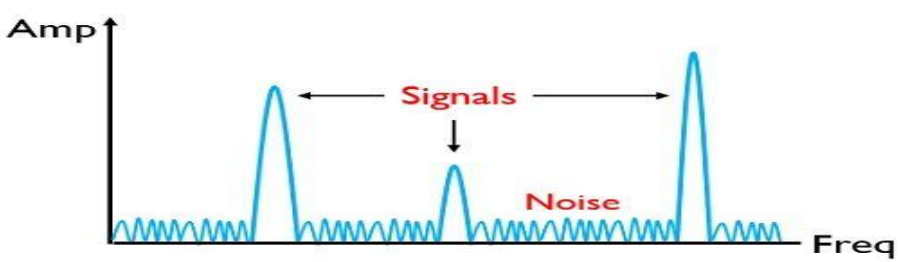
The **working** of superheterodyne wave analyzer is mentioned below.

- The RF signal, which is to be analyzed is applied to the input attenuator. If the signal amplitude is too large, then it can be attenuated by **input attenuator**.
- **Untuned amplifier** amplifies the RF signal whenever necessary and it is applied to first mixer.
- The frequency ranges of RF signal & output of Local oscillator are 0-18 MHz & 30-48 MHz respectively. So, **first mixer** produces an output, which has frequency of 30 MHz. This is the difference of frequencies of the two signals that are applied to it.
- **IF amplifier** amplifies the Intermediate Frequency (IF) signal, i.e. the output of first mixer. The amplified IF signal is applied to second mixer.
- The frequencies of amplified IF signal & output of Crystal oscillator are same and equal to 30MHz. So, the **second mixer** produces an output, which has frequency of 0 Hz. This is the difference of frequencies of the two signals that are applied to it.
- The cut off frequency of **Active Low Pass Filter (LPF)** is chosen as 1500 Hz. Hence, this filter allows the output signal of second mixer.
- **Meter Circuit** displays the reading of RF signal. We can choose the meter reading in volt range or decibel range.

So, we can choose a particular wave analyzer based on the frequency range of the signal that is to be analyzed.

Spectrum Analyzer

A spectrum analyzer is a device that measures and displays signal amplitude (strength) as it varies by frequency within its frequency range (spectrum). The frequency appears on the horizontal (X) axis, and the amplitude is displayed on the vertical (Y) axis. It looks like an oscilloscope, and in fact, some devices can function as either oscilloscopes or spectrum analyzers.



Frequency Domain display by a spectrum analyzer

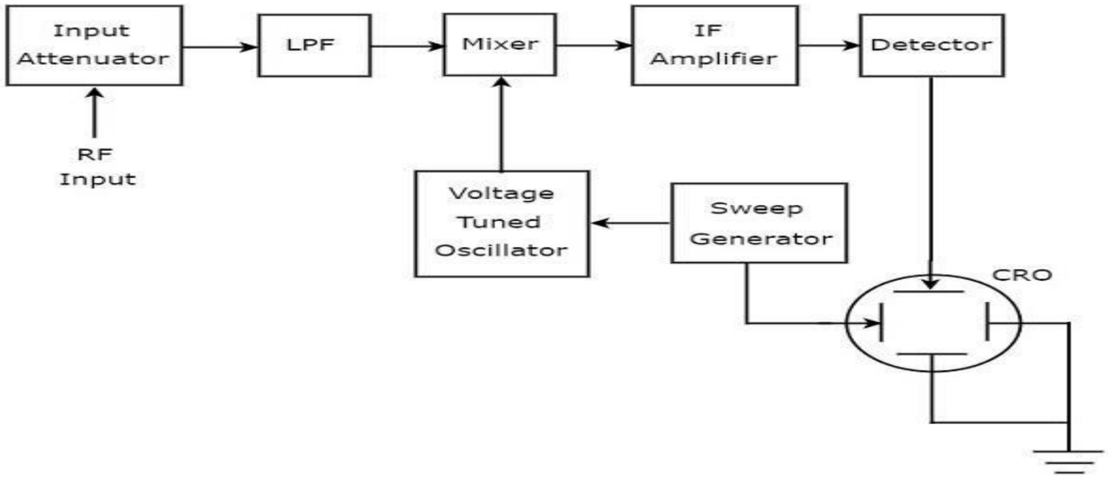
Types of Spectrum Analyzers

These instruments provide a display of the frequency spectrum over a given frequency band. Spectrum analyzers use either a **parallel filter bank or a swept frequency technique**. So, We can classify the spectrum analyzers into the following **two types**.

- Filter Bank Spectrum Analyzer
- Swept-tuned or superheterodyne Spectrum Analyzer

Basic Spectrum Analyzer using Swept Receiver Design

The spectrum analyzer, used for analyzing the signals are of RF range is called **superheterodyne spectrum analyzer**. Its **block diagram** is shown in below figure.



The **working** of superheterodyne spectrum analyzer is mentioned below.

- The saw tooth generator provides the saw tooth voltage which drives the horizontal axis element of the scope and this saw tooth voltage is frequency controlled element of the voltage tuned oscillator. As the oscillator sweeps from f_{min} to f_{max} of its frequency band at a linear recurring rate, it beats with the frequency component of the input signal and produce an IF, whenever a frequency component is met during its sweep.
- The RF signal, which is to be analyzed is applied to input attenuator. If the signal amplitude is too large, then it can be attenuated by an **input attenuator**.
- **Low Pass Filter** (LPF) allows only the frequency components that are less than the cut-off frequency.
- **Mixer** gets the inputs from Low pass filter and voltage tuned oscillator. It produces an output, which is the difference of frequencies of the two signals that are applied to it.
- **IF amplifier** amplifies the Intermediate Frequency (IF) signal, i.e. the output of mixer. The amplified IF signal is applied to detector.

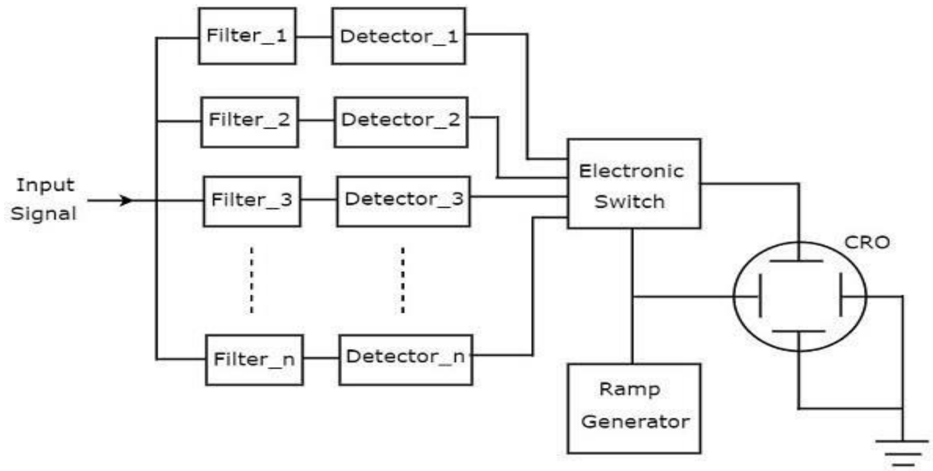
The output of detector is given to vertical deflection plate of CRO. So, CRO displays the frequency **spectrum of RF signal** on its CRT screen.

So, we can choose a particular spectrum analyzer based on the frequency range of the signal that is to be analyzed.

IRF Spectrum Analyzer/ Parallel Filter Bank Analyzer

An IRF (Intermediate Frequency) spectrum analyzer is a device used to analyze and display the frequency spectrum of intermediate frequency signals. It is commonly used in communication systems and electronic equipment for signal analysis and troubleshooting.

In a parallel filter bank analyzer, the frequency range is covered by a series of filters whose central frequencies and bandwidth are so selected that they overlap each other, The spectrum analyzer, used for analyzing the signals are of AF range is called filter bank spectrum analyzer, or **real time spectrum analyzer** because it shows (displays) any variations in all input frequencies. The following figure shows the **block diagram** of filter bank spectrum analyzer.



The **working** of filter bank spectrum analyzer is mentioned below.

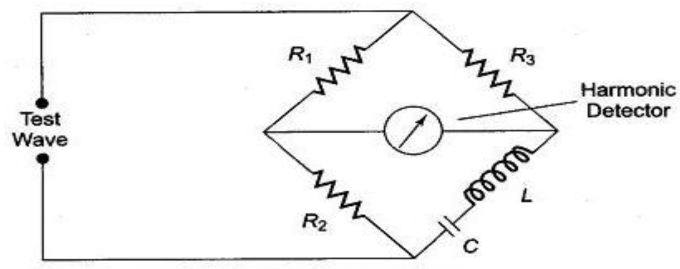
- It has a set of band pass filters and each one is designed for allowing a specific band of frequencies. The output of each band pass filter is given to a corresponding detector.
- All the detector outputs are connected to Electronic switch. This switch allows the detector outputs sequentially to the vertical deflection plate of CRO. So, CRO displays the frequency **spectrum of AF signal** on its CRT screen.

Distortion Analyzer: Harmonic Distortion Analyzer-Fundamental Suppression Type

Fundamental Suppression Type:

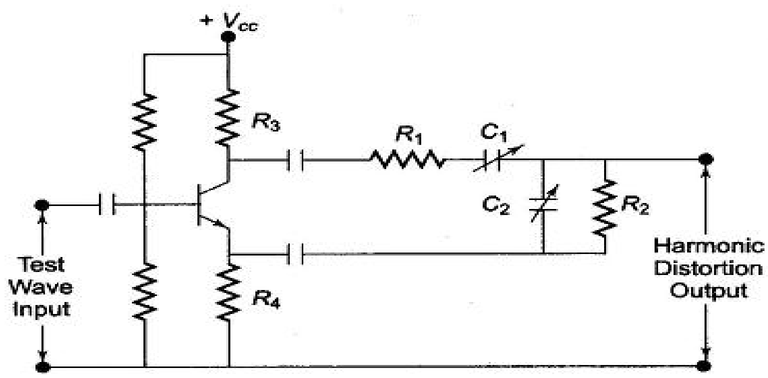
- Distortion analyzer measures the total harmonic power present in the test wave rather than the distortion caused by each component
- The simplest method to suppress the fundamental frequency by means of a high pass filter whose cut-off frequency is a little above the fundamental frequency
- Thus, the high pass filter allows only the harmonics to pass and the total harmonic distortion (THD) can then be measured
- The most commonly used harmonic distortion analyzers based on fundamental suppression are as follow:
    - **(i) Employing a Resonance Bridge,**
    - **(ii) Wien's Bridge Method**
    - **(iii) Bridged T -Network Method**

i) Employing a Resonance Bridge:



- The bridge is balanced for the fundamental frequency, i.e. L and C are tuned to the fundamental frequency.
- The bridge is unbalanced for the harmonics, i.e. only harmonic power will be available at the output terminal and can be measured.
- If the fundamental frequency is changed, the bridge must be balanced again.
- If L and C are fixed components, then this method is suitable only when the test wave has a fixed frequency.
- Indicators can be thermocouples or square law VTVMs. This indicates the RMS value of all harmonics.
- When a continuous adjustment of the fundamental frequency is desired, a Wien bridge arrangement is used.

ii) <u>Wien's Bridge Method:</u>



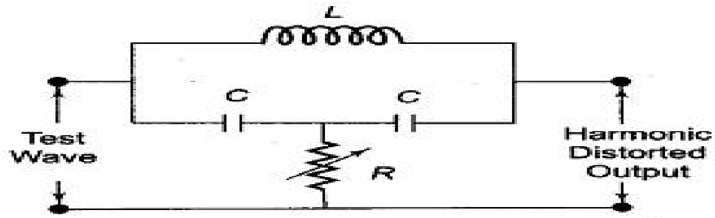
- The bridge is balanced for the fundamental frequency.
- The fundamental energy is dissipated in the bridge circuit elements.
- Only the harmonic components reach the output terminals.
- The harmonic distortion output can then be measured with a meter.
- For balance at the fundamental frequency,

$C_1 = C_2 = C$

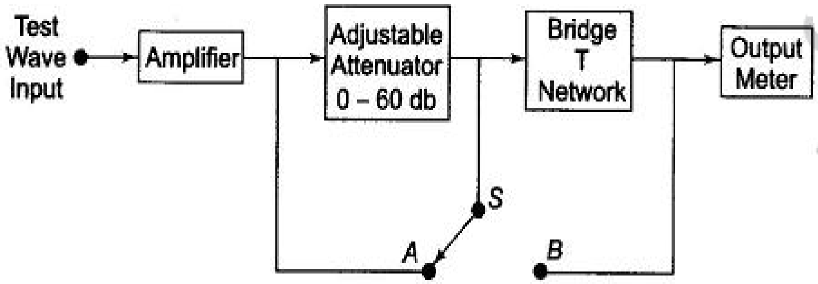
$R_1 = R_2 = R$

$R_3 = 2R_4.$

iii) <u>Bridged T-Network Method:</u>



- L and C's are tuned to the fundamental frequency, and R is adjusted to bypass fundamental frequency.
- The tank circuit being tuned to the fundamental frequency, the fundamental energy will circulate in the tank and is bypassed by the resistance.
- Only harmonic components will reach the output terminals and the distorted output can be measured by the meter.
- The Q of the resonant circuit must be at least 3-5.



- The switch **S** is first connected to point **A** so that the attenuator is excluded and the bridge T-network is adjusted for full suppression of the fundamental frequency, i.e. minimum output.
- Minimum output indicates that the bridged T-network is tuned to the fundamental frequency and that the fundamental frequency is fully suppressed.
- The switch is next connected to terminal **B,** i.e. the bridged T-network is excluded. Attenuation is adjusted until the same reading is obtained on the meter. The attenuator reading indicates the total RMS distortion.
- Distortion measurement can also be obtained by means of a wave analyzer, knowing the amplitude and the frequency of each component, the Harmonic Distortion Analyzer can be calculated.
- However, distortion meters based on fundamental suppression are simpler to design and less expensive than wave analyzers.
- The disadvantage is that they give only the total distortion and not the amplitude of individual distortion components.

Measurements of Frequency and Time: Decimal Count Assembles

Measurement of Time (Period Measurement):

In some cases it is necessary for Digital Measurement of Time rather than the frequency. This is especially true in the measurement of frequency in the low frequency range. To obtain good accuracy at low frequency, we should take measurements of the period, rather than make direct frequency measurements. The circuit used for measuring frequency can be used for the measurement of time period if the counted signal and gating signal are interchanged.

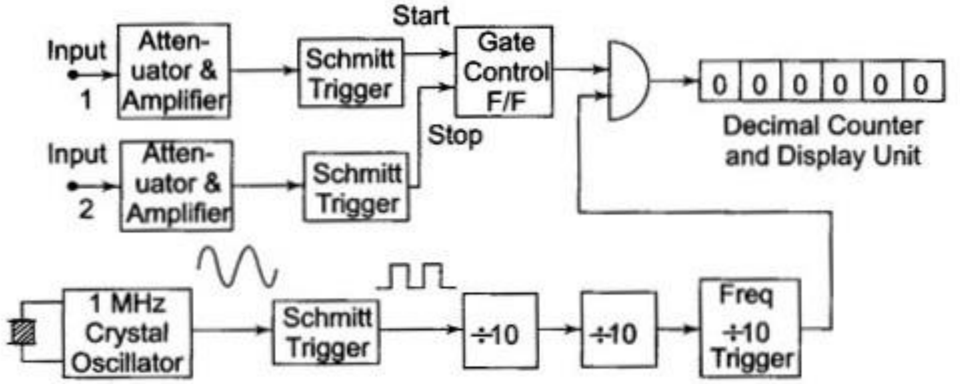


Figure shows the circuit for Digital Measurement of Time period. The gating signal is derived from the unknown input signal, which now controls the enabling and disabling of the main gate. The number of pulses which occur during one period of the unknown signal are counted and displayed by the decade counting assemblies. The only disadvantage is that for measuring the frequency in the low frequency range, the operator has to calculate the frequency from the time by using the equation f = 1/T.

For example, when measuring the period of a 60 Hz frequency, the electronic counter might display 16.6673 ms, whence the frequency is

$$f = 1/T = \frac{1}{16.6673 \times 10^{-3}} = 59.9977 \text{ Hz.}$$

Frequency Counter

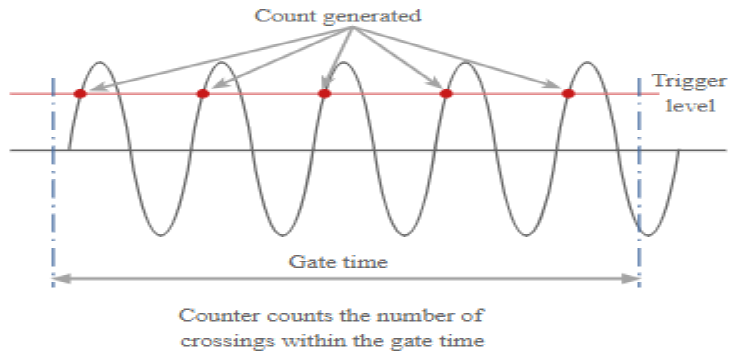
A frequency counter is an electronic instrument used to measure frequency and time. Frequency counters are used for a wide range of frequency and time measurements and display many digits of accuracy. Frequency counter helps measure the time of reputed digital signals and the frequency correctly and associates with a wide range of radio frequencies.

In simple words, these are essential instruments that count the number of cycles per second of an input signal.

These are widely used in electronics and telecommunication industries to measure frequency, bandwidth, peak-to-peak voltage, or current or rise time.

Frequency counters count the pulses and transfers them into the frequency counter when the number of pulses or events occurs in a period and displays it on the frequency range of vibrations.

The counter then sets to zero. Frequency counters are often found in-built into other devices, such as radio receivers, radar sets, and test equipment. It is a device that is easy to use, measures the frequency accurately, and displays it digitally.



Basic concept of a frequency counter

Block Diagram and Working

The frequency counter block diagram contains input signal, input conditioning, and threshold, AND gate, counter or latch, accurate timebase or clock, decade dividers, flip-flop, and display.

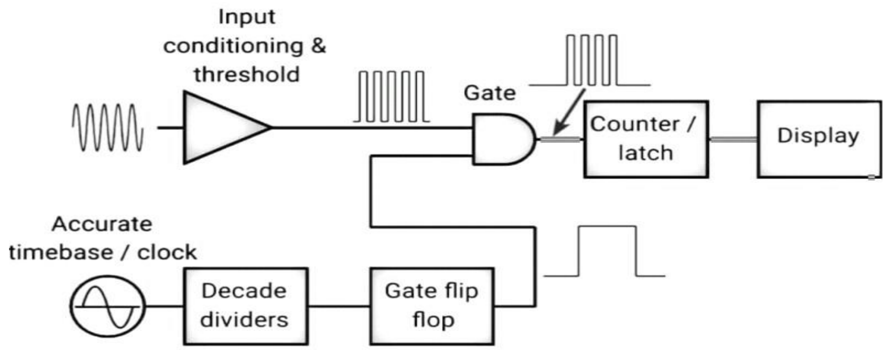


Fig: Frequency Counter Block Diagram

- A frequency counter measures a signal in the first split into the pulse setting. It operates by counting the number of times the signal passes through the voltage point to a trigger point in a duration.
- The trigger of frequency counters starts at zero crossing point automatically. It is a device that sets in a clock speed with pulse per unit cycle and the pulses present send to the device for a limited time.
- After this, vibrations/Pulses apply in a definite interval of time, counts the Pulses.
- An electric counter does the whole process, and the pulses are sent to the cycle to represent the unidentified Signal and give it a value.
- The frequency counter works on two modes to generate the pulses and time delay.
- When we talk about the working of the frequency counter, then the pulse in this device generates from the wave generator and microcontrollers. The timer in this device figures as a counter.
- It sets the count of the Pulses from high and low. The final count of the pulses takes place. It later collects in timer one, and it denotes the frequency of the vibrations by calculating it.

- The device that converts the resultant value by multiplying it by ten frequency cycles per second converts the value of the pulses in Hz. After the whole calculation inside the frequency counter, the frequency of the pulses becomes visible on the LCD or LED.

Types of Frequency Counters:

Let us know more about the types of Frequency counters here:

1. Bench Frequency Counter:

Bench Frequency Counter is a type of device that is useful in applying electronic test equipment. It helps measure the period and equal frequency precisely.

Bench frequency counter counts CPU signals, and it also provides a constant compensation for temperature change.

The device is also known for reducing measurement errors that generally happen due to temperature drift. It is also helpful in measuring the frequency of a Periodic electrical signal, and these devices are beneficial for electronic labs and electronic projects.

2. PXI Frequency Counter:

A PXI frequency counter is helpful in the control system and track system for tests. It is a valuable device in measuring the frequency and phase of an input signal as per the reference signal.

Its application is mainly in audio, video, and RF signal. This type of frequency counter is known for implementing standalone devices or integration with other instruments such as spectrum analyzers and Oscilloscopes. Some of the different application of this device is testing microwave circuit, wireless devices, and Antennas.

3. Handheld Frequency Counter:

A handheld frequency counter helps measure the frequency of cycles per second of a Periodic waveform in the signal. Along with that, it also measures the period and time interval between two events in the waveform.

It provides precise measurement and output. The application of this device helps measure the radio frequencies or any other repeating signal such as audio signals, clock frequency, etc. It represents the cycle per unit number in Hz.

4. Panel Meter:

A panel meter is a type of frequency counter available in panel mount mode. It has application in determining the frequency of audio and radio signals.

It helps incorporate items with different kinds of equipment to count the time intervals and frequency.

Compared to the other types of frequency count, two parameters are cheaper and valuable for measuring the frequency of a signal in Hz.

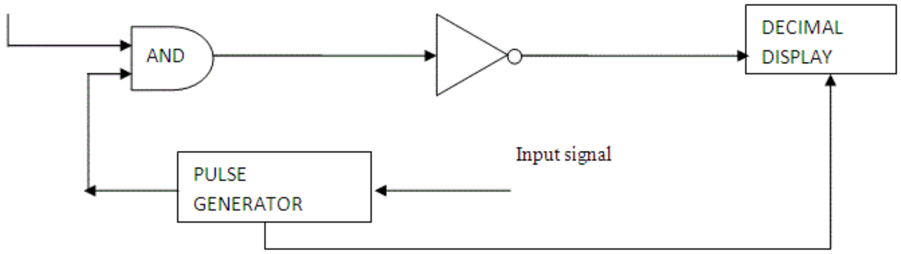
Error: Counter Error and Signal Related Error

- A counter error typically indicates a problem or discrepancy in the frequency or time measurement performed by the wave analyzer's counter. The counter is responsible for counting the number of cycles or events within a given time period.

- A counter error might occur if there are issues with the counter circuitry, calibration, or if the signal being measured is outside the counter's measurement range. In such cases, the accuracy and reliability of the frequency or time measurements may be compromised.
- A signal-related error generally refers to an error or issue related to the input signal being analyzed by the wave analyzer. This could include various factors, such as noise, distortion, interference, or improper signal conditioning. Signal-related errors can affect the accuracy of the measurements or distort the waveform being analyzed, leading to incorrect or unreliable results.

Digital Voltmeter

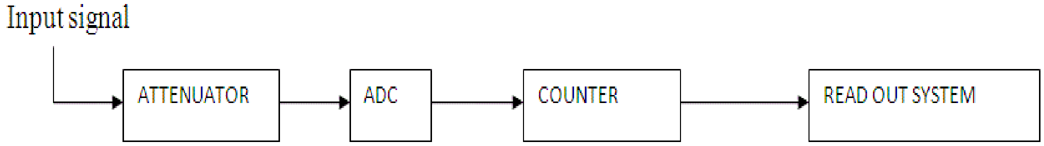
Digital Voltmeter displays the voltage readings of a circuit numerically which is used to measure the electrical potential difference between two points in a circuit. The below picture shows the **block diagram of the digital voltmeter**.



The working of DVM is explained as follows:

1. Unknown voltage signal is fed to the pulse generator which generates a pulse whose width is proportional to the input signal.
2. Output of pulse generator is fed to one leg of the AND gate.
3. The input signal to the other leg of the AND gate is a train of pulses.
4. Output of AND gate is positive triggered train of duration same as the width of the pulse generated by the pulse generator.
5. This positive triggered train is fed to the inverter which converts it into a negative triggered train.
6. Output of the inverter is fed to a counter which counts the number of triggers in the duration which is proportional to the input signal i.e. voltage under measurement.
7. Thus, counter can be calibrated to indicate voltage in volts directly.

The working of digital voltmeter that it is nothing but an analog to digital converter which converts an analog signal into a train of pulses, the number of which is proportional to the input signal. So a **digital voltmeter** can be made by using any one of the A/D conversion methods.



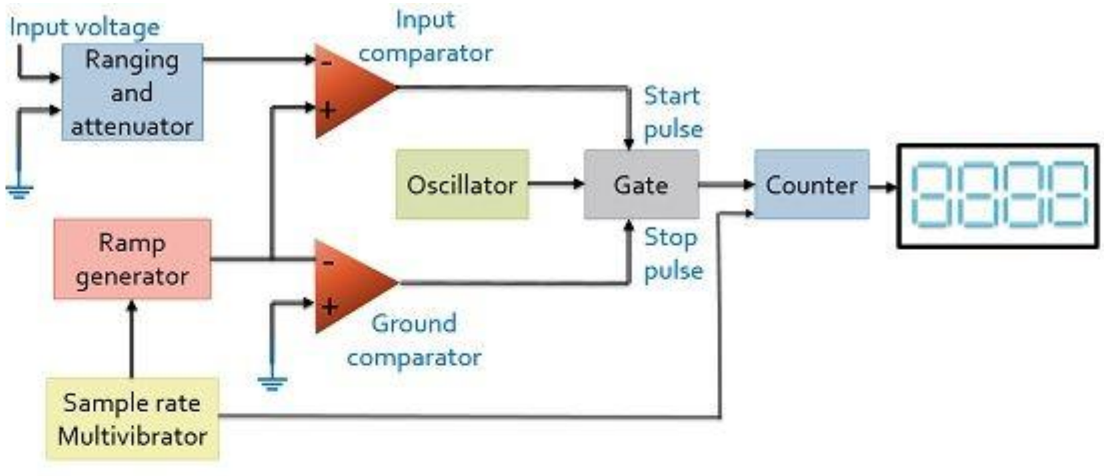
On the basis of A/D conversion method used digital voltmeters can be classified as:

- Ramp Type Digital Voltmeter
- Integrating Type Voltmeter
- Potentiometric Type Digital Voltmeters
- Successive Approximation Type Digital Voltmeter

Ramp Type Digital Voltmeter

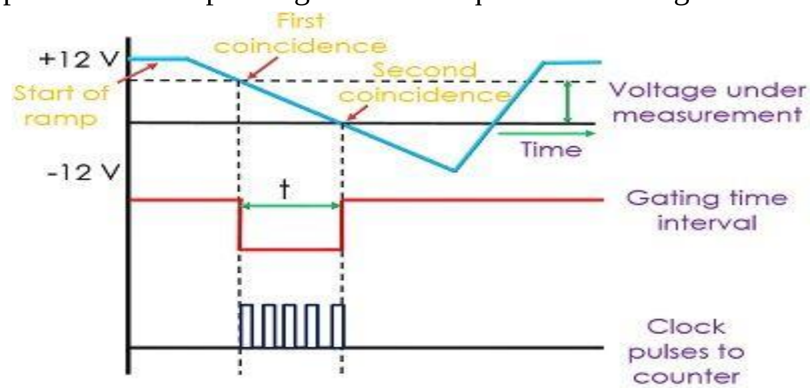
In a ramp type DVM, the operation basically depends on the measurement of time. The time which a ramp voltage takes to change from the level of the input voltage to that of 0 voltage or vice versa. An electronic time interval counter is used to measure the time interval and the count is displayed in digits as voltmeter output.

Let us have look at the block diagram and operating principle of a ramp-type DVM.



Block diagram of Ramp type DVM

Here, as we can see in the figure below a negative going ramp voltage is shown. This ramp voltage is compared with the unknown voltage. An input comparator employed in the circuit generates a pulse when ramp voltage becomes equal to the voltage under measurement.



Voltage to time conversion

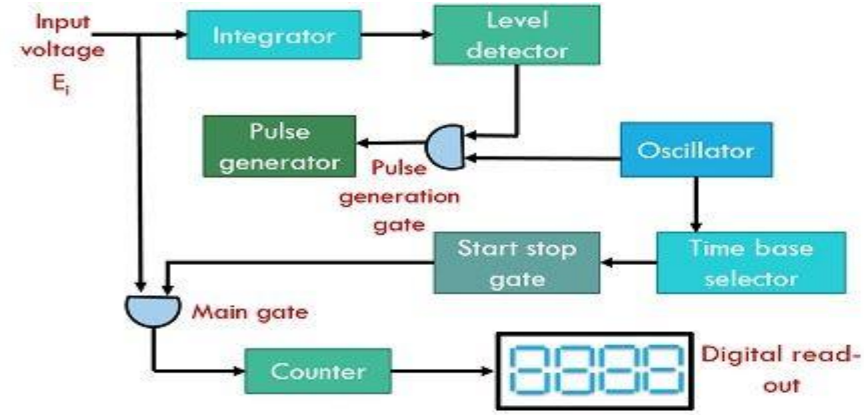
Now, the ramp voltage falls to reach 0 value. The ground comparator employed in the circuit generates stop pulse. This stop pulse closes the gate.

The **gate opening time duration** is **proportional** to the value of **input voltage**. The sample rate Multivibrator employed here is used to find the rate by which the measurement cycle begins.

Integrating Type Digital Voltmeter

In this category of Digital Voltmeter, the true value of input voltage is measured over a fixed measuring time.

Here, an integration technique is employed that uses **voltage to frequency conversion**. This voltage to frequency converter act as a **feedback control system**. This basically governs the pulse generation rate is proportional to the magnitude of applied input voltage.



Block diagram of integrating type DVM

In voltage to frequency conversion technique, a **train of pulses** is generated. The frequency of these pulses depends on the voltage being measured.

Then these pulses are counted that appears in a definite time interval. After all, the frequency of pulses is a function of input voltage, the number of pulses is an indication of the input voltage.

Servo Potentiometer Type Digital Voltmeter

A potentiometric type of DVM employs voltage comparison technique. In this DVM the unknown voltage is compared with reference voltage whose value is fixed by the setting of the calibrated potentiometer.

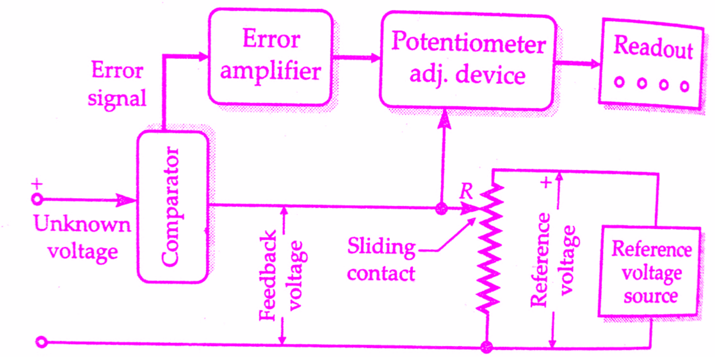
The potentiometer setting is changed to obtain balance (i.e. null conditions).

When null conditions are obtained the value of the unknown voltage, is indicated by the dial setting of the potentiometer.

In potentiometric type DVMs, the balance is not obtained manually but is arrived at automatically.

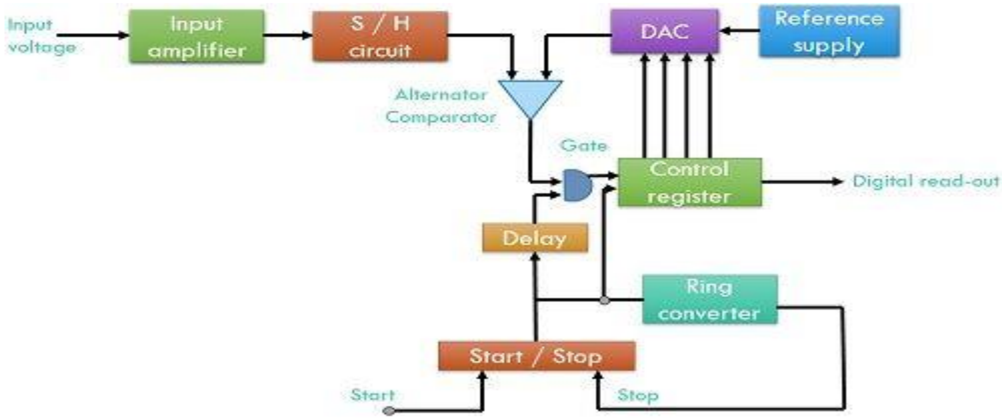
Thus, this DVM is in fact a self- balancing potentiometer.

The potentiometric DVM is provided with a readout which displays the voltage being measured.



Successive Approximation Type Digital Voltmeter

In this category of DVM, the ADC employed makes use of **successive approximation converter**. Thus it is named as so. These are capable of 1000 readings per second.



Block diagram of successive approximation DVM

In the beginning, a start pulse is applied at the start/stop Multivibrator. Due to this, MSB of the control register is set to high and all other bits to low. So, for an **8-bit control register**, the reading would be 10000000.

Thus causing the output of DAC to be half of the reference voltage.

Now, the comparator compares the output of the converter from the input voltage and produces an output that will cause the control register to retain 1 in its MSB.

The ring converter employed in the circuit advances one count next thus shifting a 1 in the second. This will cause the MSB of the control register and its reading to be 11000000.

Thus DAC increases its reference by one increment and another comparison of input voltage with that of reference takes place. In this way through successive approximation the measurement cycle proceeds. On reaching the last count, the measurement cycle stops.

The output in digital format at the control register shows the final approximation of input voltage

Vector Voltmeter

A vector voltmeter is a specialized instrument used for measuring complex voltage quantities, particularly in RF (Radio Frequency) and microwave systems. It is designed to measure both the magnitude and phase of a complex voltage or vector quantity.

nlike a standard voltmeter that measures only the amplitude of a voltage signal, a vector voltmeter provides additional information about the phase or angle of the voltage. This is particularly useful in applications where the phase relationship between multiple voltage signals is critical, such as in RF signal analysis, network analysis, or impedance measurements.
The vector voltmeter typically consists of two channels: an in-phase channel and a quadrature channel. The in-phase channel measures the real or resistive component of the voltage, while the quadrature channel measures the imaginary or reactive component of the voltage.
By processing the measurements from both channels, the vector voltmeter can calculate the magnitude and phase angle of the complex voltage. It can display these values in various formats, such as polar coordinates (magnitude and angle) or rectangular coordinates (real and imaginary components).
Vector voltmeters are commonly used in RF and microwave engineering for tasks like impedance matching, network analysis, phase measurements, and evaluating the performance of RF systems. They are especially valuable for characterizing signals with multiple components or for measuring the properties of devices operating in the frequency domain.

Digital Multimeter

A **Digital Multimeter** is a test tool used to measure two or more electrical values—principally voltage (volts), current (amps) and resistance (ohms). It is a standard diagnostic tool for technicians in the electrical/electronic industries.
Digital multimeters combine the testing capabilities of single-task meters—the voltmeter (for measuring volts), ammeter (amps) and ohmmeter (ohms). Often, they include several additional specialized features or advanced options. Technicians with specific needs, therefore, can seek out a model targeted to meet their needs.
The face of a multimeter typically includes four components:

- Display: Where measurement readouts can be viewed.
- Buttons: For selecting various functions; the options vary by model.
- Dial (or rotary switch): For selecting primary measurement values (volts, amps, ohms).
- Input jacks: Where test leads are inserted.

Test leads are flexible, insulated wires (red for positive, black for negative) that plug into the DMM. They serve as the conductor from the item being tested to the multimeter. The probe tips on each lead are used for testing circuits.
The terms counts and digits are used to describe a digital multimeter's resolution—how fine a measurement a meter can make. By knowing a multimeter's resolution, a technician can determine if it is possible to see a small change in a measured signal.

Computer Based Digital Instruments: IEEE 488 GPIB Instrument

IEEE-488 refers to the Institute of Electrical and Electronics Engineers (IEEE) Standard number 488 and is commonly called GPIB (General Purpose Interface Bus). The IEEE-488 standard, also known as GPIB, is a bus interface that connects instruments in a computer to an ATE system.
The IEEE 488 (GPIB) bus is an 8-bit parallel multi-master interface bus that is used for short-distance communications. As the bus became the key interface meeting multiple standards, it was termed as General Purpose Interface Bus. Because of its flexibility, the data transmission can take place between any instruments present in the bus having a speed appropriate for the slowest active instrument.
Achieve proper communication between the devices in GPIB requires three components which are:
Talker – This holds the ability to transmit device-dependent information from one device to another device on the bus when it is addressed to talk. On the whole device, only one GPIB instrument can function as an active talker at a time.
Listener – It is responsible to receive device-dependent information from another device present in the bus when it is addressed to listen. On the whole device, more number of GPIB instruments can function as active listeners at a time.
Controller – The name of the controller itself signifies that it is an entity that manages the entire functionality of the bus. The controller is generally a computer that provides the signal to the instruments to execute multiple activities making sure that no issues take place in the bus. When two talker devices try to talk at the same time instant, it leads to data corruption and shows the impact on the entire system.

IEEE 488 bus allows different controllers to share a similar bus whereas only one controller will be active at any specific time.
GPIB bus consists of eight data lines in order to transmit 8 bits of data at a single instance. And command messages work with seven bits out of 8 and the message format is shown below:

7	6	5	4	3	2	1	0
0	TA	LA	GPIB Primary Address				

Message Format

Bits 0 through 4 indicate the primary address of the device, for which the Talker/Listener assignment is intended. If bit 5 is high, the device should listen. If bit 6 is high, the device should talk. Bit 7 is a “don’t care” bit. Its value is ignored, so it is interpreted as a value of zero in command messages.

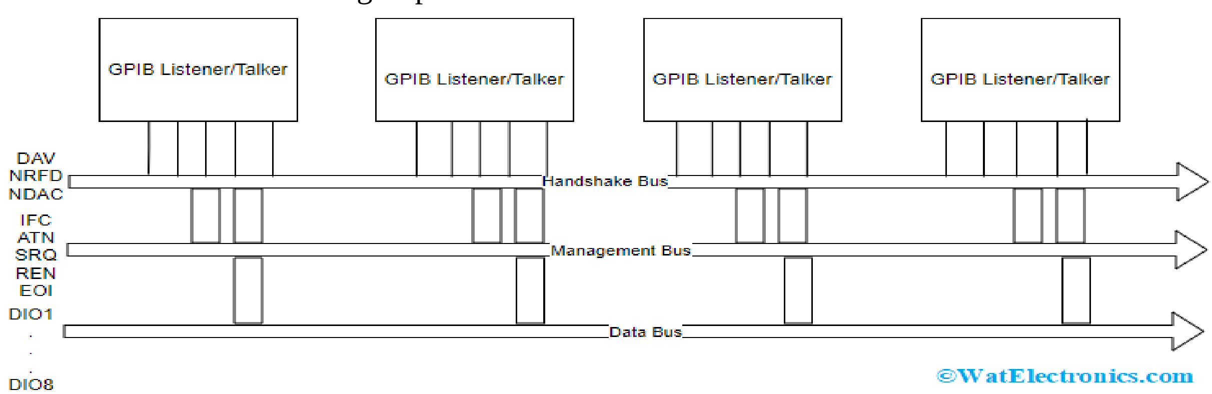
IEEE 488 Bus Features

As the main functionality of GPIB is to establish interconnection between various instruments and devices, it is recommended to know the features of the IEEE 488 bus. A few of those are:

1. The transaction between the messages is a hardware three-wire-handshake.
2. Communication happens in digital format and it transmits only one byte of data at a time.
3. To a single IEEE 488 bus, approximately 15 devices can be connected at a time.
4. The bus length can be 20 meters, but the distance between each device can be 2 meters.
5. The maximum data rates can be up to 1 Megabyte/second.
6. The width of the data bus is 8 lines.
7. The connector used in GPIB is a 24-pin Amphenol or sometimes a D-type connector is also used.
8. The bus can support 31 5-bit primary devices which are addressed from 0-to 30 by assigning a unique address for every device.
9. The topology used in GPIB is linear or forked type.
10. The protocol supports both **half-duplex and full-duplex communication modes** so that two devices can send data while at the same time receiving data from each other simultaneously

IEEE 488 Bus Block Diagram

The **IEEE 488 bus architecture** consists of 16 signaling lines that are used to carry information and allow to pass commands between various devices that have connections with the bus. These 16 signals are classified into three groups which are



IEEE 488 Bus Architecture

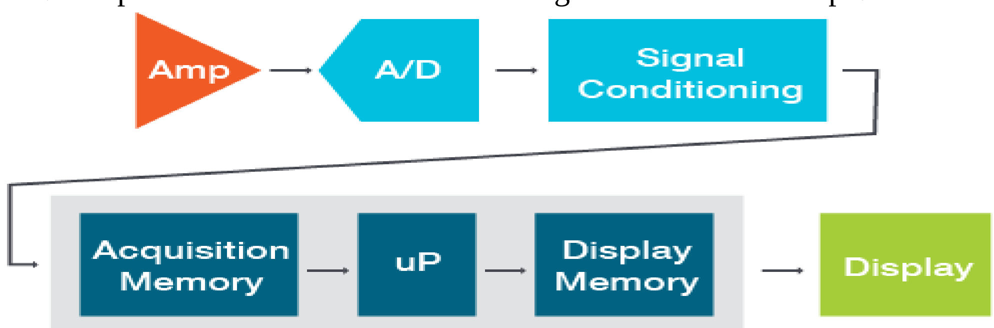
Data Bus – 8 lines, Data Byte Transfer Control Bus – 3 lines, and General Interface Management Bus – 5 lines.

Unit VI: Recorders, Displays and Storage Devices (5 hrs)

FUNDAMENTALS OF CATHODE RAY OSCILLOSCOPE

An oscilloscope is a laboratory instrument commonly used to display and analyze the waveform of electronic signals. In effect, the device draws a graph of the instantaneous signal voltage as a function of time. Oscopes are often used when designing, manufacturing or repairing electronic equipment. Engineers use an oscilloscope to measure electrical phenomena and solve measurement challenges quickly and accurately to verify their designs or confirm that a sensor is working properly.

There are three primary oscilloscope systems: vertical, horizontal and trigger systems. Together, these systems provide information about the electrical signal, so the oscilloscope can accurately reconstruct it. The picture below shows the block diagram of an oscilloscope.



The first stage attenuates or amplifies the signal voltage in order to optimize the amplitude of the signal; this is referred to as the vertical system since it depends on the vertical scale control. Then the signal reaches the acquisition block, where the analog-to-digital converter (ADC) is used to sample the signal voltage and convert it in a digital format value. The horizontal system, which contains a sample clock, gives each voltage sample a precise time (horizontal) coordinate. The sample clock drives the ADC and its digital output is stored in the acquisition memory as a record point. The trigger system detects a user-specified condition in the incoming signal stream and applies it as a time reference in the waveform record. The event that met the trigger criteria is displayed, as is the waveform data preceding or following the event

BLOCK DIAGRAM OF OSCILLOSCOPE:

The major block circuit of general purpose CRO is as follows:

1) CRT
2) Vertical Line
3) Delay line
4) Horizontal amplifier
5) Time base generator
6) Trigger circuit
7) Power Supply

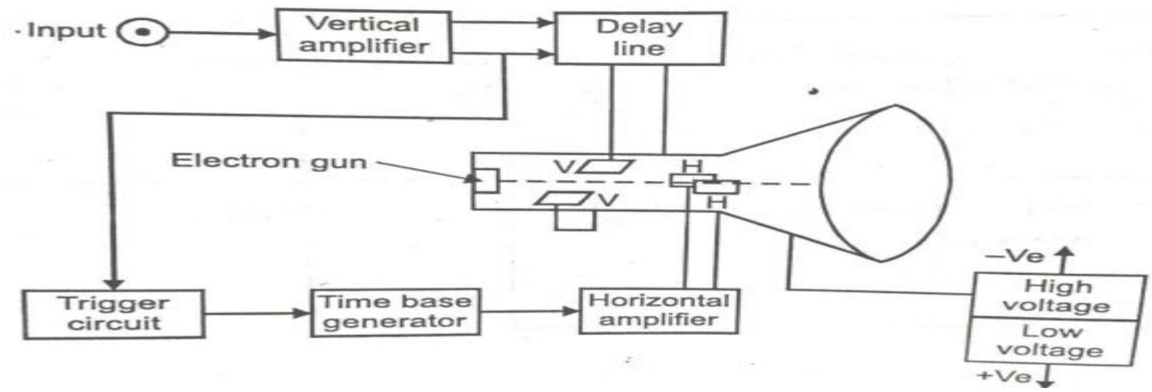


Fig: Block Diagram of oscilloscope

The description is below:

1) **Cathode Ray Tube (CRT):**

A cathode ray oscilloscope consists of a cathode ray tube (CRT) which is the heart of the oscilloscope, and some additional circuitry to operate the CRT. The main parts of a CRT are: a)Electron gun assembly. b)Deflection plate assembly c)Fluorescent screen d)Glass envelope The electron gun assembly produces a sharply focussed beam of electrons which are accelerated to high velocity. This focussed beam of electrons strikes the fluorescent screen with sufficient energy to cause a luminous spot on the screen.

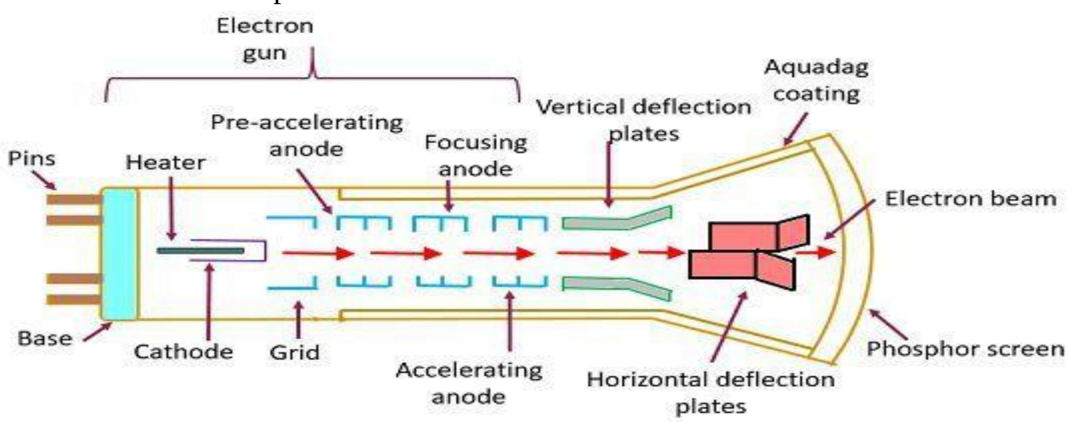
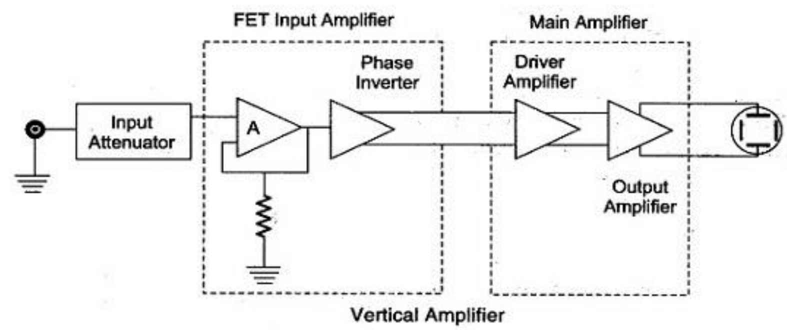


Fig: Internal Structure of CRT

After leaving the electron gun, the electron beam passes through two pairs of "electrostatic deflection plates". Voltages applied to these plates deflect the beam. Voltages applied to one pair of plates move the beam vertically up and down and the voltages applied to the other pair of plates move the beam horizontally from one side to another. Focusing anode is used to focus the beam on the screen, and the accelerating anode makes the electron beam to move with high velocity.

2) Vertical Amplifier:



This is a wide band amplifier used to amplify signals in the vertical section.

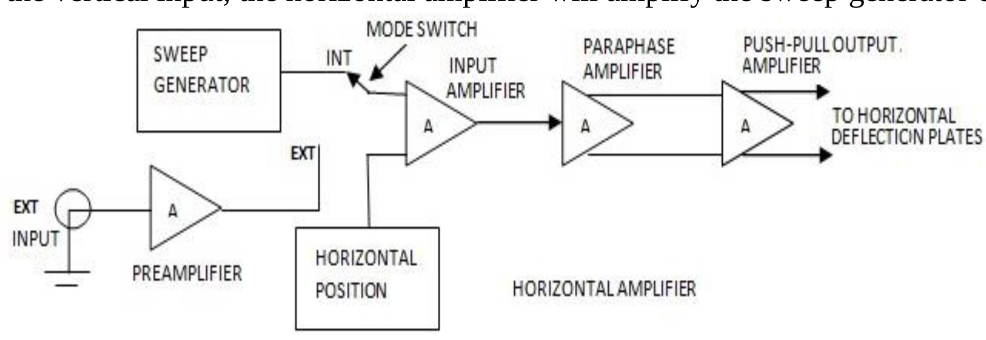
The vertical amplifier consists of several stages, with fixed overall sensitivity or gain expressed in v/divisions. The advantage of fixed gain is that the amplifier can be more easily designed to meet the requirements of stability and between the vertical amplifiers is kept within its signal handling capability by proper selection of the input attenuator switch. The first element of the pre-amplifier is the input stage, often consisting of a FET source follower whose high input impedance isolates from the attenuator. This FET input stage is followed by a BJT emitter followers to match the medium impedance of FET output with the low impedance input of the phase inverter. The phase inverter provides two anti-phase output signals which are required to operate the push pull output amplifier. The push pull output stage delivers equal signal voltages of opposite polarity to the vertical plates of the CRT. The advantages of push pull operation on CRO are similar to those obtained from push pull operation. In addition a number of focusing and non-linear effects are reduced, because neither plate is ground potential.

3) Horizontal Amplifier:

The horizontal basically serves two purposes:

a) When the oscilloscope is being in the X-Y node, the signal applied to the horizontal input terminal will be amplified by the horizontal amplifier.

b) 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 output.



4) Delay Line:

It is used to delay the signal from some time in the vertical section. Comparing the vertical and horizontal deflection circuits in the oscilloscope block diagram, we observe that the deflection signal is initiated or triggered, 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, whose output is fed to the horizontal deflection plates. This whole process takes time on the order of 80 ns. To allow the operator to observe the leading edge of the signal waveform, the signal drive for the vertical CRT plates must therefore be delayed by atleast the same amount of time. This is the function of time delay line.

CRO PROBES

The CRO probe performs the very important function of connecting the test circuit to the oscilloscope without altering, loading or otherwise disturbing the test circuit. There are three different probes:

a) Direct Reading Probe,
b) Circuit Isolation Probe,
c) Detector Probe.

They are discussed below:

a) Direct Reading Probe This probe is the simplest of all probes and it uses a shielded coaxial cable. It avoids stray pickups which may lead to problems when low level signals are being measured. It is used usually for low frequency and low impedance circuits. However in using the shielded probe, the shunt capacitance of the probe is added to the input impedance and capacity of the scope and acts to lower the response of the oscilloscope to high impedance and high frequency circuits.

b) Isolation Probe Isolation probe is used in order to avoid the undesirable circuit loading effects of shielded probe. Isolation probe which is used along with the capacitive voltage divider, decreases the input capacitance and increases the input resistance of the oscilloscope. This way the loading effects are drastically reduced.

c) Detector Probe When analyzing the response to modulated signals in communication equipment like AM, FM and TV receivers, the detector probe functions to separate the lower frequency modulation component from the higher frequency carrier. The amplitude of the modulator carrier (which is proportional to the response of the receiver to the much high frequency carrier signal) is displayed on the oscilloscope by rectifying and bypassing action. This permits an oscilloscope capable of audio-frequency response to perform signal tracing tests on communication signals in the range of hundreds of Mhz, a range which is beyond the capabilities of all oscilloscopes except the highly specialized ones.

Specification of an Oscilloscope

Bandwidth

Probably the most important specification of an oscilloscope is its bandwidth. The bandwidth of the the scope governs the maximum frequency of the signal that it can capture and analyse.

As the frequency of the signal gets closer to the maximum frequency that the oscilloscope can work with, its accuracy drops.

Sample Rate

The next important specification of an oscilloscope is its sample rate. The sample rate is the number of samples that the oscilloscope is capable of capturing per second. Obviously, the more, the better. But higher sample rates require more and faster memory to store, and faster electronics and processor to capture and process, driving up the price of the instrument.

Memory Size/Depth

Very closely related to the oscilloscope sample rate is its memory size. As the oscilloscope samples the signal from the test circuit, it stores the waveform data in its memory.

Manufacturers report the memory size of their oscilloscopes using the term "memory depth", and instead of using the regular byte unit, they use the "points" unit.

Rise Time

The Rise time of an oscilloscope describes the ability of the instrument to detect and capture rapidly rising and falling signals. This is particularly important when we work with square waves that have very sharp edges. A square wave can rise from 0V to 5V within nanoseconds.

Channels

Oscilloscopes typically offer 2 or 4 channels.

Each channel has a separate connector where you can attach a probe, and through this probe to monitor a signal.

Trigger

The trigger of an oscilloscope is fundamental to its operation. The trigger is the mechanism through which the oscilloscope can recognize a specific attribute of the input signal. Based on this attribute, the oscilloscope can achieve synchronization.

The trigger is the mechanism through which the oscilloscope can recognise a specific attribute of the input signal.

Oscilloscope Measurement Techniques

The two most basic oscilloscope measurements you can make are:

- Voltage Measurements
- Time Measurements

Voltage Measurements

Voltage is the amount of electric potential, expressed in volts, between two points in a circuit. Usually one of these points is ground (zero volts), but not always. Voltages can also be measured from peak-to-peak. That is, from the maximum point of a signal to its minimum point.

Figure shows the voltage of one peak (V_p) and the peak-to-peak voltage ($V_{p\text{–}p}$).

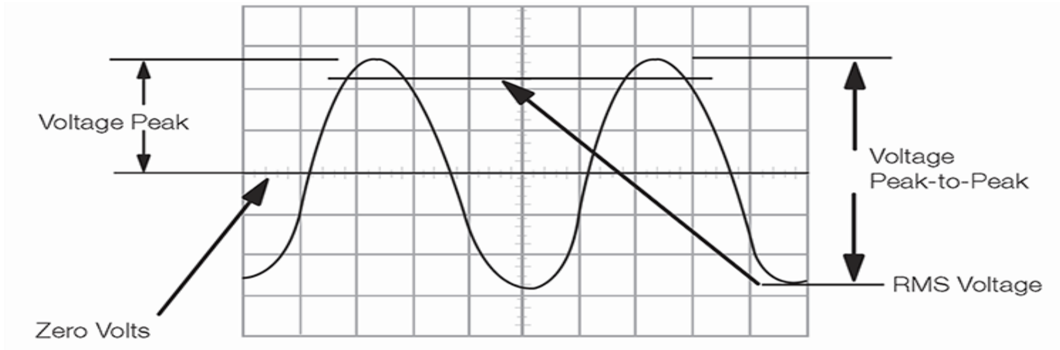


Figure: Voltage Peak (V_p) and Peak-to-Peak Voltage (V_{p-p}).

The most basic method of taking voltage measurements is to count the number of divisions a waveform spans on the oscilloscope's vertical scale. Adjusting the signal to cover most of the display vertically makes for the best voltage measurements, as shown in Figure below. The more display area you use, the more accurately you can read the measurement.

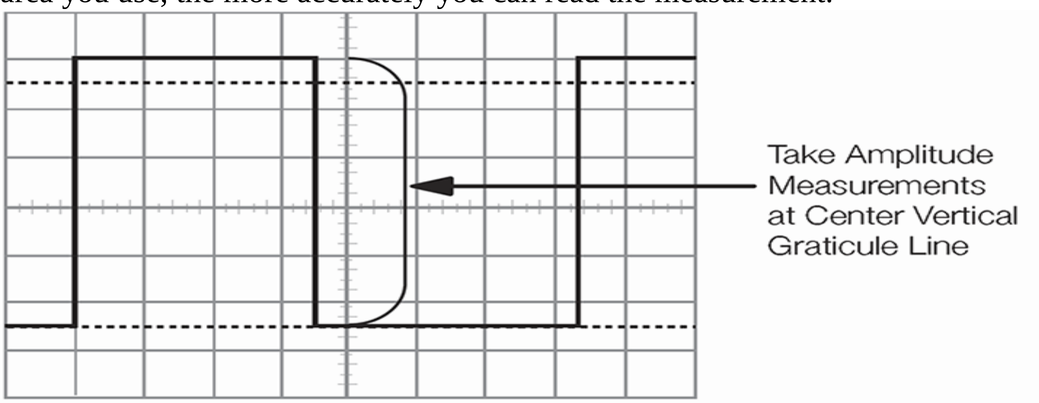


Figure: Measure voltage on the center vertical graticule line.

Many oscilloscopes have cursors that let you make waveform measurements automatically, without having to count graticule marks. A cursor is simply a line that you can move across the display. Two horizontal cursor lines can be moved up and down to bracket a waveform's amplitude for voltage measurements, and two vertical lines move right and left for time measurements. A readout shows the voltage or time at their positions.

Time and Frequency Measurements

You can make time measurements using the horizontal scale of the oscilloscope. Time measurements include measuring the period and pulse width of pulses. Frequency is the reciprocal of the period, so once you know the period, the frequency is one divided by the period. Like voltage measurements, time measurements are more accurate when you adjust the portion of the signal to be measured to cover a large area of the display, as illustrated in Figure below.

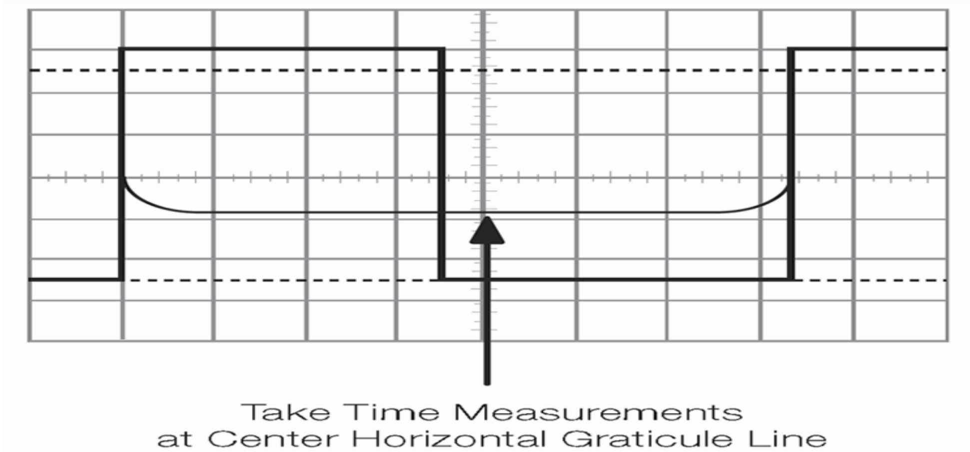


Figure: Measure Time on the Center Horizontal Graticule Line.

Special Oscilloscopes – Storage Oscilloscope, Sampling Oscilloscope

Digital oscilloscope can be classified into:

1. Digital Storage Oscilloscopes (Dsos)
2. Digital Phosphor Oscilloscopes (Dpos)
3. Sampling Oscilloscopes

Digital Storage Oscilloscopes

A conventional digital oscilloscope is known as a digital storage oscilloscope (DSO). Its display typically relies on a raster-type screen rather than luminous phosphor.

Digital storage oscilloscopes (DSOs) allow us to capture and view events that may happen only once – known as transients.

Because the waveform information exists in digital form as a series of stored binary values, it can be analyzed, archived, printed, and otherwise processed, within the oscilloscope itself or by an external computer.

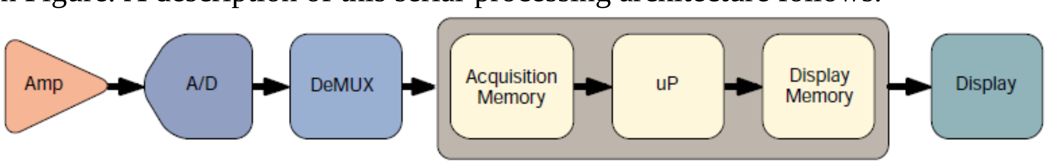
The waveform need not be continuous; it can be displayed even when the signal disappears. Unlike analog oscilloscopes, digital storage oscilloscopes provide permanent signal storage and extensive waveform processing.

However, DSOs typically have no real-time intensity grading; therefore, they cannot express varying levels of intensity in the live signal.

Some of the subsystems that comprise DSOs are similar to those in analog oscilloscopes.

However, DSOs contain additional data-processing subsystems that are used to collect and display data for the entire waveform.

A DSO employs a serial-processing architecture to capture and display a signal on its screen, as shown in Figure. A description of this serial-processing architecture follows.

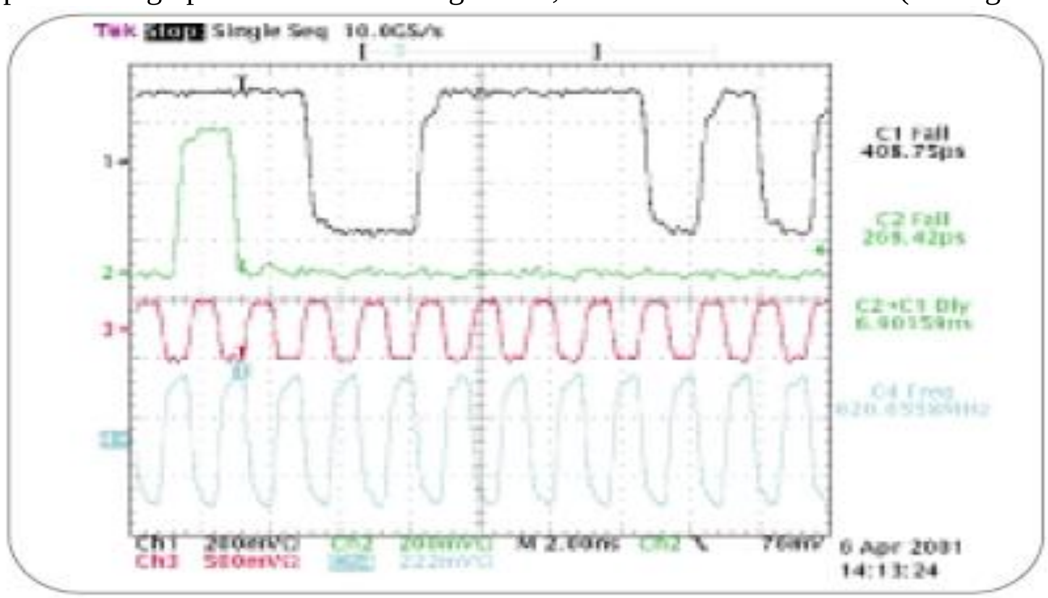


The serial-processing architecture of a digital storage oscilloscope (DSO).

<u>Serial-Processing Architecture</u>

Like an analog oscilloscope, a DSO's first (input) stage is a vertical amplifier. Vertical controls allow us to adjust the amplitude and position range at this stage.

Next, the analog-to-digital converter (ADC) in the horizontal system samples the signal at discrete points in time and converts the signal's voltage at these points into digital values called **sample points**. This process is referred to as **digitizing** a signal.
The horizontal system's sample clock determines how often the ADC takes a sample. This rate is referred to as the **sample rate** and is expressed in samples per second (S/s).
The sample points from the ADC are stored in acquisition memory as waveform points. Several sample points may comprise one waveform point. Together, the waveform points comprise one waveform record. The number of waveform points used to create a waveform record is called the **record length**.
The trigger system determines the start and stop points of the record.
The DSO's signal path includes a microprocessor through which the measured signal passes on its way to the display. This microprocessor processes the signal, coordinates display activities, manages the front panel controls, and more.
The signal then passes through the display memory and is displayed on the oscilloscope screen.
Depending on the capabilities of your oscilloscope, additional processing of the sample points may take place, which enhances the display.
Pre-trigger may also be available, enabling us to see events before the trigger point.
Most of today's digital oscilloscopes also provide a selection of automatic parametric measurements, simplifying the measurement process.
A DSO provides high performance in a single-shot, multi-channel instrument (see Figure 2).

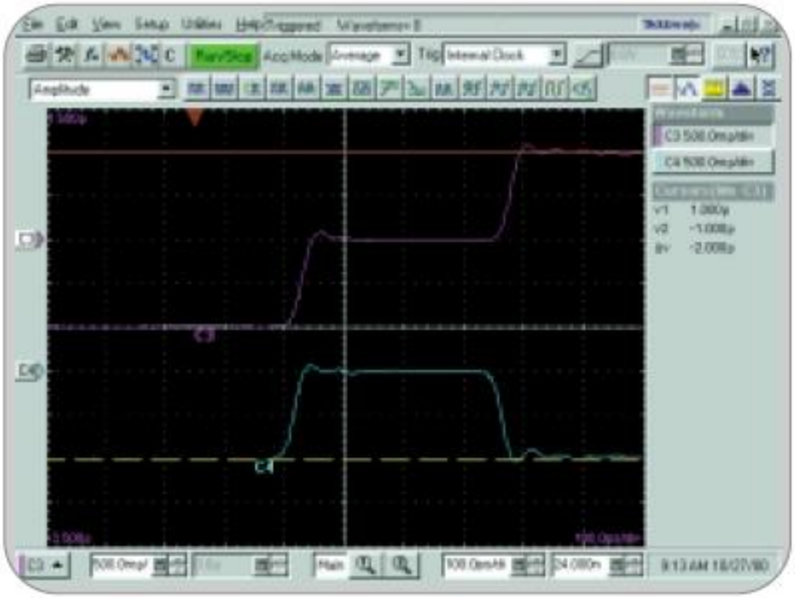


The TDS694C delivers high-speed, single-shot acquisition across multiple channels, increasing the likelihood of capturing elusive glitches and transient events.

DSOs are ideal for low-repetition-rate or single-shot, high-speed, multi-channel design applications.
In the real world of digital design, an engineer usually examines four or more signals simultaneously, making the DSO a critical companion.

Digital Sampling Oscilloscopes

When measuring high-frequency signals, the oscilloscope may not be able to collect enough samples in one sweep. A digital sampling oscilloscope is an ideal tool for accurately capturing signals whose frequency components are much higher than the oscilloscope's sample rate (see Figure).



Time domain reflectometry (TDR) display from a TDS8000
digital sampling oscilloscope and 80E04 20-GHz sampling module.

This oscilloscope is capable of measuring signals of up to an order of magnitude faster than any other oscilloscope.

It can achieve bandwidth and high-speed timing ten times higher than other oscilloscopes for repetitive signals.

Sequential equivalent-time sampling oscilloscopes are available with bandwidths to 50 GHz.

In contrast to the digital storage and digital phosphor oscilloscope architectures, the architecture of the digital sampling oscilloscope reverses the position of the attenuator/amplifier and the sampling bridge, as shown in Figure below.

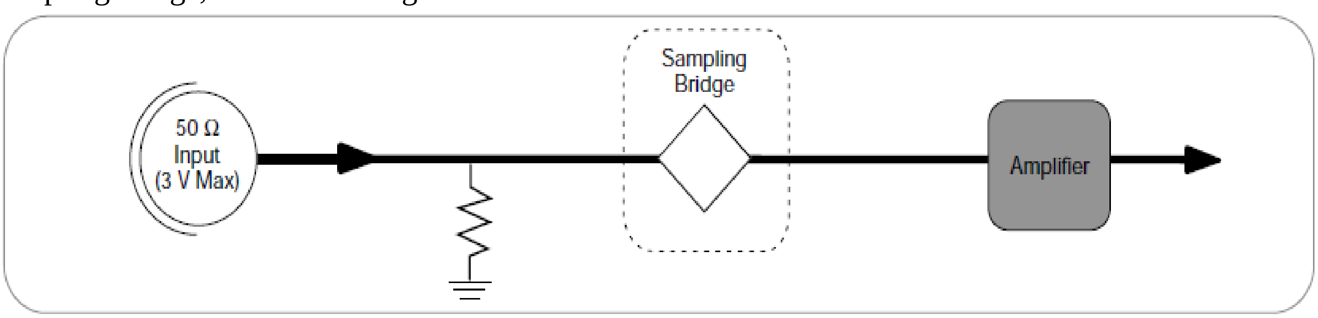


Fig: The Architecture of a Digital Sampling Oscilloscope.

The input signal is sampled before any attenuation or amplification is performed.

A low bandwidth amplifier can then be utilized after the sampling bridge because the signal has already been converted to a lower frequency by the sampling gate, resulting in a much higher bandwidth instrument.

The tradeoff for this high bandwidth, however, is that the sampling oscilloscope's dynamic range is limited.

Since there is no attenuator / amplifier in front of the sampling gate, there is no facility to scale the input.

The sampling bridge must be able to handle the full dynamic range of the input at all times. Therefore, the dynamic range of most sampling oscilloscopes is limited to about 1 V peak-to-peak.
Digital storage and digital phosphor oscilloscopes, on the other hand, can handle 50 to 100 volts. In addition, protection diodes cannot be placed in front of the sampling bridge as this would limit the bandwidth. This reduces the safe input voltage for a sampling oscilloscope to about 3 V, as compared to 500 V available on other oscilloscopes.

Recorders Basic Recording Systems.

A recorder is a measuring instrument which records time varying quantity, even after the quantity or variable to be measured has stopped. The electrical quantities such as voltage & 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 currents, using various transducers.

Electronic recorders may be classified as:

- A. Analog Recorders
  - a) Graphic Recorder
    - i) Strip Chart Recorder
      - Galvanometer Type
      - Null Type
      - Potentiometric Recorders
      - Bridge Recorders
      - LVDT Recorders
    - ii) Circular Chart Recorders
    - iii) *X-Y* Recorders
  - b) Magnetic Tape Recorders
  - c) Oscillographic Recorders
  - d) Others [Hybrid, Paperless, Ultraviolet and Thermal Dot Matrix Recorder]
- B. Digital Recorders
  - i. Incremental Digital Recorders
  - ii. Synchronous Digital Recorders

Strip Chart Recorders. Galvanometer and Potentiometer Type Recorders (Direct and Null Type)

A strip chart recorder records physical variable with respect to the independent variable time on a long paper kept in the form of a roll. The independent variable time (t) then corresponds to the strip-length axis and the physical variables measured (y) are related to the chart width. Tracings are obtained by a writing process at sites on the chart short axis (y) corresponding to the physical variables magnitudes with the strip being moved at constant velocity to generate the time axis.

Strip chart recorders consist of a roll or strip of paper that is passed linearly beneath one or more pens. As the signal changes, the pens deflect producing the resultant chart. Strip chart recorders are well suited for recording of continuous processes.

Strip Chart Recorder Components

The following are the components of strip chart recorder.

Pen(Stylus): It is used for marking data.

Chart Paper: In the Strip chart recorder, this chart paper is in the form of a strip. This strip is rolled and rotates under the pen as time passes.

Chart Paper Drive Mechanism: We need to move the chart paper under the pen to store the data. Users can adjust the speed of the moving paper (chart).

Event Marker: This marker is used to indicate the amount of time it takes to record fluctuations.

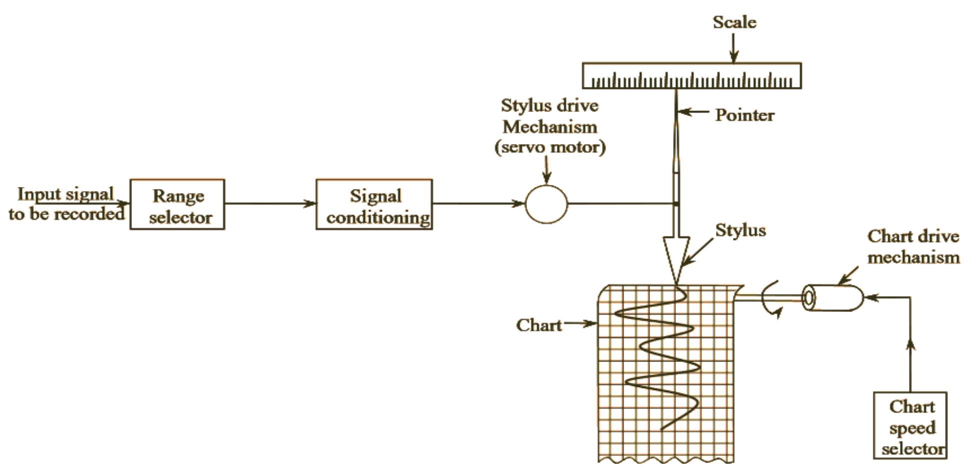
Signal Conditioning System: Signal conditioning system consist of Discrete circuits, Filters, Amplifiers, DAC, ADC etc.

Strip Chart Recorder Working Principle:

The working principle of a strip chart recorder is to record data on a continuous roll of chart paper moving at a constant speed. The recorder records the difference of one of the more variables with respect to time.

To reduce noise and interference the recorder's input DC signal is first **filtered** and then pre-amplified. This **conditioned signal** is carried to the **servo amplifier**, which is constantly compared to the feedback signal evolved by the servo potentiometer.

The difference between these two signals is a positive or negative error signal, which is used to drive a servo motor connected to a servo potentiometer in one direction to reduce the error signal to zero. Since the recorder plate is automatically connected to the **servo motor and servo potentiometer**, its position on the graph represents the accuracy of the input signal and the continuous registration of the graph.



The most commonly used mechanisms employed for making marks on the papers are:

(i) **Pen and Ink**: Marking with ink-filled stylus

(ii) **Thermal Type**: Marking with heated stylus on temperature sensitive paper (e.g. fax paper)

(iii) **Impact Type**: Marking with pressure sensitive paper (e.g. carbon paper)

(iv) **Electrostatic Stylus**: Marking with charged stylus on plain paper

(v) **Optical Type**: Marking with light ray on photosensitive paper

There are various kinds of strip chart recorders. According to their working principles, these are divided in mainly two categories. One works on the principle of the galvanometer and other is called null type.

(a) Galvanometric Type

Galvanometric instruments usually use a d'Arsonval galvanometer as the basic movement. This galvanometer consists of a moving coil suspended either on pivots or a taut ligament. The coil is then able to rotate in the field produced by a permanent magnet. When a small current is applied to the coil, a field is created which reacts with that of the permanent magnet, and the coil rotates. A control spring in a pivoted instrument and the ligament with a taut suspension provide an opposing torque. Thus, depending on the current applied, equilibrium will be established.

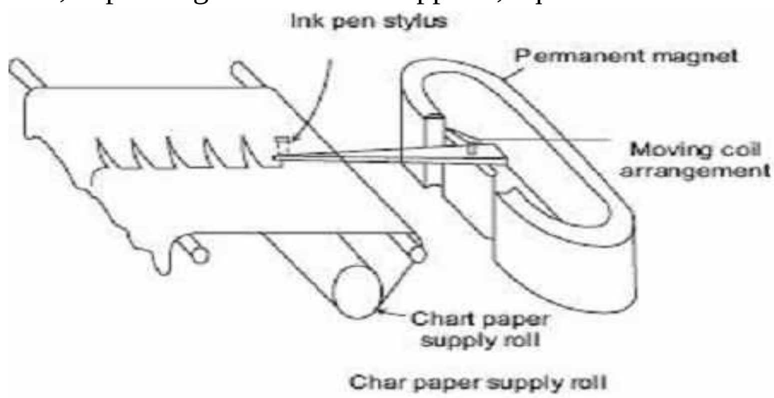


FIG: Galvanometer type recorder

(b) Potentiometric Type

The self-balancing potentiometer type of instrument consists of a bridge circuit. Across one arm of the bridge is a reference voltage, and across the other arm is a feedback network. Initially, the bridge is adjusted so that the servo amplifier and its motor are in balance and stationary. When a signal is fed to the amplifier, the output causes the servomotor to drive a balancing potentiometer, which in turn refers a feedback voltage to the amplifier input. When the two signals are equal and opposite, the system balances and the servomotor stops. If a pen unit is attached to the motor/potentiometer mechanized drive, at the point of balance, the pen will show the proportional value of the input signal. As with galvanometric instruments, this principle may be applied in various ways.

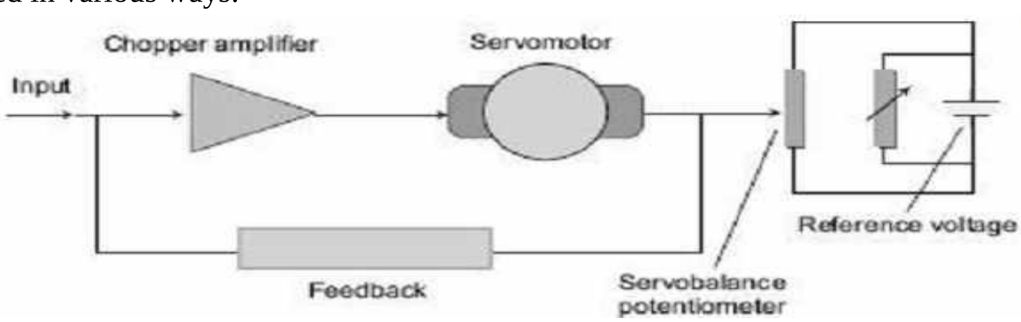


FIG. Potentiometric Type Recorder

This kind of recorders having very high input impedance, infinity at balance conditions, and a high sensitivity.

Magnetic Tape and Disc Recorders

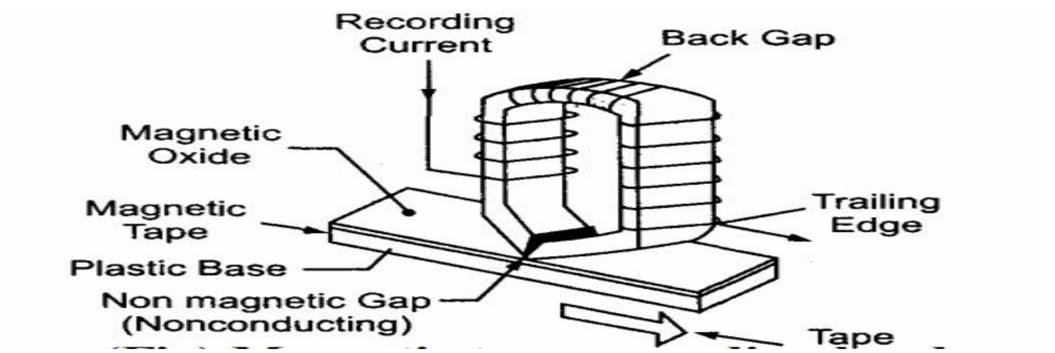
The magnetic tape recorders are used for high frequency signal recording. In these recorders, the data is recorded in a way that it can be reproduced in electrical form any time. Also main advantage of these recorders is that the recorded data can be replayed for almost infinite times. Because of good higher frequency response, these are used in Instrumentation systems extensively.

Basic Components of Tape Recorder

Following are the basic components of magnetic tape recorder

1. Recording Head
2. Magnetic Tape
3. Reproducing Head
4. Tape Transport Mechanism
5. Conditioning Devices

Recording Head: The construction of the magnetic recording head is similar to Transformer having a toroidal core with coil when the current used for recording is passed through coil wound around magnetic core, it produces magnetic flux. When the tape is passing the head, the flux produced due to recording current gets linked with iron oxide part ices on the magnetic tape and these particles get magnetized.

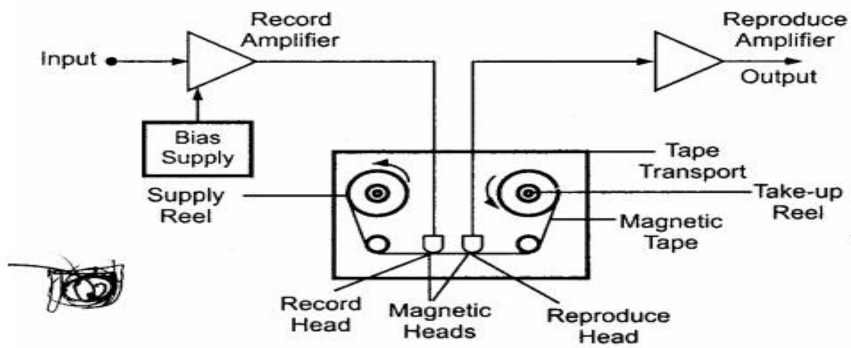


This magnetization particle remains as it is, even though the magnetic tape leaves the gap. The actual recording takes place at the trailing edge of the air gap. Any signal is recorded in the form of the patterns. These magnetic patterns are dispersed any where along the length of magnetic tape in accordance with the variation in recording current with respect to time.

Magnetic Tape: The magnetic tape is made of thin sheet of tough and dimensionally stable plastic ribbon and is wound around a reel. This tape is transferred from one reel to another. When the tape passes across air gap magnetic pattern is created in accordance with variation of recording current. To reproduce this pattern, the same tape with some recorded pattern is passed across another magnetic head in which voltage is induced. This voltage induced is in accordance with the magnetic pattern.

Reproducing Head: The use of the reproducing head is to get the recorded data played back. The reproducing head detects the magnetic pattern recorded on the tape. The head converts the magnetic pattern back to the original electrical signal. In appearance, both recording and reproducing heads are very much similar.

Tape Transport Mechanism: The tape transport mechanism 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 & other is called as take-up reel. Both the reels rotate in same direction.
The transportation of the tape is done by using supply reel and take-up reel. The fast winding of the tape or the reversing of the tape is done by using special arrangements. The rollers are used to drive and guide the tape.



Conditioning Devices: These devices consist of amplifiers and fitters to modify signal to be recorded.

Principle of Tape Recorders
When a magnetic tape is passed through a recording 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 is induced corresponding to the magnetic pattern on the tape.
When the tape is passed through the reproducing head, the head detects the changes in the magnetic pattern i.e. magnetization.
The change in magnetization of particles produces change in the reluctance of the magnetic circuit of the reproducing head, inducing a voltage in its winding.
The induced voltage depends on the direction of magnetization and its magnitude on the tape. The emf, thus induced is proportional to the rate of change of magnitude of magnetization i.e.
$e = N * (d\text{ĭ} / dt)$

Where N = number of turns of the winding on reproducing head

Suppose the signal to be recorded is Vm sinwt. Thus, the current in the recording head and flux induced will be proportional to this voltage. It is given by

$e = k_1$. Vm sinwt, where k1 = constant.

Above pattern of flux is recorded on the tape. Now, when this tape is passed through the reproducing head, above pattern is regenerated by inducing voltage in the reproducing head winding. It is given by

e= k_2 ŬVm cos wt

Thus the reproducing signal is equal to derivative of input signal & it is proportional to flux recorded & frequency of recorded signal.

Applications of Magnetic Tape Recorders:

1. Data recording and analysis on missiles, aircraft and satellites.
2. Communications and spying.
3. Recording of stress, vibration and analysis of noise.

Indicators and Display Devices - Nixie, LED, LCD and Seven Segment and Dot Matrix Displays.

Indicators and display devices play a crucial role in presenting information in various electronic systems. They are designed to visually communicate data, status, or messages to users. Here are some common types of indicators and display devices:

Nixie Tubes:

A **Nixie tube** or **cold cathode display** is an electronic device used for displaying numerals or other information using glow discharge. Nixie tubes are display devices that were popular in the mid-20th century. They use neon gas-filled tubes with cathodes shaped like numerals or symbols. The tube is filled with a gas at low pressure, usually mostly neon and a small amount of argon, in a Penning mixture. When voltage is applied, a specific cathode lights up, displaying the corresponding character. Nixie tubes have a vintage aesthetic and emit a warm orange glow. They are often used in retro-style clocks and other decorative applications.

Although it resembles a vacuum tube in appearance, its operation does not depend on thermionic emission of electrons from a heated cathode. It is hence a cold-cathode tube (a form of gas-filled tube), and is a variant of the neon lamp. Such tubes rarely exceed 40 °C (104 °F) even under the most severe of operating conditions in a room at ambient temperature. Vacuum fluorescent displays from the same era use completely different technology—they have a heated cathode together with a control grid and shaped phosphor anodes; Nixies have no heater or control grid, typically a single anode (in the form of a wire mesh, not to be confused with a control grid), and shaped bare metal cathodes.

LEDs (Light-Emitting Diodes):

LEDs are semiconductor devices that emit light when an electric current passes through them. It is basically a p-n junction photodiode when excited at forward-bias condition emits light. They are small, energy-efficient, and available in various colors. LEDs are widely used in indicators and displays due to their versatility. They can be used as individual indicator lights or arranged in arrays to form alphanumeric characters or graphical displays. LEDs are commonly found in electronic devices, signage, automotive lighting, and many other applications.

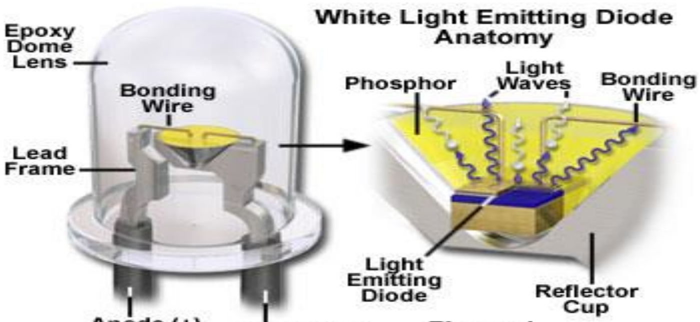


Figure 1

It can be easily interfaced with a simple electronic circuit and is durable and reliable. These LEDs are often arranged in different formats to display information. Among these, the seven segments configuration and dot matrix display are very common and widely used. The seven-segment configuration of an LED arranged in the form of the digit 8 can be restrictive in that it does not adequately allow the display of some alphanumeric characters. By contrast, the versatility of a dot-matrix arrangement allows an LED unit to display more complicated shapes. The following sections discuss the about seven-segment and dot-matrix LED display.

Seven Segment Display

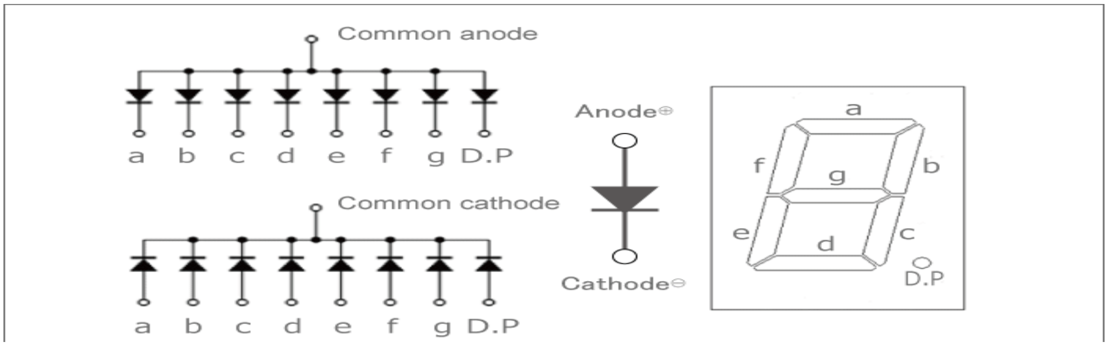
Seven segment displays are the output display device that provides a way to display information in the form of images or text or decimal numbers which is an alternative to the more complex dot matrix displays. It consists of seven segments of light-emitting diodes (LEDs) which are assembled like numerical 8.

Each one of the seven LEDs in the display is given a positional segment with one of its connection pins being brought straight out of the rectangular plastic package. These individually LED pins are labelled from a through to g representing each individual LED. The other LED pins are connected together and wired to form a common pin.

So by forward biasing the appropriate pins of the LED segments in a particular order, some segments will be light and others will be dark allowing the desired character pattern of the number to be generated on the display. This then allows us to display each of the ten decimal digits 0 through to 9 on the same 7-segment display.

There are basically two types of seven-segment displays-common cathode and common anode.

- Common anode: when the common pin is positive
- Common cathode: when the common pin is negative



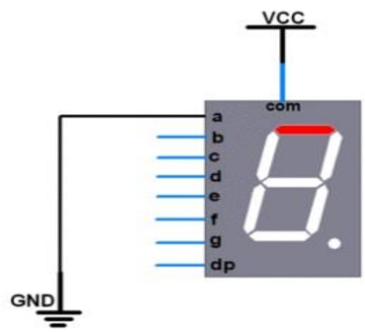


Fig: Common Anode 7 Segment Display

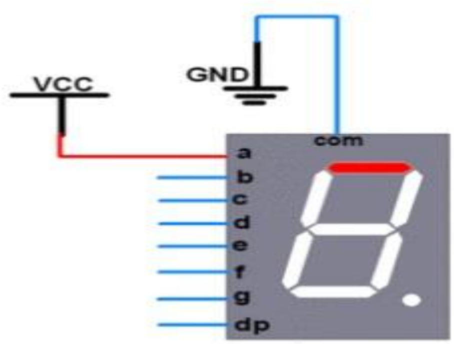
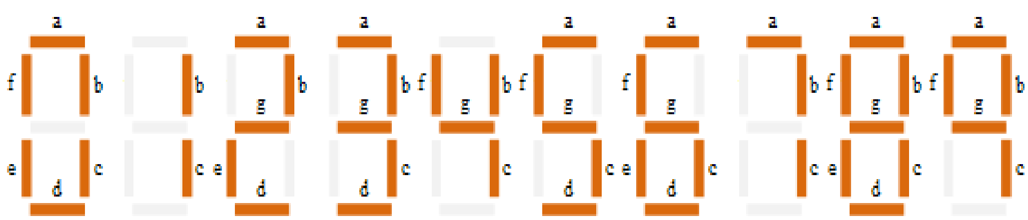


Fig: Common Cathode 7 Segment Display

Digital Segments for all Numbers



Then for a 7-segment display, we can produce a truth table giving the individual segments that need to be illuminated in order to produce the required decimal digit from 0 through 9 as shown below.

7-segment Display Truth Table

Segments Inputs							7 Segment Display Output
a	b	c	d	e	f	g	
0	0	0	0	0	0	1	0
1	0	0	1	1	1	1	1
0	0	1	0	0	1	0	2
0	0	0	0	1	1	0	3
1	0	0	1	1	0	0	4
0	1	0	0	1	0	0	5
0	1	0	0	0	0	0	6
0	0	0	1	1	1	1	7
0	0	0	0	0	0	0	8
0	0	0	0	1	1	0	9

Dot Matrix Display

LEDs are arranged in matrix form-common configurations are 5 × 7, 5 × 8 and 8 × 8, as shown in FIG. Based on the electrode connections, two kinds of LED matrices are possible, one is common anode. All the LEDs in a row having the anode are connected together. The other one is common cathode, having all LEDs in a row; the common cathode or cathodes are shorted. It is easier to understand the construction and interface capabilities of an LED matrix using an illustration. FIG. depicts a matrix construction of the common-anode type. A single matrix is formed by thirty-five LEDs arranged in five columns and seven rows (5 × 7). The anodes of the fi ve LEDs forming one row are connected together. Similarly, the cathodes of the seven LEDs of a column are connected together. In this arrangement of LEDs, the cathodes are switched to turn the LEDs of a row on or off.

The matrix (unit) illustrated in FIG. can be used to display a single alphanumeric character. Several such units can be placed next to each other to form a larger panel to display a string of characters.

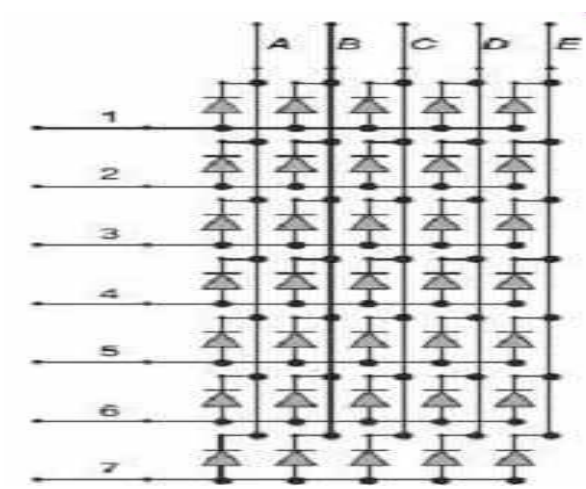


FIG. LED Matrix with common-anode arrangement.

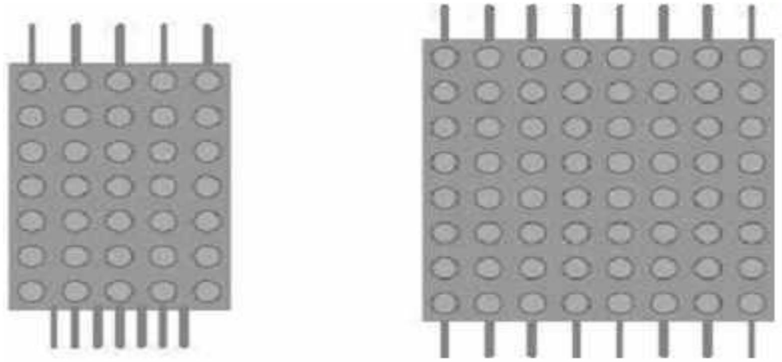


FIG. 5×7 and 8×8 dot matrix display

Data Loggers

Data loggers are is stand-alone devices that can record information electronically from internal or external sensors or other equipment that provide digital or serial outputs.

1. Key Features of Data Loggers

(a) **Stand-alone Operation**

Most data loggers are normally configured with a PC, some models can be configured from the front panel provided by the manufacturer. Once the data loggers are configured, they don't need the PC to operate.

(b) **Support for Multiple Sensor Types**

Data loggers often have universal input type which can accept input from common sensors like thermocouple, RTD, humidity, voltage, etc.

(c) **Local Data Storage**

All data loggers have local data storage or internal memory unit, so all the measured data is stored within the logger for later transfer to a PC.

(d) **Automatic Data Collection**

Data loggers are designed to collect data at regular intervals, 24 hours a day and 365 days a year if necessary, and the collection mode is often configurable.

Data logging and recording are both analog terms in the field of measurement. Data logging is basically measuring and recording of any physical phenomena or electrical parameter over a period of time. The physical phenomena can be temperature, strain, displacement, flow, pressure, voltage, current, resistance, power, and many other parameters

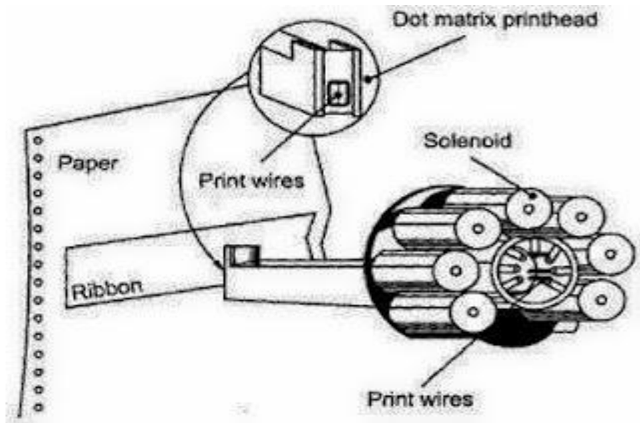
The data logger collects information about the state of any physical system from the sensors. Then the data logger converts this signal into a digital form with the help of an A/D converter. This digital signal is then stored in some electronic storage unit, which can be easily transferred to the computer for further the analysis,

A few basic components that every data logger must have which are:

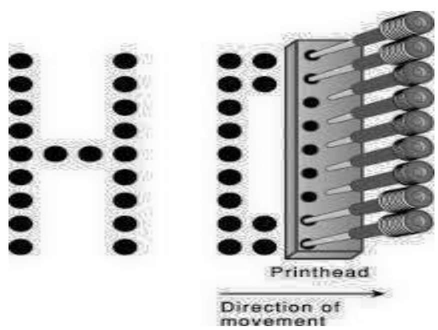
1. Hardware components like sensors signal conditioning, and analog-to-digital converter, etc.
2. Long-term data storage, typically onboard memory or a PC
3. Software for collecting data, analyzing and viewing

Dot Matrix

A **Dot Matrix Printer** or *Impact Matrix Printer* refers to a type of computer printer with a print head that runs back and forth on the page and prints by impact, striking an ink-soaked cloth ribbon against the paper, much like a typewriter. Unlike a typewriter or daisy wheel printer, letters are drawn out of a dot matrix, and thus, varied fonts and arbitrary graphics can be produced.



Because the printing involves mechanical pressure, these printers can create carbon copies and carbon less copies. Each dot is produced by a tiny metal rod, also called a “wire” or “pin”, which is driven forward by the power of a tiny electromagnet or solenoid, either directly or through small levers (pawls). Facing the ribbon and the paper is a small guide plate pierced with holes to serve as guides for the pins. The moving portion of the printer is called the print head, and when running the printer as a generic text device it generally prints one line of text at a time.



Most dot matrix printers have a single vertical line of dot making equipment on their print heads; others have a few interleaved rows in order to improve dot density. These machines can be highly durable, but eventually wear out. Ink invades the guide plate of the print head, causing grit to adhere to it; this grit slowly causes the channels in the guide plate to wear from circles into ovals or slots, providing less and less accurate guidance to the printing wires.

Advantages:

1. Can print on multi-part stationery or make carbon copies.
2. Impact printers have one of the lowest printing costs per page.
3. They are able to use continuous paper rather than requiring individual sheets.
4. The ink ribbon also does not easily dry out.

Disadvantages:

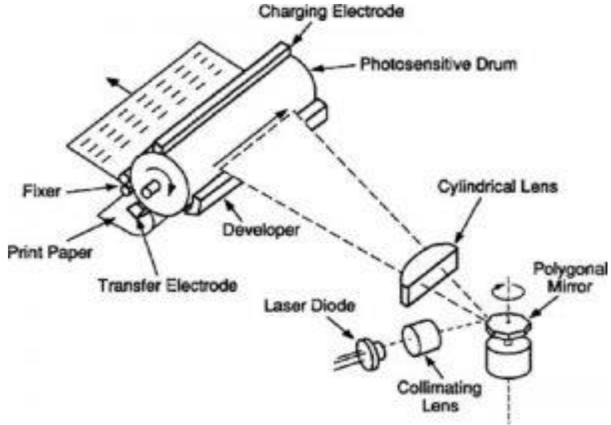
1. Impact printers are usually noisy.

2. They can only print low resolution graphics, with limited color performance, limited quality and comparatively low speed.
3. They are prone to bent pins (and therefore a destroyed print head) caused by printing a character half-on and half-off the label.

Laser Printers

A laser printer is a popular type of computer printer that uses a non-impact photocopier technology where there are no keys striking the paper.

When a document is sent to the printer, a laser beam "draws" the document on a selenium-coated drum using electrical charges. The drum is then rolled in toner, a dry powder type of ink that adheres to the charged image on the drum. The toner is transferred onto a piece of paper and fused to the paper with heat and pressure.



Working Principle

1. A photo, graphic or text image is sent to the printer, which begins the process of transferring that image to paper using a combination of positive and negative static electric charges.
2. The revolving drum gets a positive charge.
3. The system's electronics convert the image into a laser beam.
4. The laser beam bounces off a mirror onto the drum, drawing the image on the drum by burning a negative charge in the shape of the image.
5. Then the drum picks up the positively charged toner from the toner cartridge. The toner sticks to the negatively charged image on the drum.
6. Paper entering the printer receives a negative charge.
7. As the paper passes the drum, the paper's negative charge attracts toner from the positively charged drum; the toner literally sits on top of the paper.
8. The paper's charge is removed and a fuser permanently bonds the toner onto the paper.
9. The printed paper is released from the printer.
10. The electrical charge is removed from the drum, and the excess toner is collected

Compact Disc/Optical Disc Recorders

A compact disc is a portable storage medium that can record, store and play back audio, video and other data in digital form. As a result, the signals captured are a replica of the original audio stream. Text, picture images, audio, video, and software are all stored on compact discs.

It is made up of three layers.

1. Transparent Substrate with a polycarbonate wafer [plastic disc] makes up this layer.
2. Thin metallic Layer coating of aluminium alloy is applied to the wafer base.
3. Outer Layer of Protective Acrylic

The CD's layout is seen in Figure.

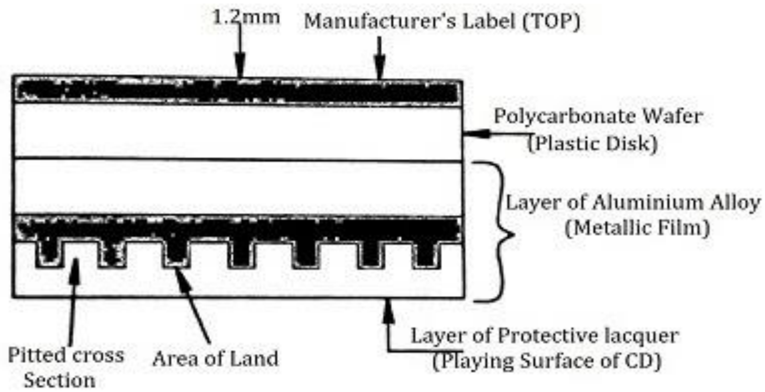


Fig: Layout CD-ROM Disc

Working

Using a sample and hold circuit and an ADC, the signal to be recorded on CD is first amplified and then transformed into a digital signal. The output of the ADC is also used by the Laser Beam Generator. The control circuit and the servo system are both controlled by the signal from the crystal oscillator and Laser beam generator.

The servo system, which is controlled by a motor, regulates the disc rotation as well as the track and focus of the Laser beam generator. The picture depicts a block schematic of a CD recording system.

The unexposed photoresist material is chemically removed after recording, leaving a helical pattern across the glass disc's surface. This becomes the glass master for mass-production CDs.

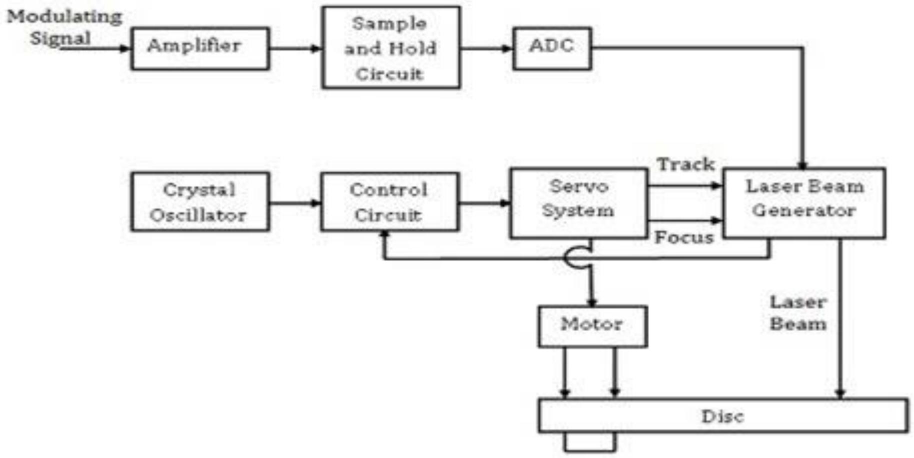


Figure: Block Diagram of CD Recording

The data retrieval system is made up of the phases listed below.

1. A servomechanism, which spins the CD.
2. A laser head that moves in a radial pattern. The laser head can both emit and detect a 70nm laser beam.

When the disc spins, the laser beam is focused onto the playing surface, where it is reflected by the ‘lands' and scattered by the ‘pits,' resulting in a change in the quantity of light reflected whenever there is a pit-to-land or land-to-pit change. As a result, the pit borders are detected by a laser beam.