Chapter: 2

Signal Measurement

12 hrs

2.1 Unit: Any physical quantity of a substance can be express-ed as a multiple of a known or standard quantity. The known or standard quantity of a substance is called unit of the substance. Or the standard measure of each kind of physical quantity is called unit. For eg: let the physical quantity be 'mass' then its unit is kg.

Units are of 2 types: fundamental and derived units.

2.1.1 Fundamental Units: The units of the fundamental quantities are called fundamental units. Here fundamental qua-ntities means those quantities which are independent of other physical quantities. For eg: for fundamental quantities like length, mass, time, the units are meter, kg and second respecti-vely. These units are fundamental units. The list of fundam-ental quantities and their respective units is as:

Fundamental Quantities	Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Temperature	Degree kelvin	°k
Current	Ampere	A
Luminous Intensity	Candela	cd
Amount of Substance	Mole	mol

2.1.2 Derived units:- The units of the derived quantites are called derived units. In other words, the units which can be expressed in terms of the fundamental units are called derived units. All the other units rather than above mentioned are derived Units. For eg: Unit of force: Newton, Unit of power: watt, Unit of area: meter square, unit of pressure: pascal etc are derived units.

2.2 Standards of Measurement

2.2.1 International Standard: The international standards are defined on the basis of international agreement. These are the units used widely all over the world. They are same all over the world and are not different for different nations. The international standards are maintained at International Bureau of weights and Measures. For eg: SI units

2.2.2 Primary Standard :- Primary standards are absolute standards of such high accuracy that they can be used as the ultimate ~~stan~~ reference standards. These standards are maintained by national standards laboratories in different parts of the world. Primary standards are not available for use outside the national laboratories. One of the main function of primary standards is the verification and calibration of the secondary standards.

2.2.3 Secondary Standard :- Secondary standards are the basic reference standards used in industrial measurement laboratories. The responsibility of maintainance and calibration of these standards lie with the particular industry involved. Secondary standards are sent to the national standard lab. periodically for calibration and comparision against primary standards. Then they are sent back with a certification.

2.2.4 Working Standard :- The working standards are the major tools of a measurement lab. These standards are used to check and calibrate general lab instruments for their accuracy and performance. For eg: a manufacturer of precision resistances, may use a standard resistance (which may be working standard) in the quality control for checking the values of resistors that are being manufactured.

2.2.5 IEEE Standard :- IEEE standards are slightly different standards and maintained by Institute of Electrical and Electronic Engineers, an engineering society that is headquatered in New York City. These standards are not physical items that are available for comparision and checking for secondary standards but are standards procedures, nomenclature, definition, etc and are ~~placed~~ updated from time to time.

IEEE standards produce a large number of standard test methods for testing and evaluation various electronics systems and components. Though any test methods should result the same results, specifying a methodology decreases the chances of possible error.

It also provides a standard for specifying test equipments for eg: the lab. oscilloscope would become difficult to use if each manufacturer adopted different arrangement of knobs and functions and even worse if different names for same functions. The standards concerning the safety of wiring power plants ships, industrial buildings etc are also provided in IEEE standards. Standard schematic & logic symbols are defined so that engineering drawings can be understood by all engineers. Various interfacing standards and communication standards are also specified by IEEE standards. For eg: IEEE 488 bits, RS 232 Connector, etc.

2.3 Performance Parameters :-

The detailed specifications of the functional behaviour of any instrument are termed as its performance ~~pa~~ characteristics. This in general indicates the capabilities and limitations of the instrument for particular application and they are judged how faithfully the system measures the desired i/p and how thoroughly it rejects the undesired i/ps. Infact it relates to the degree of approach to perform quantitatively. Thus it is important to have a good knowledge of performance parameters as it enables us with quantitative estimate of the positive as well as negative points of various commercially available instruments and ultimately to select the optimum type of instrument for the given application.

The performance parameters are broadly classified as:
Static performance parameters &
Dynamic performance parameters.

2.3.1 Static Performance Parameters :-

Some Applications involve the measurement of quantities that are either constant or very slowly varying with time. Under these circumstances it is possible to define a set of criteria that gives meaningful description of quality of measurement without interfering description that involve the use of differential eq^{ns}. These criteria are called static characteristics.

(i) Accuracy: Accuracy refers to the degree of closeness of the instruments o/p to the true value of the measured quantity (as per standard), however, in general it is specified as the "deviation or inaccuracy of the measurement from the true value. For eg: if a balance reads 1gm with an error of 0.01gm, the accuracy of the measurement would be specified as 1%. Accuracy of the instrument mainly depends on the inherent limitations of the instrument as well as the shortcoming in the measurement process. Accuracy of the instrument can be specified in either of the following ways:

* Percentage of true value $= \dfrac{\text{measured value} - \text{true value}}{\text{true value}} \times 100\%$

* Percentage of full scale deflection = $\frac{\text{measured value} - \text{true value}}{\text{max}^m \text{ scale deflection}} \times 100\%$

[Note:- The specification of the % of full scale is less accurate than the % of true value.]

(ii) **Precision** :- It is the measure of reproducibility of the measurement ie. it is the measure of the degree of agreement within a group of measurements.

Reproducibility: degree of closeness with which the given value may be measured.

Precision is composed of 2 characteristics:

* Conformity
* Significant figures.

Error caused due to the limitation of the scale reading is called precision error.

[Precision is necessary but not sufficient condition for accuracy].

(iii) Sensitivity :- Sensitivity is a measure of the change in instrument's o/p which occurs when the quantity being measured change by a given amount. Sensitivity is thus the ratio:

$$\text{Sensitivity} = \frac{\text{Scale deflection}}{\text{value of measurand causing deflection}}$$

$$\text{or} \quad \frac{\text{Change in o/p}}{\text{i/p causing the change}}$$

(iv) Linearity :- One of the best characteristics of an instrument is considered to be linearity ie. the o/p is linearly proportional to the i/p. Most of the system requires a linear behaviour as it is desirable. This is because the conversion from a scale reading to the corresponding measured value of i/p quantity is most convinient if one merely has to multiply by a fixed constant rather than consulting a non-linear calibration curve or compute from non-linear calibration eqns.

→ Linear behaviour often simplifies the design and analysis of system.

→ If for an instrument, calibration curve (o/p to i/p relationship) is not straight line, it should not be concluded that the instrument is inaccurate.

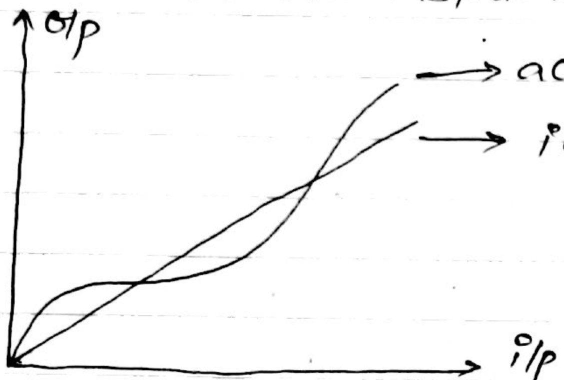


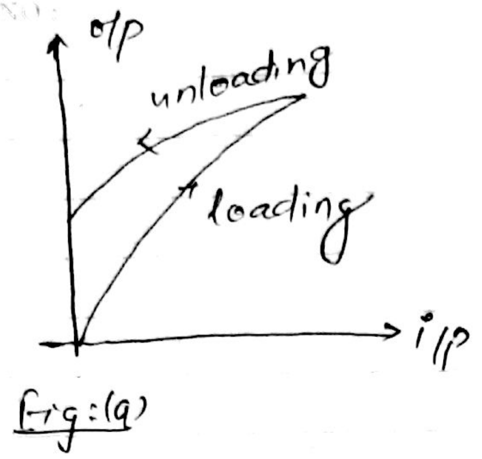
Fig: Deviation betn actual calibration curve and idealized straight line.

$$\text{Non-linearity} = \frac{\text{max}^m \text{ deviation of o/p from the idealized st. line}}{\text{actual reading}} \times 100\%$$

$$= \frac{\text{max}^m \text{ deviation of o/p from the idealized st. line}}{\text{full scale deflection}} \times 100$$

Accuracy and linearity are closely related qualities. If any instrument considered as linear, the non-linearity specification is equivalent to the specification of inaccuracy. So in many linear instruments, only linear specification is given & accuracy specification is omitted.

(v) **Hysteresis**:– Hysteresis means non-coincidence of loading and unloading curves. It is the phenomenon which ~~depends~~ depicts different o/p effects when loading and unloading. It arises due to the fact that all the energy put into the stressed parts when loading is not recoverable when unloading.



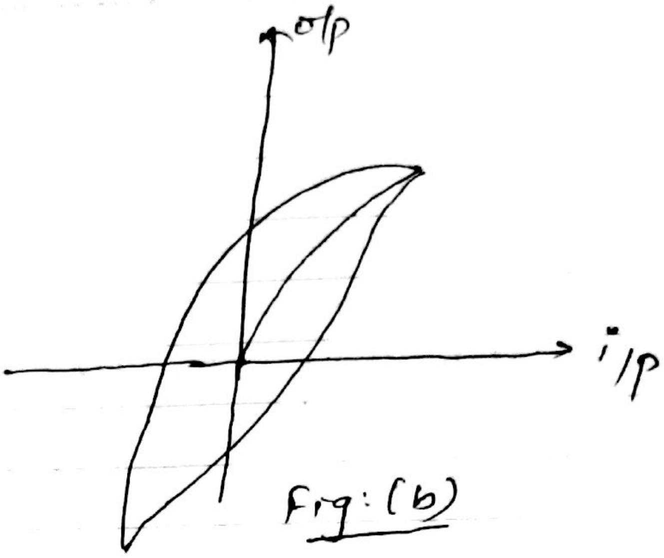


Fig: I/o relationship of instrument showing hysteresis.

(vi) Drift :- It is an undesirable quantity in industrial instrument because it is rarely apparent and cannot be easily compensated for. Thus it must be carefully gaurded against by continuous prevention, inspection and maintenance. For eg: electromagnetic fields can be prevented from affecting the instruments by proper shielding. Temperature changes during the measurement process should be preferably avoided or otherwise be properly compensated.

Reproducibility is the degree of closeness with which a given value may be repeatedly measured. Perfect reproducibility means that the instrument has no drift. No drift means that with a given i/p the measured values do not vary with time.

Causes of drift :-

- electric and magnetic fields
- Thermal emfs
- change in temperature
- Mechanical vibration
- wear and Tear
- High mechanical stresses.

Drift →
- Zero drift ⇒ If the whole calibration gradually shifts
- Span drift / sensitivity drift ⇒ If there is proportional change in the indication all among the upward scale.
- Zonal Drift ⇒ If drift occurs only over a portion of span of an instrument.

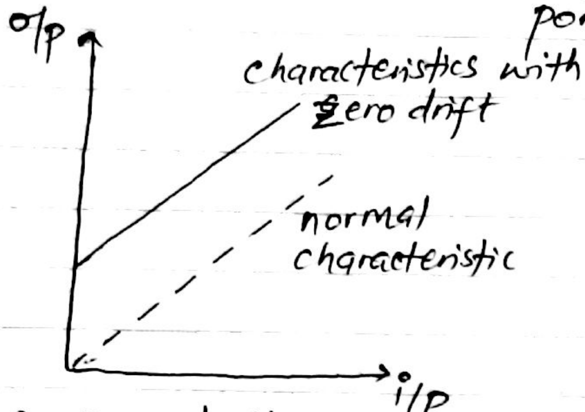


Fig: Zero drift

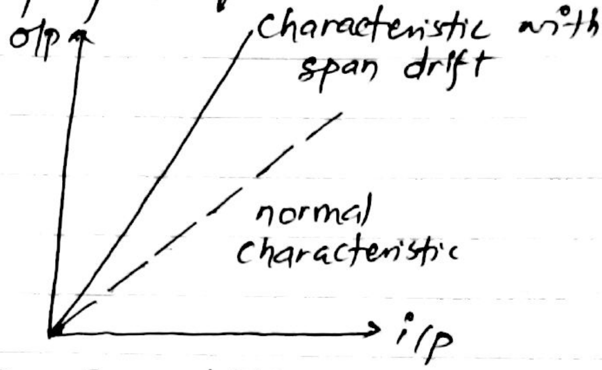


Fig. Span drift

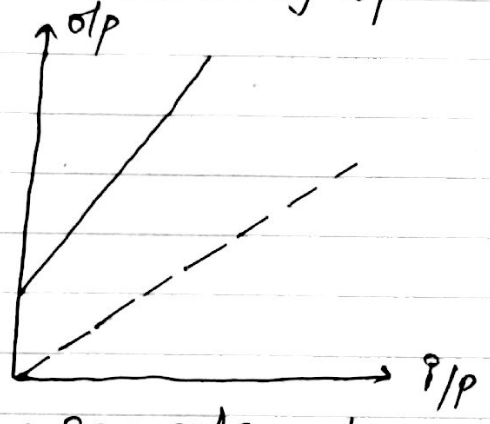


Fig: Zero and Span drift

(vii) Error : Error is the difference between the measured value and the true value of the quantity. Any deviation of measured value from the true value is undesirable in any instrument. The lesser the error, the more accurate is the instrument.

(viii) Range or Span :- The range or span of an instrument defines the max^m and min^m values of a quantity the instrument is designed to measure.

(ix) Bias :- Bias refers to the constant error, which exists over the full range of measurement of an instrument. This error is normally removable by calibration. For eg: a weighing balance indicates 1kg even when there is no load on it. If a man with 50kg stands on it, the balance would indicates 51kg. Again if we want to measure a load of 60kg then the balance would indicate 61kg. There is a constant bias of 1kg & this can be removed by proper calibration.

(X) Dead Space (or Dead Zone):- It is defined as the largest change of i/p quantity for which there is no o/p of the instrument. For eg: the i/p applied to the instrument may not be sufficient to overcome the friction and will in that case, not move at all.

(Xi) Threshold:- Threshold is the minimum value of i/p below which no o/p can be detected.

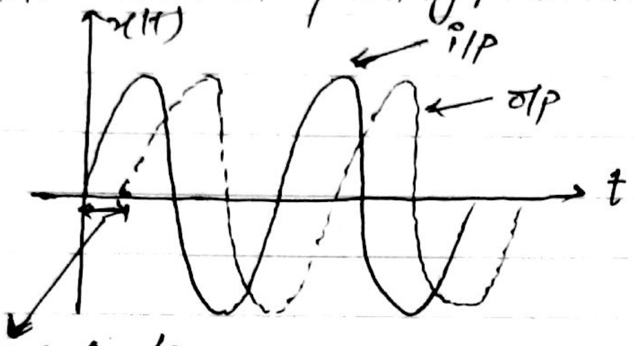
(Xii) Resolution:- It is the smallest change in the measured that can be detected with specified accuracy by the instrument. In other words, it is the degree of ~~fitness~~ fineness with which a measurement can be made.

2.3.2 Dynamic Performance Parameter:-

Many measurements are concerned with rapidly varying quantities and therefore for such cases we must examine the dynamic relations which exists betn o/p and i/p. This is normally done with the help of differential equations. Performance criteria based upon dynamic relations constitute dynamic characteristics.

The dynamic characteristics of a measuring instrument describes its behaviour betn the time a measured quantity changes value and the time when the instrument o/p attains a steady value in response and its characteristics are:

(i) Measuring lag: Delay in the occurrance of the o/p signal.
It is the delay in the response of an instrument to a change in the measured quantity/variable.



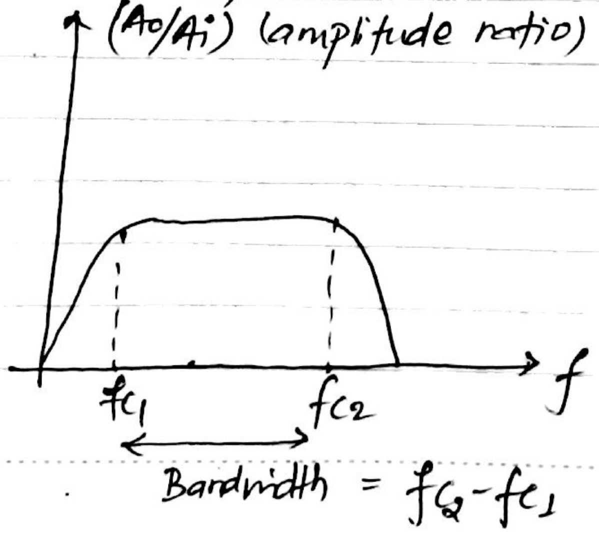
(ii) Dynamic Error :- It is the difference between the true value of the quantity change with time and value indicated by the instrument when no static error is assumed. It is also called Measurement Error.

(iii) Fidelity :- It is the ability of the system to reproduce the o/p in the same form of i/p.
In other words, it is the degree to which an instrument indicates the change in the measured ~~value~~ variable without dynamic error.

(iv) Bandwidth :-

$$\text{Dynamic Sensitivity} = \frac{\text{Peak amplitude of o/p Signal } (A_o)}{\text{" " " i/p " } (A_i)}$$

The range of frequency to which the dynamic sensitivity is satisfactory is known as bandwidth.



$$\text{Bandwidth} = f_{c2} - f_{c1}$$

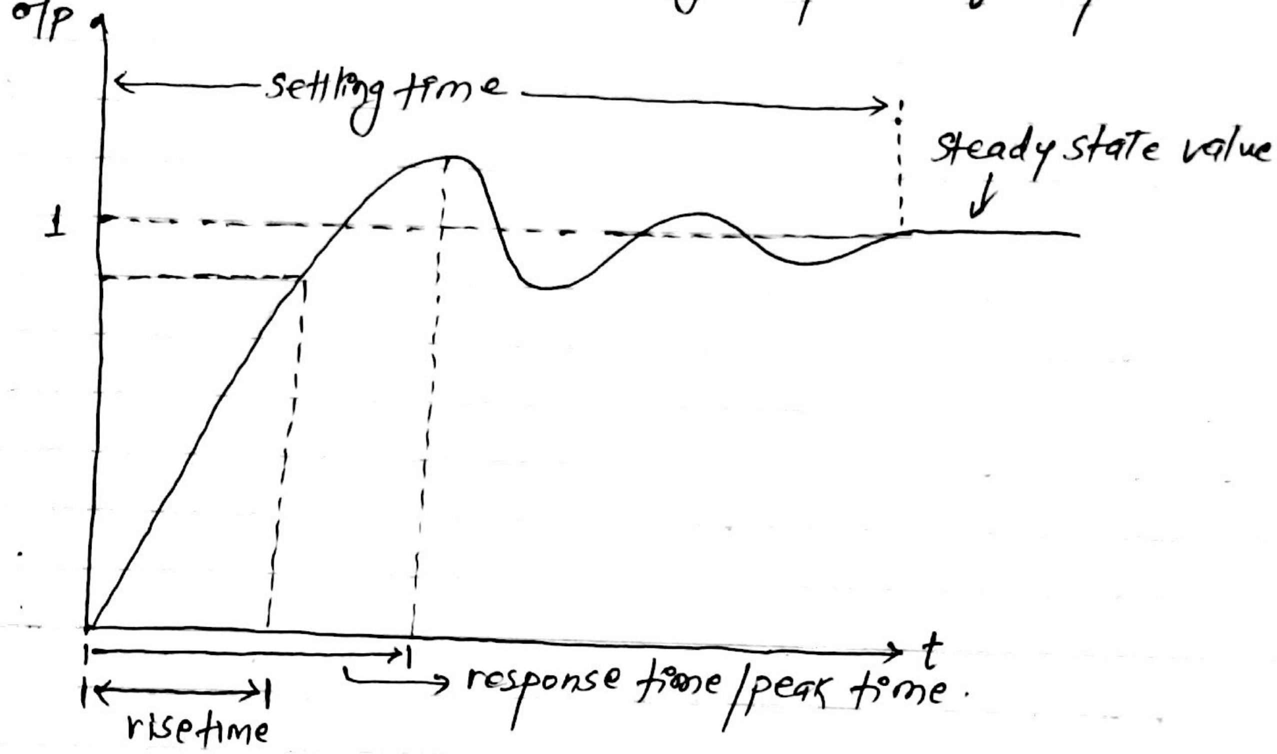
(v) Speed of Response :- It is defined as the rapidity with which a measurement system responds to the change in a measured quantity. Speed of response is measured in terms of

* Time Constant
* Rise time.

(A) Time Constant :- Time taken by a system to reach 63% of final steady state o/p. Higher time constant lowers the speed of response & vice-versa.

* Rise time : Time taken by the system to ~~re~~ be within a close range of steady state value.

Small rise time indicates high speed of response.



2.4 Error and its Types :-

Static error may be defined as the difference between measured value and true value of the quantity then,

$$\delta A = A_m - A_t$$

where δA = error

A_m = measured value, A_t = true value

δA is also called absolute static error of quantity A.

i.e. $\epsilon_o = \delta A$

Absolute value of δA doesnot indicate precisely the accuracy of measurement. The quality of measurement is produced by relative static error i.e. ratio of absolute error to true value.

i.e. $$\epsilon_r = \frac{\delta A}{A_t} = \frac{\epsilon_o}{A_t}$$

$$\% \epsilon_r = \epsilon_r \times 100\%$$

Static correction = true value - measured value

$$\delta C = A_t - A_m$$
$$= -\delta A.$$

Types of errors is given by the following diagram:

- Error
  - Gross Error / Human Error
  - Systematic Error
    - Instrumental Error
    - Environmental Error
    - Observational Error
  - Random / Residual Error

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(1) Gross Error : this class of error mainly covers human mistakes in reading instruments, recording and calculating measurement results.

For eg: Due to oversight, an experimenter may read 56·8°c while the temp. is 46·8°c or he may transpose the reading while recording eg: he may read 53·8°c and while recording he may record 58·3°c.

Causes:

→ Misreading of instrument
→ Erraneous calculation.

Elimination:-

→ Great care should be taken in reading and recoording data.
→ 2, 3 or more readings should be taken.
→ Use two or more users to take the data.

(2) Systematic Error : Divided into 3 catagories:

(i) Instrumental error :- these errors are due to the mechanical structure ie. construction, calibration or operation of an instrument. Causes of instrumental error can be studied under three headings:

* inherent shortcoming in the instrument :- These errors are inherent in instrument due to their mechanical structure. It may be due to construction, calibration and operation of the system. For eg: if the spring of an instrument is weak, it shows high reading.

* Misuse of the instrument :- The errors caused in measurements are due to the fault of the operator than that of the instrument. A good instrument used in an unintelligent way may give error. eg: initial zero adjustment.

* Loading effect: It is the inability of a system to faithfully measure, record or control the i/p signal in undistorted form.
Reduction:
→ Correction factor should be applied
→ Instrument may be re calibrated.

(ii) Environmental Error :- These errors are due to the condns of external environment that surrounds the instrument. These may be the effects of temperature, pressure, dust, humidity, vibration, magnetic & electric fields, etc.
Reduction:
→ Keep the environmental conditions nearly constant as possible.
→ Using equipments which are immune to these effects.
→ Shielding the equipment.
→ Applying computed corrections.

(iii) Observational Error :- Errors due to the inaccuracy human observational or sensing power. For eg: parallax error. Elimination → Modern electrical devices can be used with digital display.

③ Random/Residual Error :- Even after all the systematic error are accounted for, the instrument may show variation in readings. The measurand is affected by many happenings in the universe. We are aware of and account for some of the factors influencing the measurement but about the rest we are unaware. The disturbances about which we are unaware are lumped together and called random/ residual. ~~errors~~ Hence, the errors caused by these disturbances or happenings are called Random errors. They are called residual error because these errors remain even after the systematic errors have been taken care of.

Apart from these errors, there are some other errors. They are:

* **Limiting error:-** It is also called Guarantee error. In most of the instruments, the accuracy is guaranteed to be within a certain percentage of full scale reading. Components are guaranteed to be within the certain percentage of the rated value. Thus the manufacturer has to specify the deviation from the normal value of a particular quantity. The limits of these deviations from the specified value are limiting errors.

if nominal value is A_s
limiting error $= \pm \delta A$
then the actual value $A_a = A_s \pm \delta A$

i.e. if the nominal magnitude of a resistor is $100\,\Omega$ with limiting error $\pm 10\,\Omega$, the magnitude of the resistance will be betn $(90-110)\,\Omega$

* **Probable error:** It comes under the statistical analysis.

2.5, Statistical Analysis of measured data and Errors:-

Some statistical tools are:

(i) Average or Mean value (Arithmetic Mean):-

$$\bar{X} = \frac{X_1 + X_2 + X_3 + \dots + X_n}{n}$$

(ii) Deviation from the mean value:-

$$d_1 = X_1 - \bar{X}$$
$$d_2 = X_2 - \bar{X}$$
$$\vdots$$
$$d_n = X_n - \bar{X}$$

(iii) Average Deviation :-

$$D = \frac{|d_1| + |d_2| + \dots + |d_n|}{n}$$

lesser the deviation, higher is the precision.

(iv) Range $= X_{max} - X_{min}$

(v) Standard Deviation (Root mean square deviation)

$$\sigma = \sqrt{\frac{d_1^2 + d_2^2 + \dots + d_n^2}{n-1}}$$

(vi) Variance (mean square deviation)

$$V = \sigma^2$$

(vii) Probable error(r) $= 0.6745 \times \sigma$

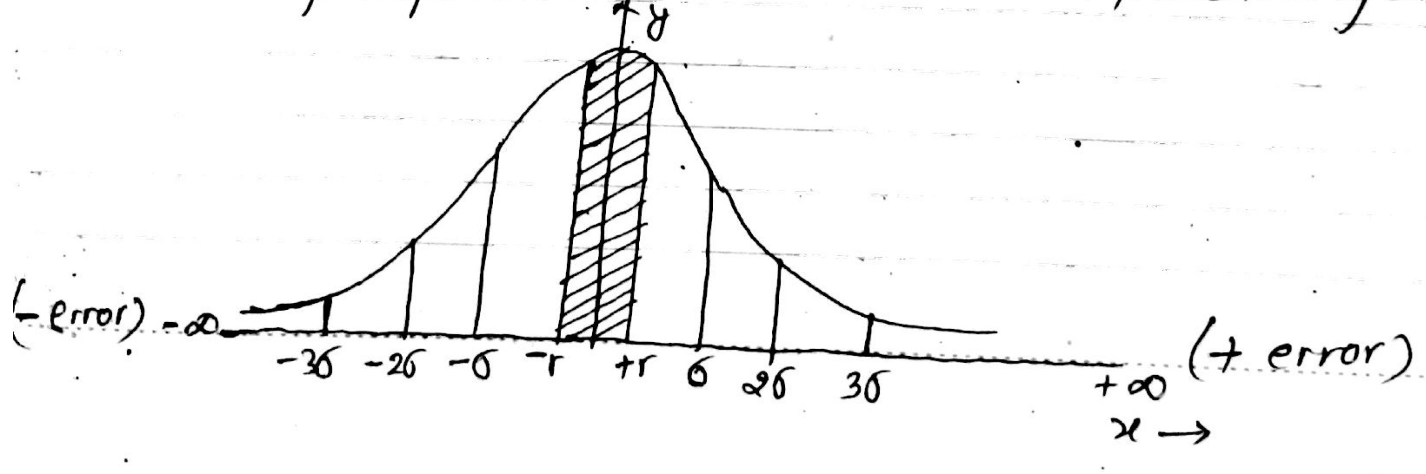
2.6 <u>Normal or Gaussian Distribution of Errors (Probability of Errors)</u> :-

The normal distribution or Gaussian law of errors is the basis for the major part of study of random effects. This type of distribution is most frequently met in practice. The law of probability states that the normal occurrance of deviations from average value of an infinite no. of measurement can be expressed by

$$y = \frac{h}{\sqrt{\pi}} \exp(-h^2 x^2) \quad \text{——} ①$$

where, x = magnitude of deviation from mean.
y = no. of readings at any deviation x (probability of occurrance of deviation)
h = a constant called precision index

The curve for eqn ① is Normal or Gaussian Probability Curve.



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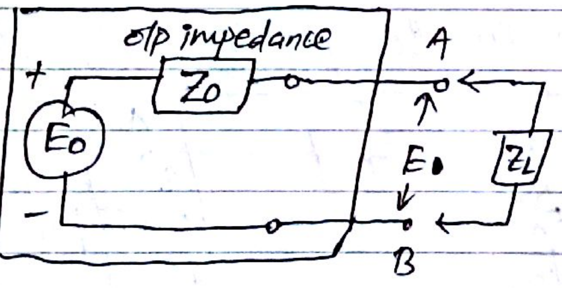
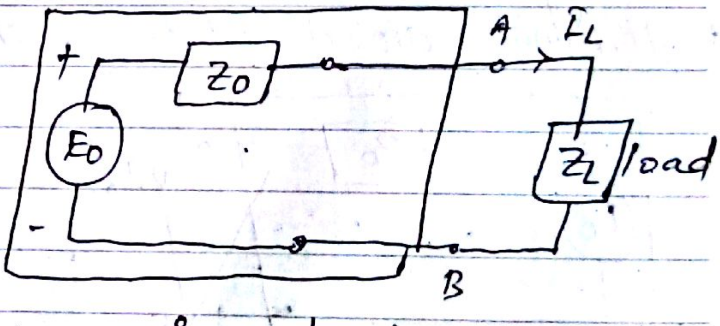
→ true value is near about mean value.
→ +/- error is equally probable.
→ Probability of getting less error is higher than large error.

2.7 Loading Effect :- The ideal situation in a measurement system is that when an element used for any purpose (may be sensing, conditioning, transmission or detection) is introduced into the system, the original signal should remain undistorted. This means the original signal should not be distorted in any form by the introduction of any element in the measurement system. It has been found that introduction of any element in a system results introduction of energy from the system thereby distorting original signal. The inability of the system to faithfully measure, record or control the i/p signal (measurand) in undistorted form is called loading effect. It can be analysed under two headings as under:

(a) Loading effect due to shunt connected instrument :-





In measurement system, voltage measuring, displaying and recording instruments like voltmeter, oscilloscope & strip-chart are connected across the shunt ckt.
The figure shows a ckt with a Thevenin's generator of voltage Eo and an o/p impedance Zo in series. Let Eo be the open ckt voltage. When the load is connected to the AB terminal the voltage remains the same. The load

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impedance is not infinite and when Z_L is connected I_L flows across A and B terminal, this causes the voltage drop of $Z_L I_L$ ie.

$$E_L = I_L Z_L.$$

Now, o/p voltage under load condition,

$$E_L = E_0 - I_L Z_0 = I_L Z_L.$$

$$\therefore E_0 = I_L(Z_0 + Z_L)$$

$\therefore$ Ratio of actual voltage appearing across the load to the voltage under no load condition (ideal case)

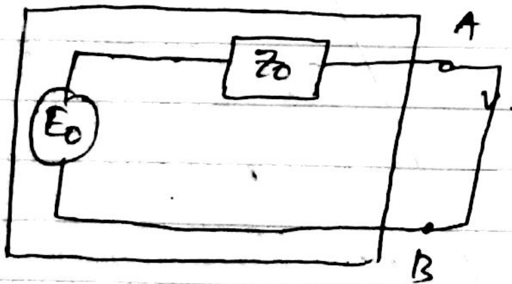
$$\frac{E_L}{E_0} = \frac{I_L Z_L}{I_L(Z_L + Z_0)} = \frac{1}{1 + Z_0/Z_L}$$

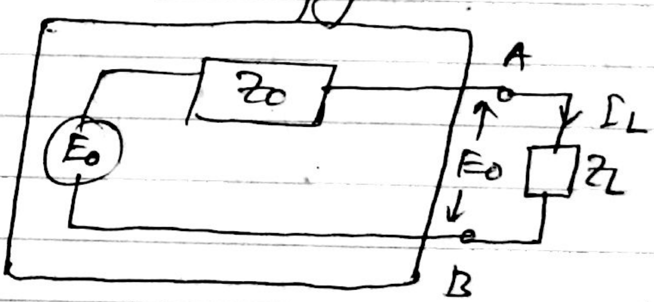
$\therefore$ Actual voltage measured $= E_L = \dfrac{E_0}{1 + Z_0/Z_L}$ ——— (1)

Thus, the voltage which is measured is modified. this means the original voltage signal is distorted on account of connection of measuring instrument accross it.

(b) Loading effect due to series Connected Instrument :-

Consider a n/w represented by voltage source having a voltage E_0 and an o/p impedance Z_0. The o/p terminals are A and B as shown in the fig below:





The value of current flowing betn A and B under ideal condition is I_0. It is the current that flows when terminals A and B are shorted.

$$I_0 = \frac{E_0}{Z_0} \quad \text{or,} \quad E_0 = I_0 Z_0$$

However, when we measure current, a current measuring device is introduced between terminals A and B. It is usually an ammeter. When an ammeter is placed beth o/p terminals, it adds to the impedance of ckt. This added impedance modifies the value of the current. Suppose Z_L be the o/p impedance of ammeter. So measured value of current is

$$I_L = \frac{E_0}{Z_0 + Z_L} = \frac{I_0 Z_0}{Z_0 + Z_L} = \left(\frac{1}{1 + Z_L/Z_0}\right) I_0$$

In order that the measured value of current be equal to the actual value of the current, the value of $Z_0 \gg Z_L$. This means, the i/p impedance of the ammeter should be very small as compared to the o/p impedance of the source.

2.8 Measuring Instrument :

Permanent Magnet Moving Coil (PMMC) Instrument :-

The operation of PMMC is based on D'Arsonval movement which states that "when current is passed through coil placed in the magnetic field, the coil will ~~have~~ move and the direction and the magnitude of current through the coil provided that the other parameters are unchanged".

Construction :-

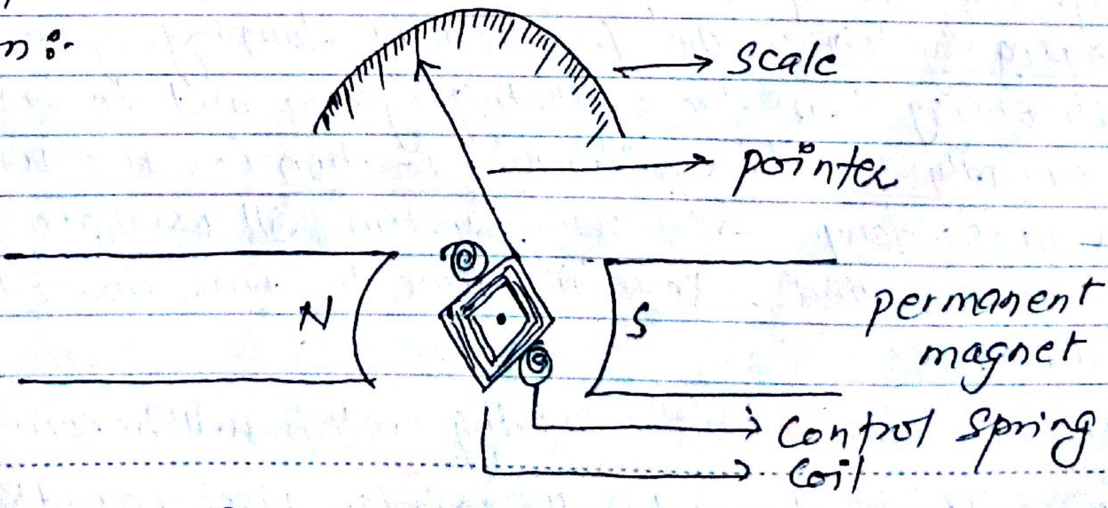


Fig: PMMC Instrument

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It consists of:

(i) Moving Coil

(ii) Magnet Systems

(iii) Control System

(iv) Damping System

(v) Pointer and scale.

(i) Moving System:- It consists of a rectangular former (it may be Al or Cu) wounded by multi-turn coil (it also may be Al or Cu). Al former is prefered because of its weight and inertia. The turn of the coil may have 0.02 to 0.2 mm diameter and length to breadth ratio of the former is betn 1.3 and 1.5. The coil is so pivoted that its sides lie on the air gap betn the poles of a permanent magnet.

(ii) Magnet System:- Simple U-shaped permanent magnet is most widely used magnet in PMMC instrument. The magnets used produce magnetic field. For a small instrument, a large magnet is used while for large instrument, the size of the magnet is big.

(iii) Control System:- The controlling torque is provided by 2 springs. They may be either hellical or spiral, coiled in opposite direction normally equal in strength. The control springs also conduct the operating current in and out of the moving coil. The springs may be of phosphor Bronze.

(iv) Damping System:- The function of damping system is to absorb energy from the oscillating system and to bring into rest promptly in its equilibrium position (or rest position).

* when under damped → moving system will oscillate about its final position and take some time to come to rest in its steady state.

* when over damped → the moving system will become slow.

* when critically damped → the pointer rises rapidly to its deflected ~~portion~~ position without oscillations.

In practice to obtain best result the damping is adjusted to the value slightly less than critical value.

Usually eddy current damping is employed in this instrument.

(v) Pointer and Scale :- The pointer is carried by a spindle and moves over a graduated scale and indicates the angular deflection of the coil & therefore the current flowing thru the coil. The pointer is a light aluminium tube flattened at one end into the form of vertical knife edge. The scale markings are usually linearly spaced. In order to eliminate parallax error, a mirror is provided beneath the pointer.

Operation of PMMC :

Here we have a coil suspended in the magnetic field of a permanent magnet. The coil is suspended such that it can rotate freely in the magnetic field. When the current flows thru the suspended coil, the electromagnetic torque causes the coil to rotate freely in the air gap. The electromagnetic torque produced is counter balanced by the mechanical torque produced by the ~~coil~~ control spring. The control spring strength is calibrated so that the current causes a rotation through a specific angle. The balance of the torques and the angular position of the coil is indicated by the pointer against a well graduated scale.

Thus, the deflection of pointer is directly proportional to the current flowing thru the coil, provided that the magnetic field is uniform and spring tension is linear.

The electromagnetic torque, T_d developed by the current thru the coil is;

$T_d \propto I$

or, $T_d = GI$ ——— (i)

where G is a constant and is given by $G = BNA$

where B = magnetic flux density in the gap.

N = No. of turns of the coil.

A = effective area of the coil.

$\therefore T_d = BINA$ ——— (ii)

Thus, the torque developed is directly proportional to the flux density of the field in which the coil rotates.

Also, the torque developed by the rotating control spring T_c is proportional to the deflection θ, ie.

$T_C \propto \theta$

or, $T_C = K\theta$ ——— (iii)

where K = spring constant

Since these two torques counter balance,

$T_d = T_c$

or, $GI = K\theta$

or, $I = \frac{K}{G}\theta$

$\therefore \boxed{I \propto \theta}$

Thus, the current flowing thru the coil is directly proportional to the deflection of the pointer.

Merits of PMMC :-

→ The scale is uniformly distributed

→ Low power consumption.

→ Single instrument may be used for many different current & voltage ranges.

→ Due to high flux density (B) errors due to strong magnetic fields are small.

is stated as $R_x = \frac{R_1 R_2}{R_3}$, where

$R_1 = 500\Omega \pm 1\%$
$R_2 = 615\Omega \pm 1\%$
$R_3 = 100\Omega \pm 0.5\%$

Calculate:

(i) the nominal value of the unknown resistor
(ii) the limiting error in ohm of the unknown resistor.
(iii) the limiting error in percent of the unknown resistor.

⑥ The voltage generated by a ckt is given by eqn

$V_{out} = \frac{R_1 R_2}{R_3}$. If the tolerance of each resistor is 0.1%, what is the maximum error of generated voltage.

2.9 Bridge Circuit :-

Bridge circuits are commonly used for accurate measurement of resistance, inductance and capacitance. They are of very important in measurement system and for interfacing transducers as many transducers measuring physical quantities have output which is expressed as a change in resistance, capacitance and inductance. A displacement measuring transducer, which has a varying resistance o/p, is an example of this class of transducers.

Excitation of bridge is normally by dc voltage for resistance measurement and by ac voltage ~~by~~ for the measurement of inductance and capacitance.

Both null type and deflection types of bridge exist. Generally, null type are employed for calibration purpose and deflection type are used within closed loop automatic control schemes.