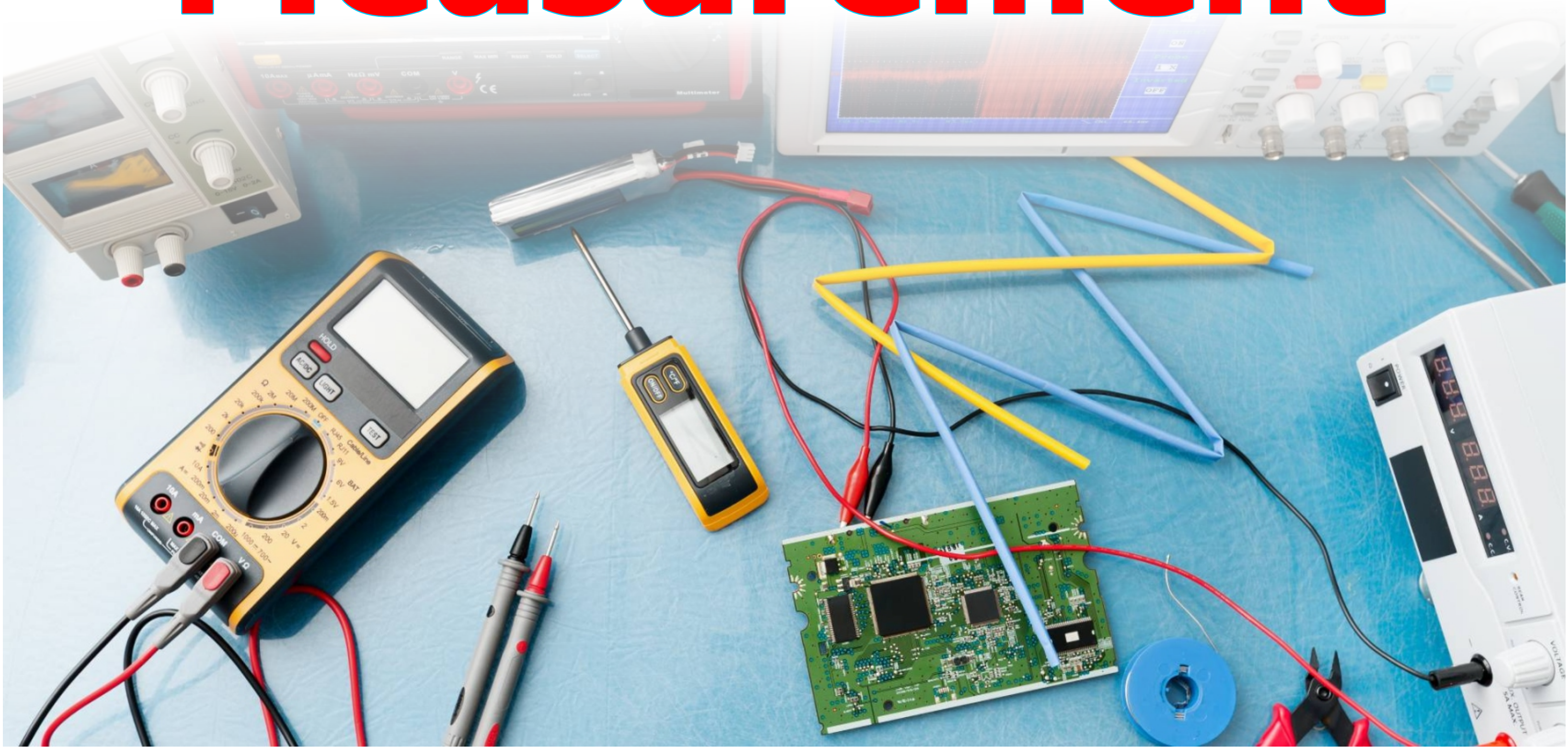
Electrical and Electronic Measurement



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ELECTRICAL AND ELECTRONIC MEASUREMENT

INDEX

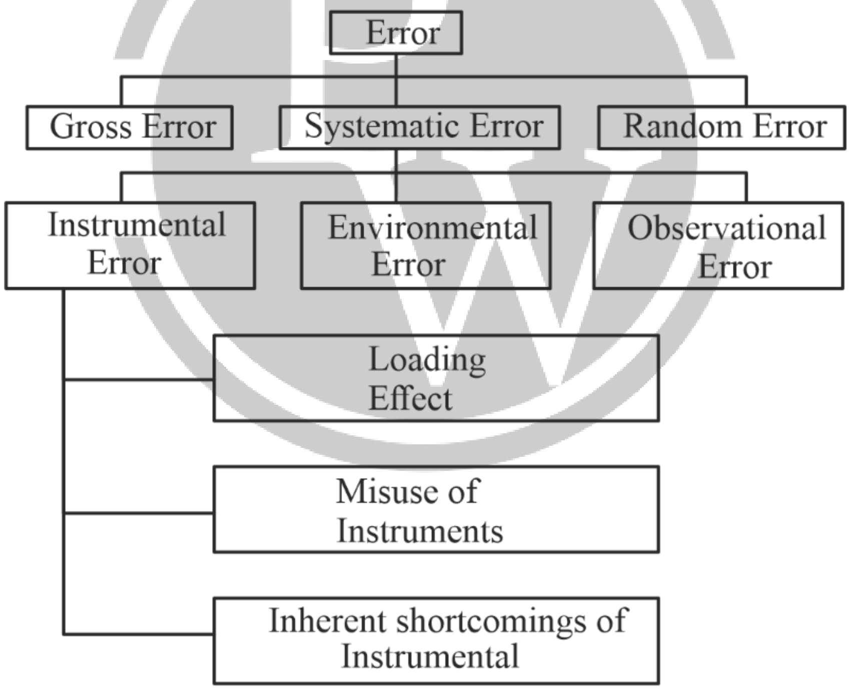
1 ERROR ANALYSIS AND MEASUREMENT

1.1. Error Analysis

1.1.1. Types of Errors

Basically, three types of errors are studied: -

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



Gross Error:

Gross Errors mainly covers the human mistakes in reading instruments and recording and calculating measurement results.

Example: Due to oversight, the read of Temperature as 31.5° while the actual reading may be 21.5°.

Gross Errors may be of any amount and then their mathematical analysis is impossible. Then these are avoided by adopting two means: -

1. Great care is must in reading and recording the data.
2. Two, Three or even more reading should be taken for the quantity under measurement.

Systematic Error:

Systematic Errors are classified into three categories:

1. Instrumental Errors
2. Environmental Errors
3. Observational Errors

Instrumental Error:

These errors arise due to three main reasons.

1. Due to inherent shortcoming in the instrument.

   Example: If the spring used in permanent magnet instrument becomes weak then instrument will always read high. Errors may cause because of friction, hysteresis, or even gear backlash.
2. Due to misuse of the instruments.
3. Due to Loading effects of instruments.

Environmental Error:

- These errors are due to conditions external to the measuring Device including conditions in the surrounding instruments.
- These may be effects of Temperature, Pressure, Humidity, Dust, Vibrations or of external magnetic or electrostatic fields.

Observational Error:

There are many sources of observational errors: -

- Parallax, i.e., Apparent displacement when the line of vision is not normal to the scale.
- Inaccurate estimate of average reading.
- Wrong scale reading and wrong recording the data.
- Incorrect conversion of units between consecutive reading.

Random Error:

The quantity being measured is affected by many happenings in the universe. The errors caused by happening or disturbances about which we are unaware are Random Errors. It’s also known as residual Errors.

Statistical Analysis of Data:

The Experimental Data is obtained in Two Forms of the tests: -

1. Multi sample Test
2. Single Sample Test

   1. **Multi sample Test:** In this test, the repeated measurement of a given quantity are done using different test conditions such as employing different instruments, Different ways of measurement and by employing different observers.
   2. **Single Sample Test:** A single measurement for succession of measurement done under identical conditions excepting for time is known as single sample Test.

Statistical Analysis:

- A statistical analysis of measurement data is common practice because it allows an analytical determination of the uncertainty of the final test result.
- To make statistical methods and interpretations meaningful, a large number of measurements is usually required.

Arithmetic Mean :

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

where $\bar{x}$ = arithmetic mean $x_1, x_2, \ldots x_n$ = reading taken n = number of reading

Average range of error:

- Max error = Max- mean
- Min error = Mean-min
- Avg Range of error = (Max error + Min error)/2

Deviation from the mean :

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

$d_1 = x_1 - x$

$d_2 = x_2 - x$

$d_n = x_n - x$

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

Average Deviation:

- The average deviation is an indication of the precision of the instruments used in making the measurements.
- Average deviation is the sum of the absolute values of the deviation divided by the number of readings.

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

Standard Deviation:

By definition, the standard deviation σ of an infinite number of data is the square root of the sum of all the individual deviations squared, divided by the number of readings

Mathematically:

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

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

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

Variance :

- Variance or mean square deviation, which is the same as the standard deviation except that the square root is not extracted.
- Variance V = mean square deviation = σ square

1.2. Relative static error & % Static Error

Thus the quality of measurement is provided by the relative static error, i.e., the ratio of absolute static error A to A_t, the true value of the quantity under measurement. Therefore the relative static error is given by

$$\epsilon_r = \frac{\text{absolute error}}{\text{true value}} = \frac{\delta A}{A_t} = \frac{\epsilon_0}{A_t}$$

Percentage static is given by the equation shown below

$$\%\in_r = \in_r \times 100$$

$$A_t = A_m - \delta A$$

$$A_t = A_m - \in_0 = A_m - \in_r A_t$$

$$A_t = A_t = \frac{A_m}{1+\in_r}$$

Static Correction:

- It is the difference between the true value and the measured value of the quantity or opposite to static error

% Guaranteed Accuracy Error:

- When accuracy is expressed in terms of error, it is called percentage guaranteed accuracy error
- % GAE is expressed with respect to full scale deflection of meter.
- It is called a constant error for meter.
- It is fixed by manufacturer.

Limiting Error :

- Limiting Error is defined as the maximum deviation either in positive side or negative side in the measurement by an instrument from the nominal value or true value.
- Let us assume that the true value or nominal value of a quantity is At and the measured value by the instrument is A_m, then

  Limiting Error $\delta A = (A_m - A_t)$.
- For example, the nominal value of a resistor is 100 Ω with a limiting error of ±10 Ω. The magnitude of measurement will be between the limits, (100 ±10)Ω i.e. 90 and 110Ω. Thus the measurement of resistor by the instrument is guaranteed to be between 90 & 110 Ω.

% Limiting error:

$$\%\text{ Limiting error} = \frac{(A_m - A_t)}{A_t} \times 100$$

% limiting error is a variable error

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2 Basic Instruments

2.1 Permanent Magnet Moving Coil (PMMC) instrument

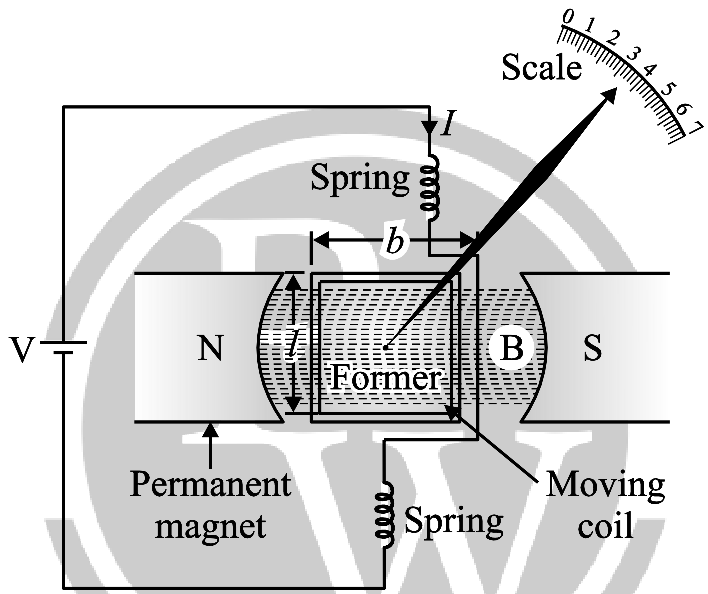


Fig. Circuit diagram

PMMC Instrument:

$\boxed{\tau_d = BINA,\ \tau_c = k_c\theta}$

$\boxed{\theta \propto I}$ (Linear Scale)

$\boxed{\tau_d \propto I}$ (Works only for D.C)

$\boxed{S_{PMMC} = \dfrac{\Delta\theta}{\Delta I}}$ (20Ω/v - 30Ω/v)

$\boxed{\uparrow\uparrow S \propto \dfrac{T_d}{A} \propto \dfrac{T_d \uparrow}{\text{weight} \downarrow}}$

$\boxed{\dfrac{\text{"Torque"}}{\text{weight}} \text{ratio represent sensitivity(unity)}}$

$$\downarrow\downarrow \text{Frictional error} \propto \frac{\text{weight}\downarrow}{\text{Torque}\uparrow}$$

Advantage:

Used in aeroplane, aerospace industry. ‘0’Hz frequency, uniform scale.

Disadvantage:

Only for D.C, not A.C.

PMMC Ammeter:

(0 - 5)μA without only shunt.

Extend the range of PMMC ammeter. We connect low value resistance in parallel with meter.

$$R_{sh} = \frac{R_m}{\left(\frac{I_{ext}}{I} - 1\right)} \qquad R_{sh} = \frac{R_m}{m-1}\ \Omega\ (m > 1)$$

Shunt: Manganin (24% Cu + 12% Mn + 4% Ni)

$\alpha = 0°$, No effect due to age.

- Ammeter is always connected in series.
- Internal Resistance of Ideal Ammeter is always ‘Zero’.

PMMC Voltmeter:

To connect the higher value resistance in series with meter is known as multiplier.

$$R_{se} = R_m(m-1)\ \text{k}\Omega$$

- Internal Resistance of Ideal Voltmeter is ‘∞’.
- Voltmeter is always connected in parallel.
- To reduce the +ve temperature co-efficient, swamping resistance is connected.

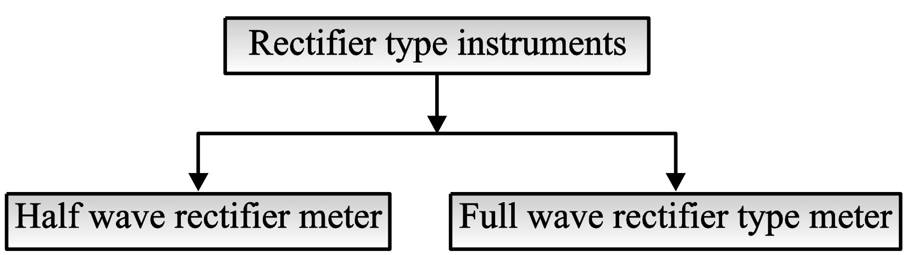
Advantage:

Used in aeroplane, aerospace industry. ‘0’ Hz frequency, uniform scale.

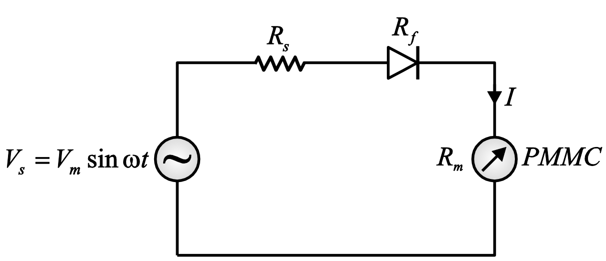
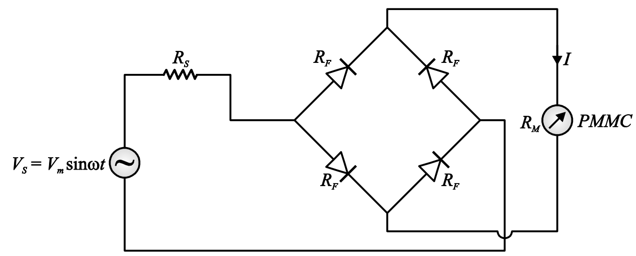
Disadvantage:

Only for D.C, Not A.C.

2.1.2 Application of PMMC



Rectifier type instruments can be used for both a.c. and d.c. voltage and current measurement. These instrument consist of a rectifier and a PMMC instrument.

Half wave rectifier meter	Full wave rectifier type meter
 **Fig. Circuit diagram** **(1) H.W.R type:** $\text{Reading of Rectifier type inst.} = F.F \times V_{DC}$ **Case I:** Input is sinusoidal wave: $\text{Reading of Rectifier type inst.} = 2.22 \times V_{DC}$ Case II: Input is Δ / sawtooth wave: $\text{Reading of } \Delta \text{ Rectifier type inst.} = 2.30 \times V_{DC}$ $S_{D.C} > S_{A.C}$ **Case III:** Input is square wave: $\text{Reading of square wave Rectifier type} = 2.30 \times V_{DC}$	 **Fig. Circuit diagram** **(2) F.W.R type Instrument:** **Case I:** I/P is sine wave: $F.F = 1.11$ $S_{DC} = 1.11 \times S_{AC}$ **Case II:** I/p is sawtooth wave: $V_{AC} = 1.15 \times V_{DC}$ **Case III:** I/P is square Wave: $V_{AC} = V_{DC}$

2.1.3 Moving Iron (MI) Instruments

Attraction type moving iron instrument

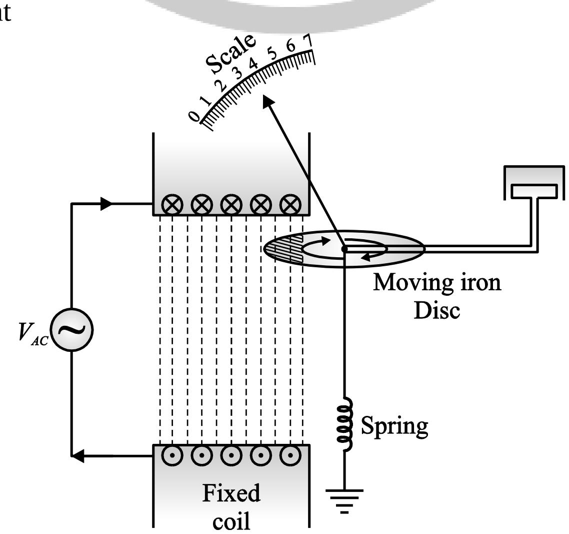


Fig. Circuit diagram of attraction type moving iron instrument

Repulsive type moving iron instrument

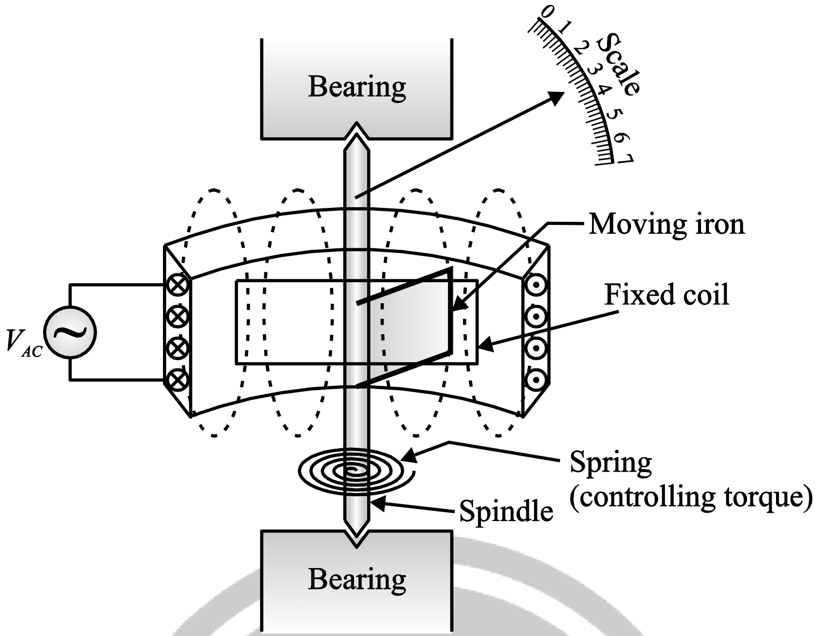


Fig. Relation between deflection and current

Moving iron type instrument (M.I Type)

It works on the self-inductance of coil.

$$\boxed{\tau_d = \frac{1}{2} I^2 \frac{dL}{d\theta}} \quad \boxed{\theta = \frac{1}{2k_c} I^2 \frac{dL}{d\theta}}$$

$\boxed{\tau_d \propto I^2}$ (Work for both A.C & D.C)

M.I type, scale does not follow square law.

Not true RMS value, non-linear scale, non-uniform

Advantage:

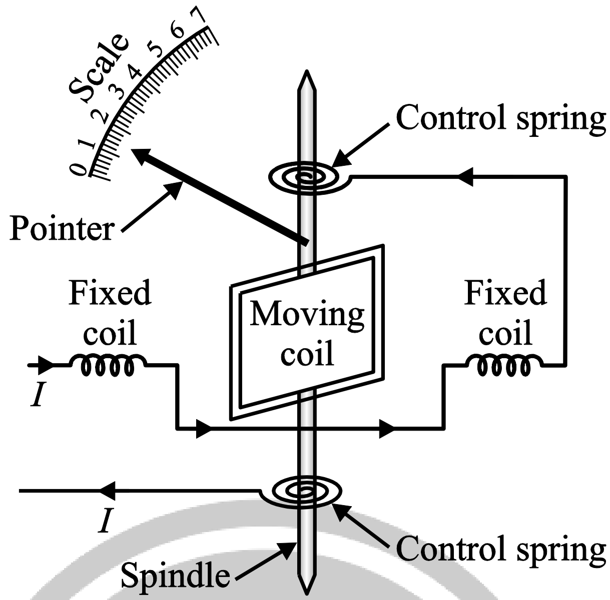
- Works on AC & DC, lowest hysteresis error used only for power frequency range.
- M.I type, wattmeter does not exist.
- M.I type Ammeter:

$$\boxed{\frac{L_m}{R_m} = \frac{L_{sh}}{R_{sh}}} \quad \boxed{\tau_m = \tau_{sh}}$$

- M.I type voltmeter:

$$\boxed{c = 0.41 \frac{L_m}{R_{Se}^2}}$$

2.1.4 Electro Dynamometer type Instrument (Electromagnetic Moving Coil Instrument)



#Electromagnet Moving Coil (EMMC) Type

- It works on the charge in Mutual Inductance.

$$\boxed{\tau_d = |I_{FC}| \cdot |I_{MC}| \cdot \cos \angle I_{FC} \,\&\, I_{MC} \cdot \frac{dM}{d\theta}}$$

- for measurement of current & voltage both F.C & M.C are connected in series.

$$\boxed{\tau_d = I^2 \frac{dM}{d\theta}} \text{ (A.C + D.C) (Non - uniform)}$$

- scale does noy follow square law.
- for measurement of power both F.C & M.C are connected in parallel.

Advantage:

A.C + D.C, no hysteresis error & no eddy current error, used as Transfer instrument.

Disadvantage:

Non-linear scale, highest Cost, Lowest Sensitivity.

2.2. Thermal Instrument or Electrothermic

(1) Hot wire type Instrument:

$$\boxed{\Delta l \propto \text{Heat}}$$

$$\Delta l \propto I^2 Rt$$

$\boxed{\Delta l \propto I^2}$ Hot wire type "Ammeter"

$\boxed{\Delta l \propto V^2}$ Hot wire type "Voltmeter"

Advantage:

Works on A.C + D.C, True R.M.S meter, No Hysteresis error, frequency Range "MHZ".

Disadvantage:

Non-uniform scale, slow & sluggish, more power consumption.

(2) Thermocouple:

$$\text{Temperature} \rightarrow \text{E.m.f.}$$

3) Temperature:

- Change in Resistance.
- Example: RTD, Thermistor

2.2.1. Electrostatic Voltmeter (ESV)

(1) Linear Motion Type:

- It works on the change in capacitor.

$$\boxed{F_d = \frac{1}{2}V^2\frac{dc}{dx}} \quad \boxed{x = \frac{1}{2}\frac{V^2}{K_c}\cdot\frac{dc}{dx}}$$

- Suitable for H.V measurement.

(2) Circular Motion Type:

$$\boxed{\tau_d = \frac{1}{2}V^2\frac{dc}{d\theta}} \quad \boxed{\tau_c = K_c\theta}$$

Advantage:

Works on A.C + D.C, No Hysteresis error, No eddy current, low power consumption. Best suitable for H.V.

Disadvantage:

Non-uniform, no electrostatic Ammeter, Largest in size, Not suitable for L.V.

- To extend the range of ESV – Potentiometer Method.

$$\boxed{V_{ext} = V_m\left(\frac{L}{l}\right) = m\cdot V_m}$$

- To using series capacitor:

$$\boxed{C_{se} = \frac{C_m}{m-1}} \quad (m > 1)$$

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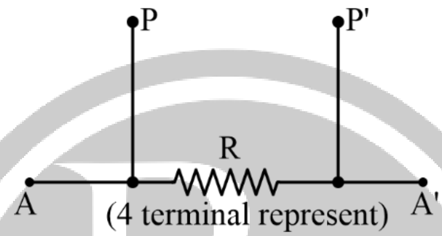
3 MEASUREMENT OF RESISTANCE AND AC BRIDGES

3.1 MEASUREMENT OF RESISTANCE

3.1.1. Measurement of Low Resistance

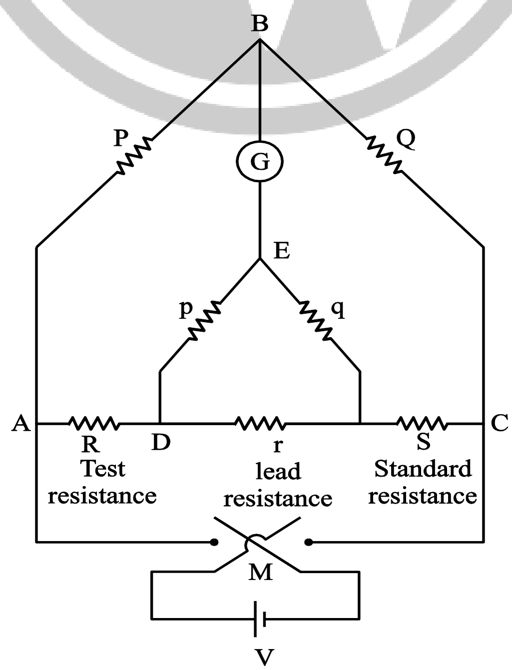


$R < 1\Omega$

Method for low Resistance:

- Potentiometer method
- Ammeter-voltmeter method
- Kelvin Double bridge method

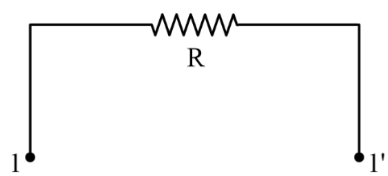
Kelvin double bridge:



$$R = \frac{PS}{Q} + \frac{qr}{p+q+r}\left[\frac{P}{Q} - \frac{P}{q}\right]$$

3.1.2. Measurement of Medium Resistance

$\boxed{1\Omega < R < 100k\Omega}$

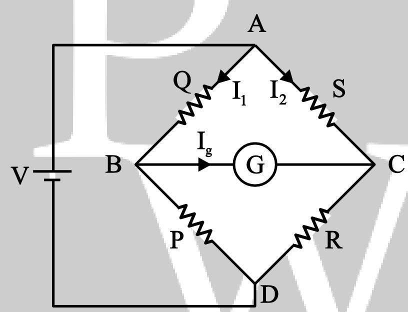


(2 - terminal represent)

Method for medium Resistance:

- Wheatstone Bridge Method
- Substitution Method
- Voltmeter – Ammeter Method
- Ω - meter method

Wheatstone bridge:

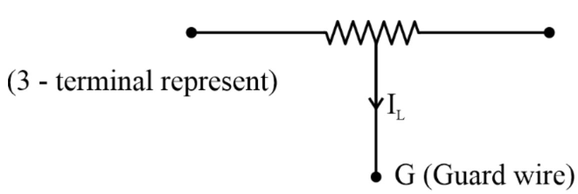


Circuit diagram

$$R = \frac{PS}{Q}$$

3.1.3. Measurement of High Resistance

$\boxed{R > 100k\Omega}$



→ Method for high Resistance:

- Direct Deflection Method
- Loss of charge method
- Meggar
- Megohm Bridge method

Comparison between D.C & A.C Bridge:

D.C Bridge	A.C Bridge
Used only for Resistance	Used in frequency L, C, Q-factor
D'Arsonval Galvanometer at '0' Hz Frequency	Vibrational Galvanometer power frequency (0 Hz-125Hz)
Supply- D.C Battery	Supply 1) Low Power Oscillator 2) High Power Generator
Only Magnitude Balance	Both phase & Magnitude balance
Example: Wheatstone bridge, kelvin double bridge.	Headphone – Audio frequency (up to 20 kHz) Tuneable Amplifier – Radio Frequency (MHz)

3.2 AC BRIDGES

AC Brdiges:

1. Maxwell Inductance Bridge
2. Maxwell Inductance capacitance bridge
3. Hay's Bridge
4. Owen's bridge
5. Anderson's Bridge
6. Desauty's Bridge
7. Schering Bridge
8. Wiens Bridge

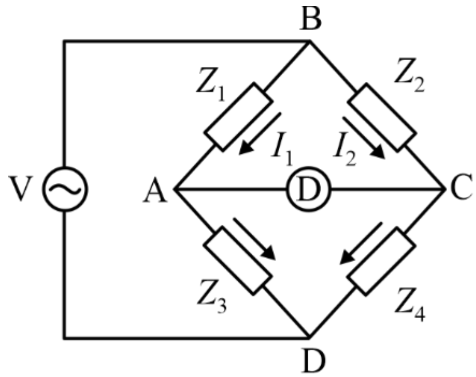
AC Bridge Sources:

- For low frequency applications – power line
- For high frequency applications – high frequency electronic oscillator

AC Bridge Detectors:

Detectors	Frequency
D C Galvanometer	0 Hz dc
Vibration Galvanometer	2-100 Hz
Head phone Galvanometer	250 Hz – 4kHz
Tuneable Amplifier Galvanometer detector	10 Hz to 100k Hz
CRO	In MHz Range

Ac Bridge: Balance Condition



- All four arms are considered as impedance (frequency dependent components)
- The detector is an ac responding device: headphone, ac meter
- Source: an ac voltage at desired frequency

Z_1, Z_2, Z_3 and Z_4 are the impedance of bridge arms at balance point:

$$E_{BA} = E_{BC} \text{ or } I_1Z_1 = I_2Z_2$$

General form of the AC Bridge: $I_1 = \dfrac{V}{Z_1 + Z_3}$ and $I_2 = \dfrac{V}{Z_2 + Z_4}$

Complex Form: $\boxed{Z_1Z_4 = Z_2Z_3}$

Polar Form: $\boxed{Z_1Z_4(\angle\theta_1 + \angle\theta_4) = Z_2Z_3(\angle\theta_2 + \angle\theta_3)}$

- → Magnitude Balance: $\boxed{Z_1Z_4 = Z_2Z_3}$
- → Phase Balance: $\boxed{\angle\theta_1 + \angle\theta_4 = \angle\theta_2 + \angle\theta_3}$

Q Factor:

$$Q = \frac{2\pi(\text{Max Energy Stored})}{\text{Energy dissipated / Cycle}}$$

$$= \frac{2\pi\left(\frac{1}{2}LI_0^{\ 2}\right)}{I_{rms}^{\ 2} \cdot RT} \qquad \boxed{I_0 = \sqrt{2} \cdot I_{rms}}$$

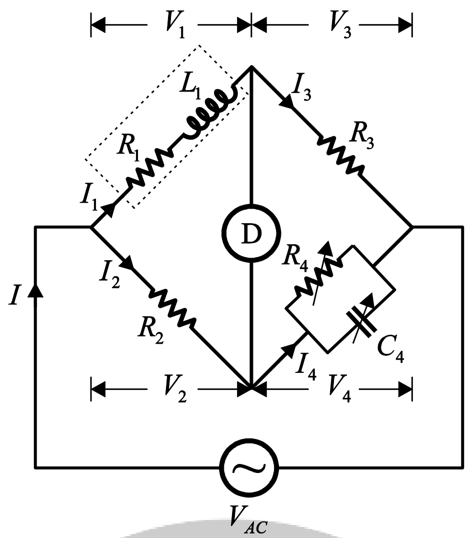
$$= \frac{\pi \cdot L \cdot 2I_{rms}^{\ 2}}{I_{rms}^{\ 2} \cdot RT}$$

$$= \frac{2\pi L}{R \cdot T}$$

$$= \frac{2\pi L}{R \cdot 2\pi} \cdot \omega$$

$$\boxed{Q = \frac{\omega L}{R}}$$

1. Maxwell (L-C) bridge

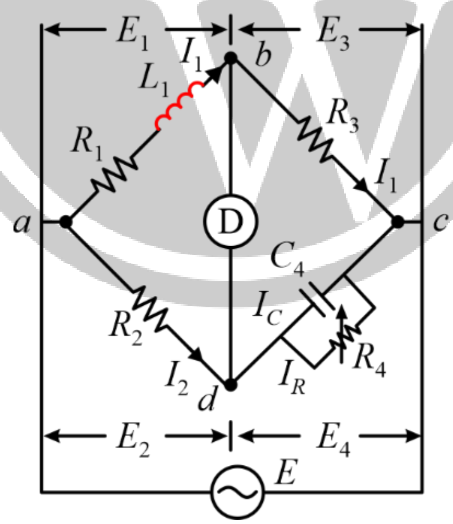


$$R_1 = \frac{R_2 R_3}{R_4}$$

$$L_1 = R_2 R_3 C_4$$

$$Q = \omega C_4 R_4$$

2. Maxwell Inductance Capacitance Bridge:



Maxwell's Inductance Capacitance Bridge

It measures inductance by comparing with a standard capacitance

Let L_1 – unknown inductance of resistance R_1.

R_1 – Variable inductance of fixed resistance r_1.

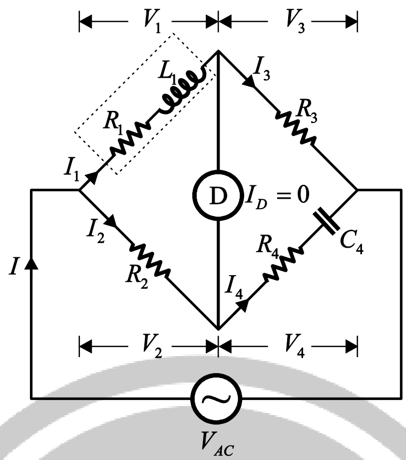
R_2, R_3, R_4 – variable resistance connected in series with inductor L_2.

C_4 – known non-inductance resistance.

$$R_1 = \frac{R_2 R_3}{R_4}, \quad Q = \frac{\omega L_1}{R_1} = \omega C_4 R_4$$

$$L_1 = R_2 R_3 C_4$$

3. Hay's bridge

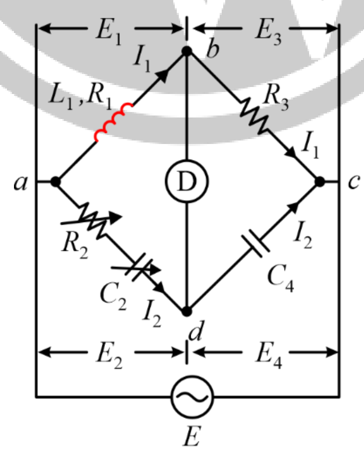


$$R_1 = \frac{\omega^2 R_2 R_3 R_4 C_4^2}{1+\omega^2 R_4^2 C_4^2}$$

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

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

4. Owen's bridge

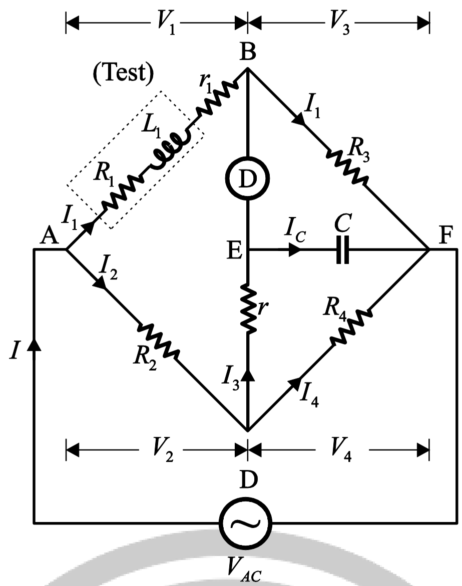


$\Rightarrow$ $L_1 = R_2 R_3 C_4$

$$\frac{-R_1}{\omega C_4} = \frac{-R_3}{\omega C_2}$$

$\Rightarrow$ $R_1 = R_3 \dfrac{C_4}{C_2}$

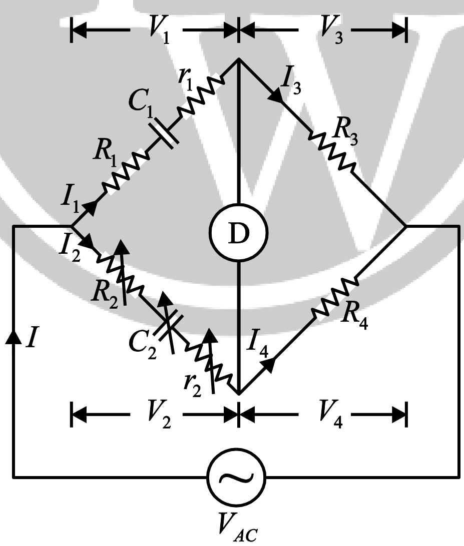
5. Anderson Bridge



$$L_1 = R_2 R_3 C_4$$

$$R_1 = \frac{R_3 C_4}{C_2}$$

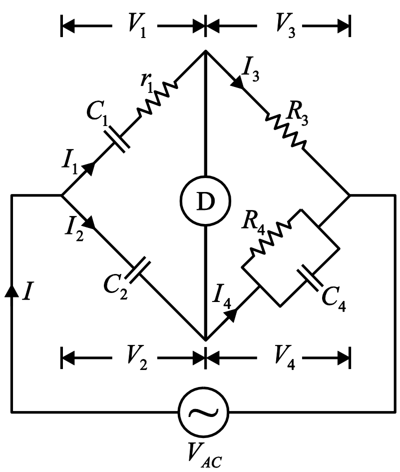
6. De-Sauty's Bridge



$$r_1 = \frac{R_3(R_2 + r_2) - R_1}{R_4}$$

$$C_1 = \frac{R_4 C_2}{R_3}$$

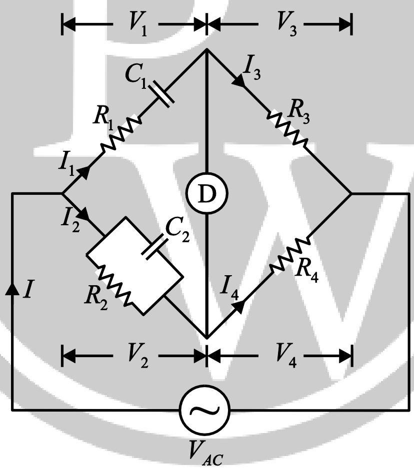
7. Schering Bridge



$$C_1 = \frac{R_4 C_2}{R_3}$$

$$r_1 = \frac{R_3 C_4}{C_2}$$

8. Wein's Bridge



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

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

$$\frac{R_1}{R_2} + \frac{C_2}{C_1} = \frac{R_3}{C_4}$$

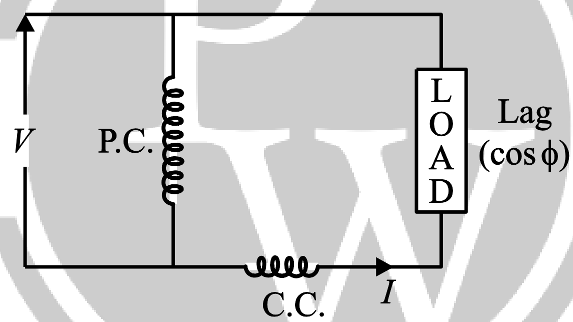
4 MEASUREMENT OF ENERGY AND POWER

4.1 MEASUREMENT OF ENERGY

5.1.1 Single Phase Energy Meter (Induction Type)

- AC induction energy meter working on principle of induction is used to cumulatively record energy consumed by the load and hence it is an integrating type meter.
- Potential coil of an energy meter must be highly inductive so that the error in measurement of energy is minimized.

4.1.2 Equivalent Circuit



4.1.3 Recording or Registering Mechanism

Reduced gear train are used for recording the number of revolutions made by the disc. So that energy consumed by load is recorded cumulatively so energy meter working is integrating instrument.

4.1.4 Important Formulae

(i) Energy meter constant $(K) = \frac{\text{Number of revolutions made by disc}}{\text{Energy recorded in KWhr}} = \frac{N}{Pt}$

(ii) Measured energy $(W_m) = \frac{\text{Total number of revolution}}{\text{K}}$

(iii) True energy $(W_T) = \frac{VI\cos\phi}{1000} \times \frac{t}{3600}\,\text{KWhr}$

Where, $V =$ Voltage and I = Current.

(iv) $\% \text{ Error}(\varepsilon_r) = \frac{\text{Measured energy} - \text{True energy}}{\text{True energy}} \times 100\%$

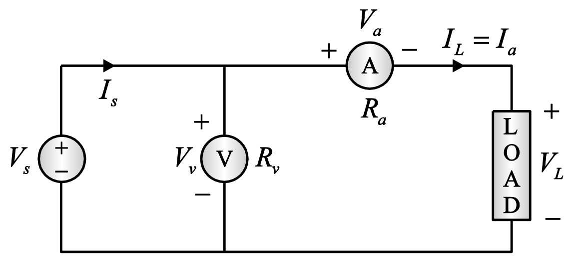
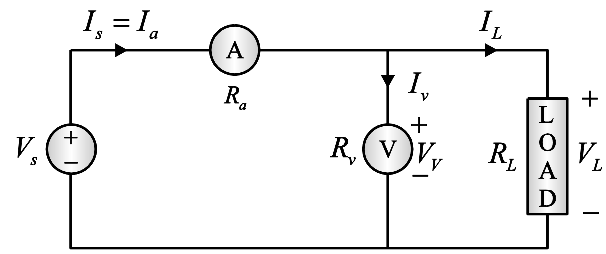
$\varepsilon_r = +\text{ve}$ means meter is running fast, $\varepsilon_r = -\text{ve}$ means meter is running slow.

4.2. Energy Measurement:

- $E = \int_0^t v(t) I(t).dt.$ Joule or w-sec
- $w_T = \frac{VI \cos\phi.t}{1000 \times 3600} (\text{kWh})$
- Meter constant (k) $\Rightarrow \frac{\text{No. of rev of disc}}{\text{Energy recorded in kWh}}$
- $w_m = \frac{\text{Totel no. of revolution}}{\text{k}}$
- Speed of induction type energy meter $\alpha \frac{1}{\text{Distance of braking mognet from the disc}}$
- Coulomb/rev = Amp sec/rev
- 1 $kwHr$ – 36 × 10^5 Volt-Amp sec, for volt $\rightarrow \frac{36 \times 10^5}{v}$ *Amp-sec*
- Speed of meter disc = $\frac{\text{revolution}}{60}$ rpm
- % kreeping = $\frac{\text{No. of rev/kWh due to kreeping}}{\text{No. of rev/kWh load}} \times 100$
- Error in Energy meter Power $(P_e) \rightarrow VI[\sin(\Delta - \phi) - \cos\phi]$
- $\Delta \rightarrow 90, P_e = 0$
- 2 analog b/w applied vol & Flux
- Multifaction factor of watt meter = $\frac{\text{Voltage setting} \times \text{current setting} \times A}{\text{Max range of scale}}$

4.3 MEASUREMENT OF POWER

4.3.1 Power in D.C. Circuits

Ammeter connected near the load (Ammeter-voltmeter method)	Voltmeter connected near the load (Voltmeter-Ammeter method)
 **Fig. Circuit Diagram**	 **Fig. Circuit Diagram**
$\%\text{Error} = \frac{P_m - P_T}{P_T} \times 100\%$ $\%\text{Error} = \frac{(P_L + P_a) - P_L}{P_L} \times 100\%$ $\%\text{Error} = \frac{P_a}{P_L} \times 100\% = \frac{V_a I_L}{V_L I_L} \times 100\% = \frac{V_a}{V_L} \times 100\%$ $\%\text{Error} = \frac{V_a}{V_L} \times 100\% = \frac{I_L.R_a}{I_L.R_L} \times 100\%$ $\%\text{Error} = \frac{R_a}{R_L} \times 100\%$ From the above equation it is clear that the error in the reading will be small when load resistance is large. Therefore, the above should be preferred for large resistance.	$\%\text{Error} = \frac{P_m - P_T}{P_T} \times 100\%$ $\%\text{Error} = \frac{(P_L + P_v) - P_L}{P_L} \times 100\%$ $\%\text{Error} = \frac{P_v}{P_L} \times 100 = \frac{\frac{V_L^2}{R_v}}{\frac{V_L^2}{R_L}} \times 100\%$ $\%\text{Error} = \frac{R_L}{R_v} \times 100\%$ From the above equation it is clear that the error in the reading will be small when load resistance is small. Therefore, above circuit should be preferred for measurement of power consumed by small resistance.

In measurement of power with voltmeter-ammeter method and ammeter-voltmeter method, the measured power is equal to the true power consumed by load and power consumed by the meter connected near the load.

Case I : Ammeter near the load, $P_m = P_T + P_a$

4.4. Power & Energy

4.4.1. DC Power Measurement

- $V - A\ method - \%Error = \frac{P_m - P_T}{P_T} \times 100 = \frac{I_L^2 R_a}{V_L I_L} \times 100 = \frac{R_a}{R_L} \times 100$
- $A - V\ method - \%Error = \frac{V_L^2 / R_V}{V_L \times X_L} \times 100 = \frac{R_L}{R_V} \times 100$
- To get equal error $\Rightarrow I_a^2 R_a = V_L^2 / R_V$

4.4.2. AC Power Measurement

- $P_{avg} = V_{rms}.I_{rms}.\cos\phi = V_{Pc} = V_{Pc}.I_{cc}\cos[V_{Pc} \,\&\, I_{cc}]$
- Instantaneous Power = $V_m I_m \sin \omega t . \sin(\omega t - \phi)$
- Signals with harmonics applied to Pc & c.c.
- $v(t) = v_0 + v_1 \sin(\omega t + \phi_1) + v_2 \sin(2\omega t + \phi_2) ---$
- $I(t) = I_1 + I_1 \sin(\omega t + \phi_1^{'}) + I_2 \sin(2\omega t + \phi_2^{'}) ---$
- $P_{avg} = V_0 I_0 + \frac{1}{2}\left[\sum_{k=1}^{n} V_k I_k \cos(\phi_k - \phi_k^{'})\right]$

4.4.3. EDM Type watt meter method

- $I_d = I_1 I_2 \cos\alpha \frac{dM}{d\theta} = I_{cc}.I_{pc}\cos\phi \frac{dM}{d\theta} = I.\frac{V}{R_S}\cos\phi \frac{dM}{d\theta} = \frac{P_{avg.}}{R_S}.\frac{dM}{d\theta}$
- $R_S = R_P$
- $\theta = \frac{P_{avg}}{k_c R_P}\frac{dM}{d\theta}$
- Error due to pressure coil connection:
- M-C short → $I_L^2 R_{CC}$ To get equal error
- LC short → I_L^2/R_{PC} $I_L^2 R_{CC} = V_L^2/R_{PC}$
- Error due to inductance of Pressure coil:
- $P_T = VI\cos\phi$ $\tan\beta = \frac{(\omega L_P)}{R_S}$
- Reading of meter-VI cos (ϕ–β). cos β
- CF. = Correction factor $= \frac{\cos\phi}{\cos(\phi-\beta).\cos\beta} = \frac{P_T}{P_m} = \frac{VI\cos\phi}{VI\cos(\phi-\beta)\cos\beta}$

  – V_e for lag load
  + Ve for ag load
- % Error due to P.C. Inductance = $\mp\tan\phi\ \tan\beta \times 100$
- In watt → $V_L I_L \sin\phi \tan\beta$ → actual error
- For lag load → $P_M = P_T + VI\sin\phi\tan\beta$
- $P_M > P_T$
- For lag load → $P_M = P_T - VI\sin\phi\tan\beta$
- $P_M < P_T$
- P_T = (C.F.).P.M. $\approx \frac{P_M}{1+\tan\phi\tan\beta}$

4.5. Two-watt meter Method

4.5.1. Blondel's Theorem: In N phase system 1 phase is common to other, no of wattmeter (N – 1)

- $P_1 = \sqrt{3}\, V_{Pn} I_{Ph} \cos(30 \mp \phi);\ P_2 = \sqrt{3}\, V_{Pn} I_{Pn} \cos(30 \pm \phi)$
- $P_{3\phi} = P_1 + P_2 = \sqrt{3}\, V_L I_L \cos\phi = 3 V_{Pn} I_{Pn} \cos\phi$
- $P_1 - P_2 = \sqrt{3} V_{Pn} I_{Pn} \sin\phi = Q_{3\phi} / \sqrt{3}$. $\mp \pm$ *lag load*
- $P.F. = \cos\left[\tan^{-1}\left(\frac{\sqrt{3}(P_1 - P_2)}{P_1 + P_2}\right)\right]$
- 3ϕ Reactive Power by 1 wattmeter:
- $|P| = V_{PC} I_{CC} \cos(V_{PC} \& I_{CC}) = Q$ $\quad Q_{3\phi} = \sqrt{3}\, Q$
- To improve power F. Capacitor is introduced in series to load.
- While drawing phasor Remember the +ve & –ve terminal
- Like $\rightarrow V_{13} = V_1 - V_3$ & $V_{31} = V_3 - V_1$

4.5.2 Blondel's theorem:

- 'n'-phase, (n + 1) wire –

Balance	**Unbalance**
1-watt-meter required	'n' wattmeter required

- 'n'-phase, 'n' - wire –

Balance	Unbalance
(n – 1) watt-meter required	(n – 1) watt-meter required

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5 CRO & ELECTRONIC MEASUREMENT

5.1 Cathode Ray Tube (CRT)

5.1.1 Cathode Ray Tube (CRT) & Its Components

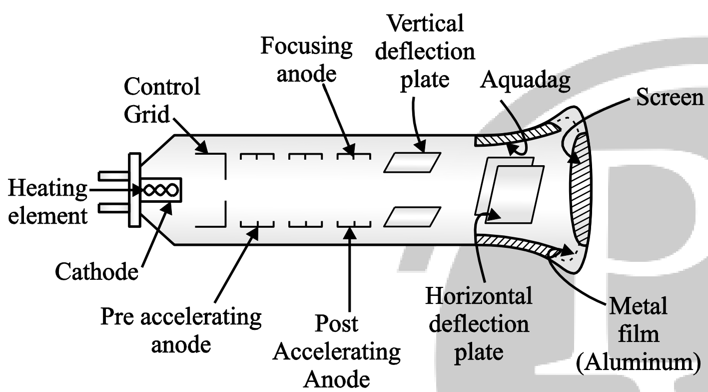


Fig. Circuit diagram of CRT

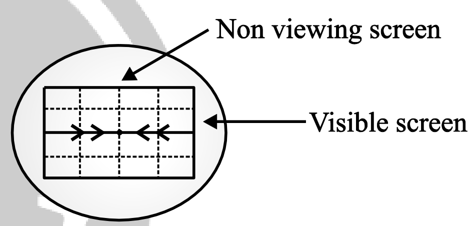


Fig. Sweep Generator is connected to Horizontal plates

- Used in display, measurement, analysis of wave form.
- CRT is the heart of CRO.
- Screen is coated with phosphur.
- ‘Al’ film act as heat sink and avoid the buring of phosphur.
- Aquadag is aqueous solution of Graphite used to collect secondary emitted e^-.

5.2. Time base Generator

In is an integrated which is used to sweep to e^- beam across the screen.

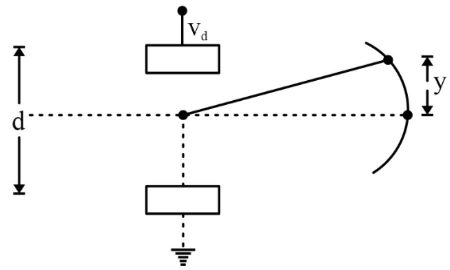
- Mode of operation of CRO: Two types

  (a) Normal mode – O/P of time base Generator is given to x-plate & unknown signal-y-plate

  (b) x-y plate – x – input channel connected to horizontal deflecting plate.

  y-input channel connect – vertical deflecting plate.

- Formula for Electrostatic deflection (y):



$$y = \frac{V_d . x . \ell}{2d . V_a}$$

S_{CRO} = 0.1 mm/V

5.3. Measurement by CRO

We can measure voltage, Phase angle, Time period, freq, current

(1) Voltage measurement by CRO:

- Scale is 10 × 8 division.
- CRO measures V_{PP}.]
- $X - \text{division} \rightarrow \frac{\text{Time}}{div}, Y - \text{division} \rightarrow \frac{\text{Voltage}}{div}$

(2) Current measurement by CRO:

- Current cannot be measured directly by CRO.

(3) Measurement of phase by CRO:

- Lissajous Patterns is used.
- Two sinusoidal signals having equal magnitude but different phase.

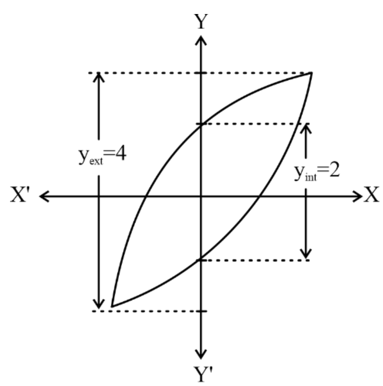
Case I : ϕ = 0°, 360° → Straight line

Case II : ϕ = 90°, 270° → Circle

Case III : ϕ = 180° → Straight line

Case IV : ϕ = 0 < ϕ < 180° → direction of rotation is in C.W.

Case VI : ϕ = 180° < ϕ < 360° → direction of rotation is in CCW.



$$\phi = \sin^{-}\left(\frac{y_{int}}{y_{ext}}\right).$$

(4) Measurement of frequency by CRO:

- Frequency ratio.

  F_y = Maximum no. of horizontal Intersection drawn to LP

  F_y = Maximum no. of vertical Intersection drawn to LP

  F_y = Maximum no. of horizontal tangent drawn to LP

  F_x = Maximum no. of vertical tangent drawn to LP

$$\frac{f_{high}}{f_{low}} = \frac{\text{Total no. of Bright spot in LP}}{1}$$

$$\frac{f_{high}}{f_{low}} = \frac{\text{Total no. of Corner in LP}}{1}$$

Example:

$$= \frac{f_{high}}{f_{low}} = \frac{4}{1}$$

$$= \frac{f_{high}}{f_{low}} = \frac{5}{1}$$

5.4. Digital Voltmeter

5.4.1 Specifications of DVM

Resolution (R):

Resolution is the term used to describe the smallest input value that a digital meter can measure.

$$R = \frac{1}{10^N} \text{ in fraction}$$

$$R = \frac{V_{max}}{10^N} \text{ in volts}$$

$$R = \frac{I_{max}}{10^N} \text{ in Ampere}$$

N= Number of full digits

Sensitivity :

Sensitivity is the lowest input value that a digital meter can measure within the specified range.

Number of digits in display = N + 1 where N is the number of full digits which may display any digit from 0 to 9 and one left most digit is called half digit which may display only 0 or 1.

$3\frac{1}{2}$ Digits display :

	3 V	30 V	300 V
Resolution of minimum voltage	0.001	0.01	0.1
Maximum voltage	2.999	29.99	299.9

$3\frac{3}{4}$ Digits display :

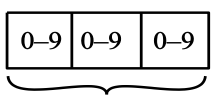
	3 V	30 V	300 V
Resolution of minimum voltage	0.001	0.01	0.1
Maximum voltage	2.999	29.99	299.9

4-Digits display :

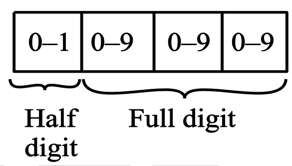
	1 V	10 V	100 V
Resolution of minimum voltage	0.0001	0.001	0.01
Maximum voltage	0.999	9.999	99.99

5.4.2 Over Ranging

The extra $\frac{1}{2}$ digit is switched ON is called over ranging.



3-Digit Display



$3\frac{1}{2}$ Digits display

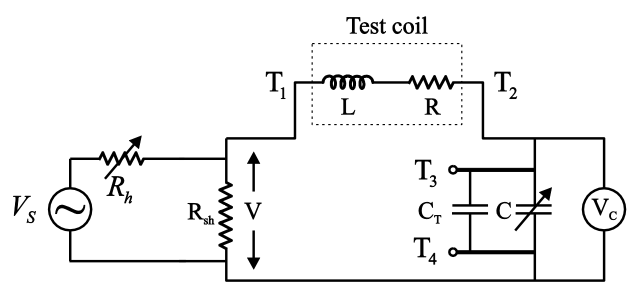
Percentage error due to extra count is given by,

$$\text{Error} = \text{Percentage error due to reading} + \frac{\text{Count} \times \text{Full scale value}}{\text{Number of counts}}$$

5.5. Q-Meter

5.5.1 Applications of Q-Meter

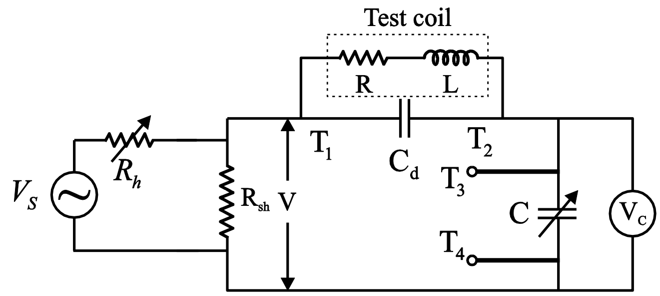
1. Measurement of unknown capacitance



Circuit diagram

$$C_T = C_2 - C_1$$

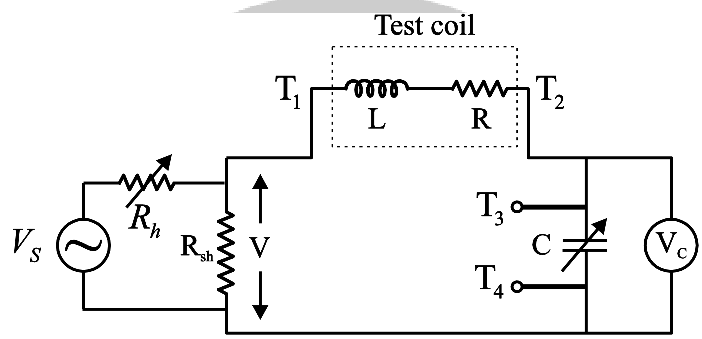
2. Measurement of distributed capacitance of the coil



Circuit diagram

$$C_d = \frac{C_1 - n^2 C_2}{n^2 - 1}$$

3. Measurement of Q-factor of test coil

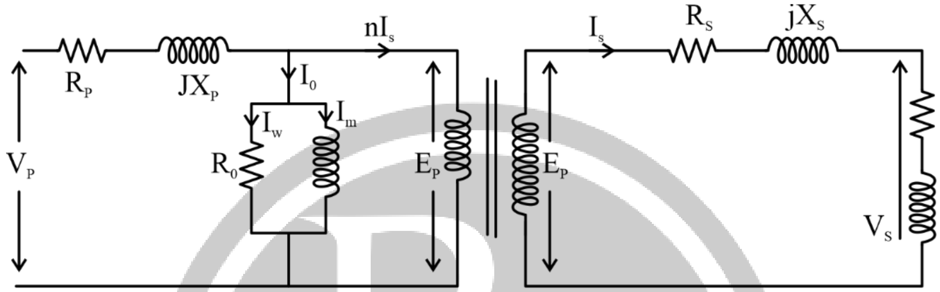


Circuit diagram

$$Q_{true} = Q_{measured}\left(1 + \frac{R_{sh}}{R}\right)$$

6 INSTRUMENT TRANSFORMERS

6.1. Current Transformer



- Turns ratios = $(n) = \frac{N_2}{N_1}$, nominal ratio = $\frac{I_P}{I_S}$
- Actual/Transformation ratio = $(R) = \frac{I_P \text{ actual}}{I_S \text{ actual}}$
- Secondary burden angle $\Rightarrow (S) = \tan^{-1}\left(\frac{X_e + X_s}{R_e + R_s}\right)$
- $$R = \frac{I_w \cos\delta + I_m \sin\delta}{I_S} + n$$
  $\downarrow$
  not valid for $\delta = 0$ because some approximation is made
- $I_w = I_o \sin\alpha$
- $I_m = I_o \cos\alpha$
- $I_p = \sqrt{(nI_S)^2 + I_m^2}$
  when $S = 0$ for R burden
- Ratio corelation factor = $\frac{R}{K}$
- Ratio error = $\frac{K - R}{R} \times 100\%$
- Phase angle error = $(\theta) = \frac{I_m \cos S - I_w \sin S}{nI_S} \times \frac{180}{\pi}$ degree

  Phase angle b/w I_P & I_S = $(180^o - \theta)$

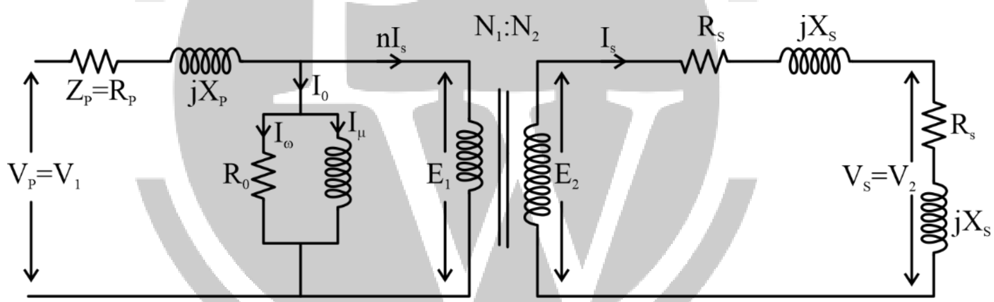
- Magnetising MMF = I_m × primary turns
- Iron loss = $E_P \times I_w$
- $E_P = \frac{E_2}{n}$
- $E_S = I_S \cdot Z_S$
- Bar primary = 1 turn
- V_A rating of a current transformer expressed the burden on it.
- Compensation of turns method, by it we can reduced ratio error, phase angle error reduction is identical (No effect)

$$\phi = \frac{E_S}{\sqrt{2}\pi f N_S}$$

$$B_m = \frac{\phi}{A}$$

$$E_P = \frac{V_A}{I_P}$$

6.2. Potential Transformer



- Turns ratio = (n) = $\frac{N_1}{N_2}$
- Nominal ratio (k) = $\frac{V_P}{V_S} = \frac{V_1}{V_2}$
- Actual transformation ratio = (R) = $\frac{V_P}{V_S} = \frac{V_1}{V_2} \rightarrow$ T.V.
- Secondary burden angle = (Δ) = $\tan^{-1}\left(\frac{X_1}{R_1}\right)$
- $R = \frac{\overline{V_P}}{V_S} = n + \frac{V\,I_S\left(R_{2e}\cos\Delta + X_{2e}\sin\Delta\right) + I_w R_p + I_u \times p}{V_S}$

- $R_{2e} = R_S + \frac{R_P}{n^2}$
- $Z_{2e} = X_S + \frac{X_P}{n^2}$
- Ratio error = % σ = $\frac{K - R}{R} \times 100$
- Phase angle error (θ) = $\frac{I_S}{V_S}\left[X_{2e}\cos\Delta - R_{2e}\sin\Delta\right] + \frac{I_w\ pr \times p}{nV_S}$ (rad)
- Phase angle b/w V_1 & $V_2 \rightarrow (180 - \theta)$ degree $(\pi - \theta)$ rad
- In these N_S are increased slightly & primary & secondary way are closely as possible to compensate ratio K phase angle error respectively. And place co-axially to reduced leakage reactance.
- Size of P.T > Size of power T/F
- The conductor size is used in P.T. > power T/F.

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