MODULE- 3

INSTRUMENT TRANSFORMER

Contents :

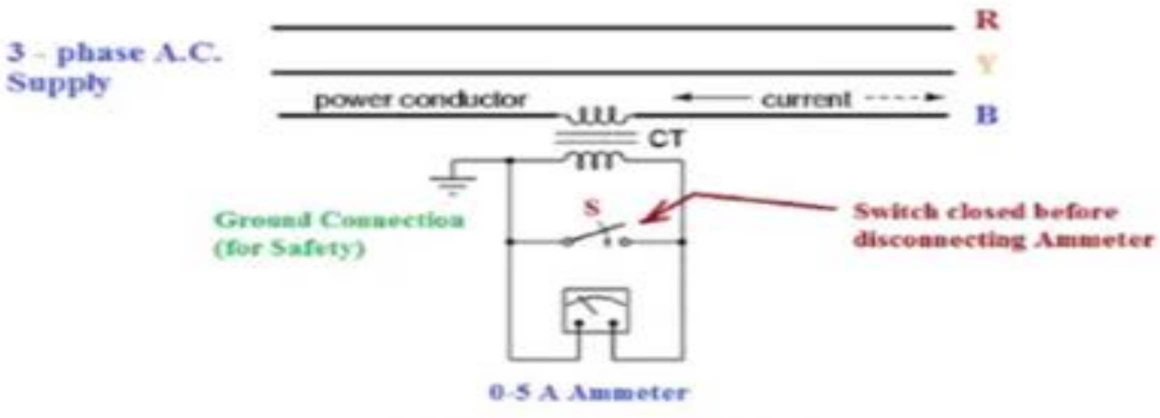
Potential Transformer

Current Transformer

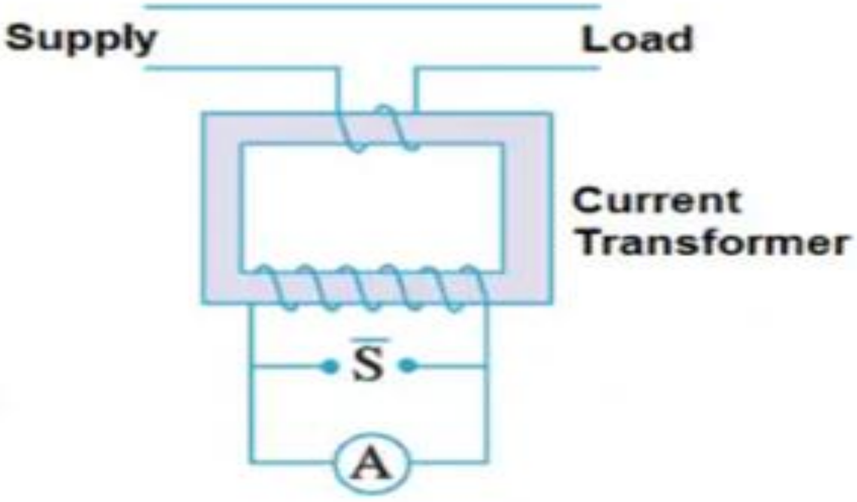
Introduction:

1. Considering a overhead lines, transmitting even more than 220KV and current rating of 3000A. Therefore transmitting the very high voltage and current and to measure this v and I is very difficult voltage decides how much value of insulation is required and current requires the size of conductor which in turn increases the relay size.
2. In Power systems currents and voltage handled are very high and hence direct measurement with conventional instruments is not possible without compromising operator safety.
3. The solution is to step down these currents and voltages with the help of **instrument transformer**.
4. The transformers used in conjunction with the measuring instruments for the measurement purpose are called **instrument transformer.**
5. The transformer are used in AC system for the measurement of current, voltages, power and energy , power facto frequency and indication of synchronism.

What is Instrument Transformer?



Current Transformer (C.T.)



Need of instrument Transformer / use of instrument Transformer

1. To provide isolation and protection from high voltage supply circuit.
2. To supply protective relays which operated at lower voltage and current so that size and cost will be reduced.
3. Needed in protection circuit of power system for this operation of over current, under voltage, earth fault and various other types of relays.
4. Instrument Transformer not only extend the range of the low range instruments but also isolate them from high current and high voltage AC circuit. Generally measuring instruments are designed for 5A and 110V.
5. The transformer used for measurement of current is called **current transformer(CT).**
6. The Transformer used for measurement of voltage is called **Potential Transformer(PT).**

Advantages of instrument Transformer

1. Instrument of **moderate size** are used for metering **5A for current and 100 to 120V for voltage** measurements
2. Several instruments can be operated from a **single instrument transformer**.
3. Instruments and meters can be standardized so that there is a **saving in overall cost**. Replacement of damaged instruments is easy.
4. The metering circuit is **isolated from the high voltage power circuits**. Hence **insulation is no problem** and **safety is assured for the operator.**
5. Single range instruments can be used to **cover large current or voltage ranges**, when used with suitable multirnge instrument transformer.

1. The measuring instruments can be placed for away from the high voltage side by connecting long wires to the instrument transformer. This ensures the safety of instruments as well as the operator.
2. This instrument transformers can be used to extend the range of measuring instruments like ammeters and voltmeters.

3. The power loss in instrument transformers is very small as compared to power loss due to the resistance of shunts and multipliers.
4. By using current transformer with tong tester, the current in a heavy current circuit can be measured.

Basic Terminologies in Instrument Transformer

Transformation Ratio (R):/Actual Ratio

The transformation ratio is the ratio of the magnitude of the primary phasor to the secondary phasor of the instrument transformer.

R=Magnitude of primary phasor/Magnitude of the secondary phasor➔ Primary winding current/Secondary winding current or Ip/Is (Current Transformer)

R= Primary winding voltage/Secondary winding Voltage or Vp/Vs (potential transformer)

For the current transformer,

R=magnitude of primary current (I_p)/Magnitude of the secondary current (I_s)

For the potential transformer,

R=magnitude of primary voltage (V_p)/magnitude of the secondary voltage (V_s)

$$R = \frac{\text{Magnitude of actual primary current}}{\text{Magnitude of actual secondary current}} \quad \text{... For C.T.}$$

$$R = \frac{\text{Magnitude of actual primary voltage}}{\text{Magnitude of actual secondary voltage}} \quad \text{... For P.T.}$$

Turns Ratio(n)

If N_p is the number of turns in the primary winding and N_s is the number of turns in the secondary winding of the instrument transformer then,

Turns ratio of the current transformer (C.T) is,

Number of turns of secondary winding/Number of turns of Primary winding $n=N_s/N_p$

Turns ratio of the potential transformer (P.T) is,

$n=N_p/N_s$

$$n = \frac{\text{Number of turns of secondary winding}}{\text{Number of turns of primary winding}} \quad \text{... For C.T.}$$

$$n = \frac{\text{Number of turns of primary winding}}{\text{Number of turns of secondary winding}} \quad \text{... For P.T.}$$

Nominal Ratio (K_n)

The nominal ratio is the ratio of the rated value primary phasor to the rated secondary phasor of the instrument transformer.

For the current transformer,

K_n=Rated primary current ($I_{p\ rated}$)/Rated secondary current ($I_{s\ rated}$)

For the potential transformer,

K_n=Rated primary voltage ($V_{p\ rated}$)/Rated secondary voltage ($V_{s.\ rated}$)

$$K_n = \frac{\text{Rated primary current}}{\text{Rated secondary current}} \quad \text{... For C.T.}$$

$$K_n = \frac{\text{Rated primary voltage}}{\text{Rated secondary voltage}} \quad \text{... For P.T.}$$

Ratio Correction Factor: The ratio correction factor of a transformer is the transformation ratio divided by nominal ratio.

RCF= Transformation Ratio/ Nominal Ratio = R/Kn

R= RCF*Kn

$$RCF = \frac{R}{K_n}$$

$$\boxed{R = RCF \times K_n}$$

Burden on Instrument Transformer

Burden of an instrument transformer refers to the maximum allowable load connected to its secondary winding(expressed in volt-amperes) presents to the primary circuit (rated secondary terminal voltage or current) with errors not exceeding the limits for a particular class of accuracy.

Total Secondary winding Burden = (Secondary winding induced voltage)^2 / (Total impedance of secondary circuit including load and winding)

= Es^2/TZs

=(Secondary winding current)^2 * (Total impedance of secondary circuit including load and winding)

=Is^2*TZs

If only the impedance of the load is considered then the burden due to the only load can be obtained.

$$\text{Total secondary winding burden} = \frac{(\text{Secondary winding induced voltage})^2}{\text{Total impedance of secondary circuit including load and winding}}$$

$$= \begin{pmatrix}\text{Secondary winding}\\ \text{current}\end{pmatrix}^2 \times \begin{bmatrix}\text{Total impedance of secondary circuit}\\ \text{including load and winding}\end{bmatrix}$$

$$\text{Secondary winding burden due to load} = \frac{(\text{Secondary winding induced voltage})^2}{\text{Impedance of the load on secondary}}$$

$$= \begin{pmatrix}\text{Secondary winding}\\ \text{current}\end{pmatrix}^2 \times [\text{Impedance of the load on secondary}]$$

Secondary Winding Burden due to the load = (Secondary Winding induced voltage)^2/ Impedance of the load on Secondary.
=(Secondary Winding Current)^2 * (Impedance of the load on secondary)

Note:

1. Burden is not an action tat is undertaken but rather a parameter that must be considered and specified when designing, selecting or using instrument transformer to ensure accurate and reliable measurement in electrical systems.
2. The burden of an instrument transformer refers to the electrical load.
3. Es^2/TZs this calculation helps us to determine the total load or impedance that the secondary winding presents to the primary circuit and is important for ensuring accurate measurements and compliance with accuracy standard for the instrument transformer
4. The choice of the burden for an instrument transformer should match the requirement of the connected measuring instrument, if the burden is too high, it can lead to inaccuracies in measurements due to voltage drops and deviations from the ideal transformer ratio. Therefore , selecting an appropriate burden is crucial to ensure accurate and reliable measurement in electricals systems.

Types of an Instrument Transformer

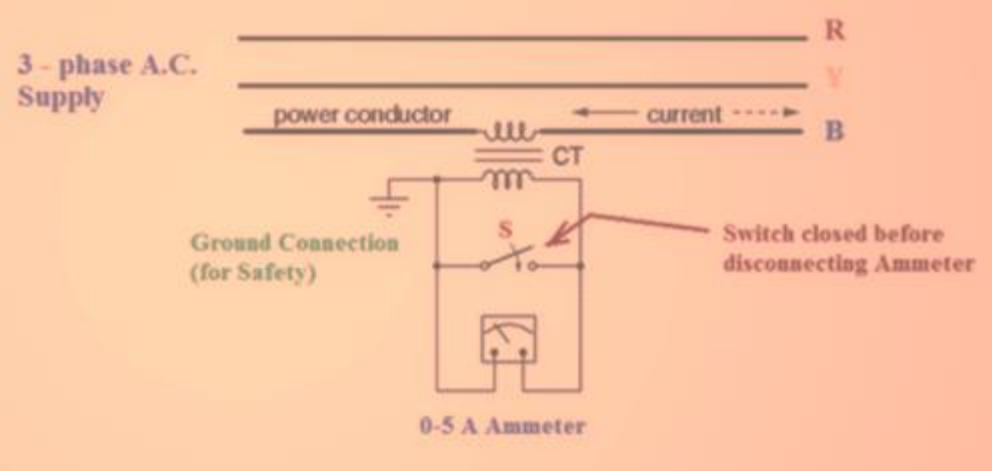
There are two types of instrument transformers, and they are namely

1.Current transformer (C.T)

2.Potential transformer (P.T), also known as the voltage transformer.

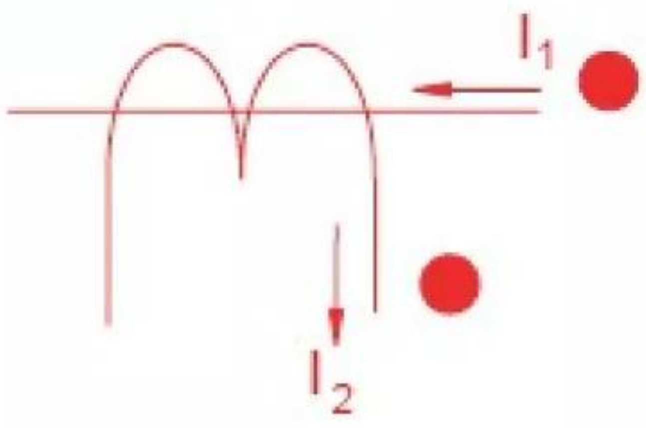
Current Transformer

The instrument transformer connected in series with the high-power circuit to measure the current is known as the current transformer. Apart from the measuring applications, we can also use the current transformers to feed the protective relays in the power system protection. The below figure shows the basic circuit arrangement of the current transformer.

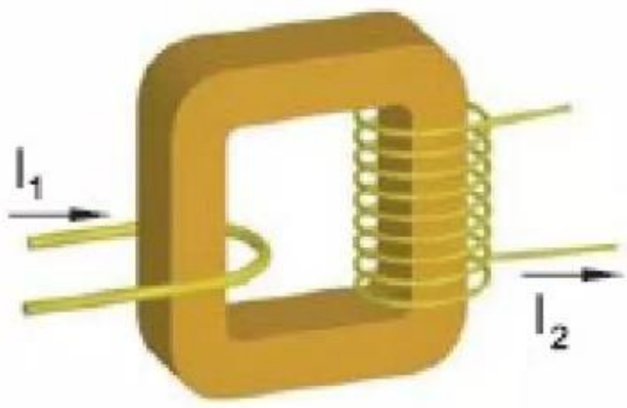


Current Transformers

Symbol of a
Current Transformer

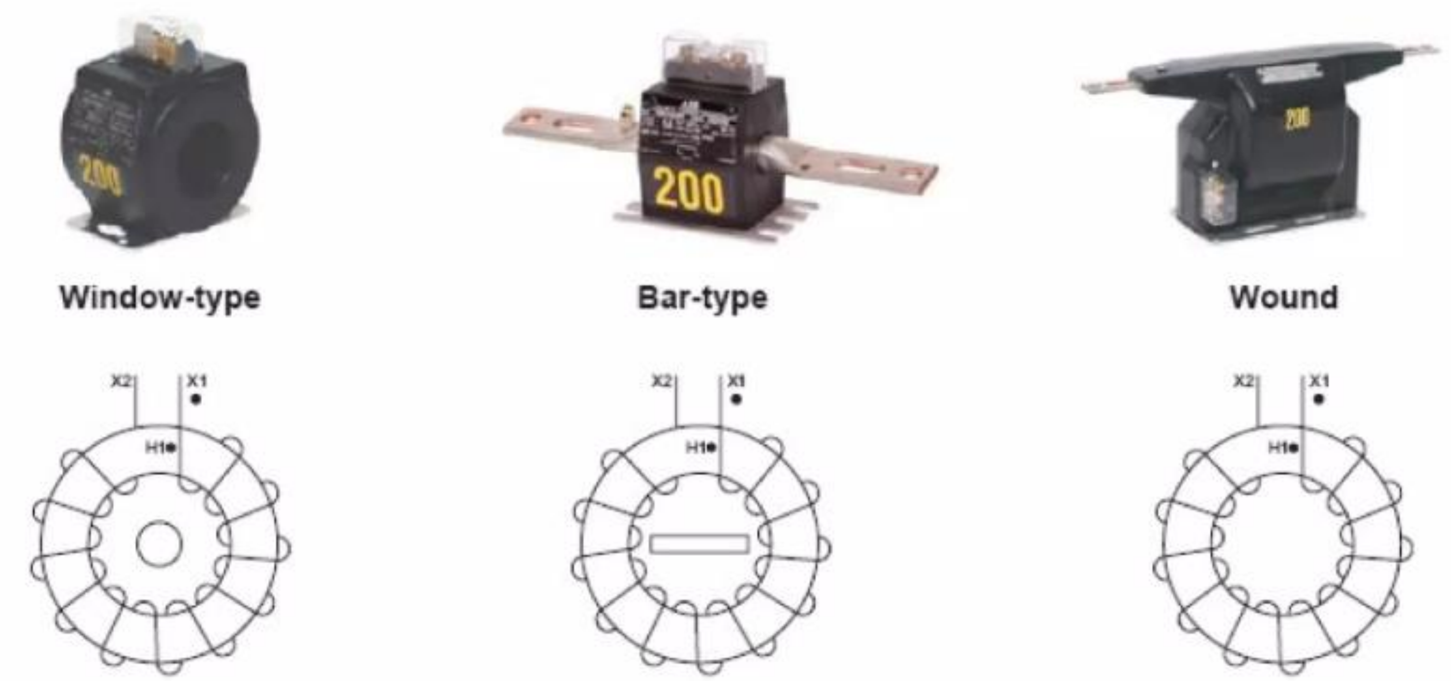


Conceptual picture of
a Current Transformer



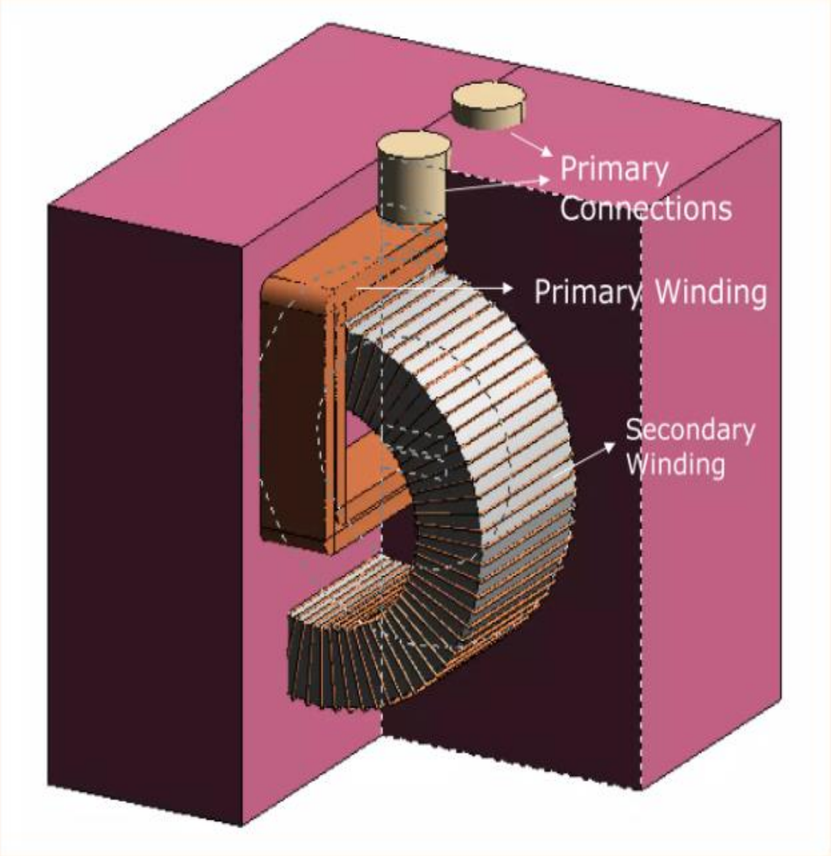
Types of CT

Construction Types

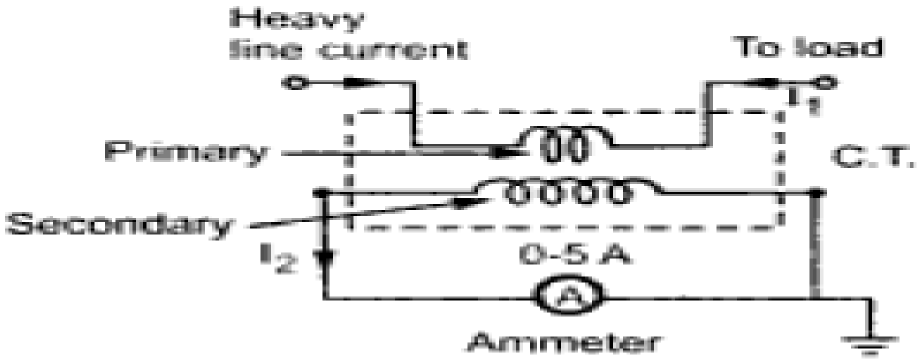


Constructional Details of Window

Constructional Details of wound CT



1. The large alternating currents which can not be sensed or passed through normal ammeters and current coils of wattmeter's, energy meters can easily measured by use Of current transformers along with normal low range instruments.
2. A CT basically has a primary coil of one or more turns of heavy cross sectional area, which is connected in series with line carrying current and secondary winding of more turns can be determined by turns ratio, which is connected ammeter to measure current/ current coil of wattmeter to measure power or relay coil to measure over current. Therefore Secondary of CT operates under short circuit condition. One of the terminals of the secondary winding is earthed so as to protect equipment or if simulates within the CT fails, it gives safety.
3. In order to avoid voltage drop/ Effect on the main system, it should have minimum possible turns in primary, more thickness in wire/ minimum resistance so that voltage drop is reduced.



Current transformer

Primary current is fixed and MMF in primary = N_1I_1, Flux produced by the primary that flux links with secondary , EMF is induced and current start flowing in such a way that the secondary will produce exactly same flux and same MMF so to counter balance the primary MMF .Therefore NET FLUX in the core will be = NO LOAD or magnetizing component

MMF1 =MMF2

$N_1I_1 = N_2I_2$

Let N_1 = Number of turns of primary

N_2 = Number of turns of secondary

I_1 = Primary current

I_2 = Secondary current

For a transformer,

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

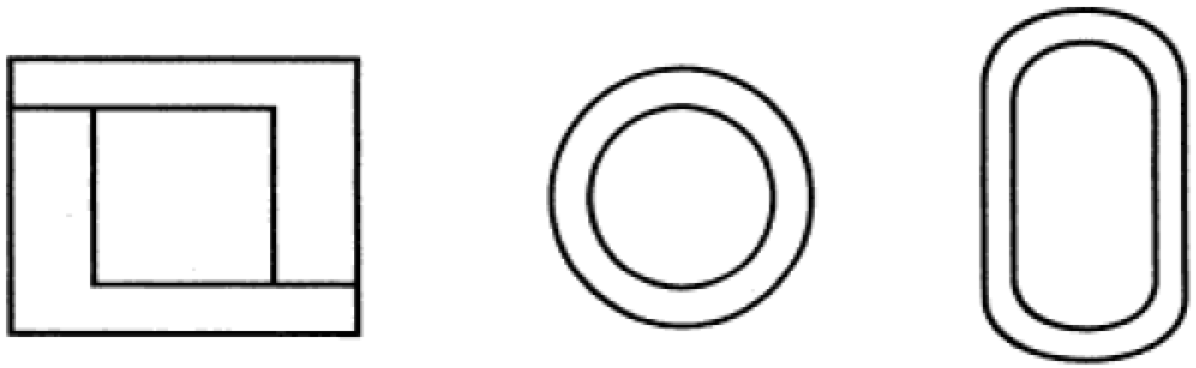
Construction of Current Transformers

are two Types Of constructions used for the current transformers will are,

I. Wound type 2. Bar type

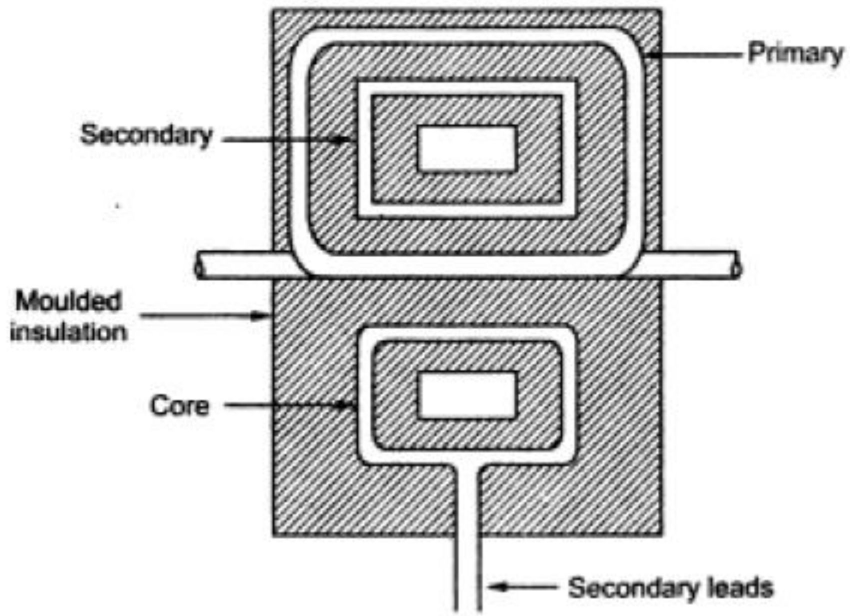
1. Wound type current Transformer

- In wound type construction, the primary is wound for more than one full turn, on the core. The construction is shown in the fig.
- The core material for the wound type is nickel-iron alloy or an oriented electrical steel.
- The heavy primary winding is directly wound on the top of the secondary winding with a suitable insulation in between the two. Otherwise the primary is wound completely separately and then taped with suitable insulating material and assembled with the secondary on the core.
- Insulating materials such as pressboard or insulating tape are used to protect the winding from damage due to sharp corner.
- Before installing the secondary winding on the core it is insulated with the help of the END collars and Circumferential wraps of pressboard.
- The current Transformer can be ring/Window , Rectangular and stadium Type



(a) Rectangular (b) Ring (c) Stadium

Fig. - Stampings for current transformers



Wound type current transformer

2. Bar type Current Transformer

- In bar type current Transformer uses a primary conductor which is straight metal bar or tube, it passes through central opening or window in core.
- Bar type primary is the integral part of the current transformer and the insulation on primary is bakelized paper tube or a resin directly moulted on bar.
- To avoid the corona effect, Bar type primary tube diameter is kept large and winding are close to each other to reduce leakage reactance.
- To minimize the reluctance in the corners of the laminations it's essential to use stampings in laminations with a substantial cross-sectional area , thereby magnetizing current also reduced.

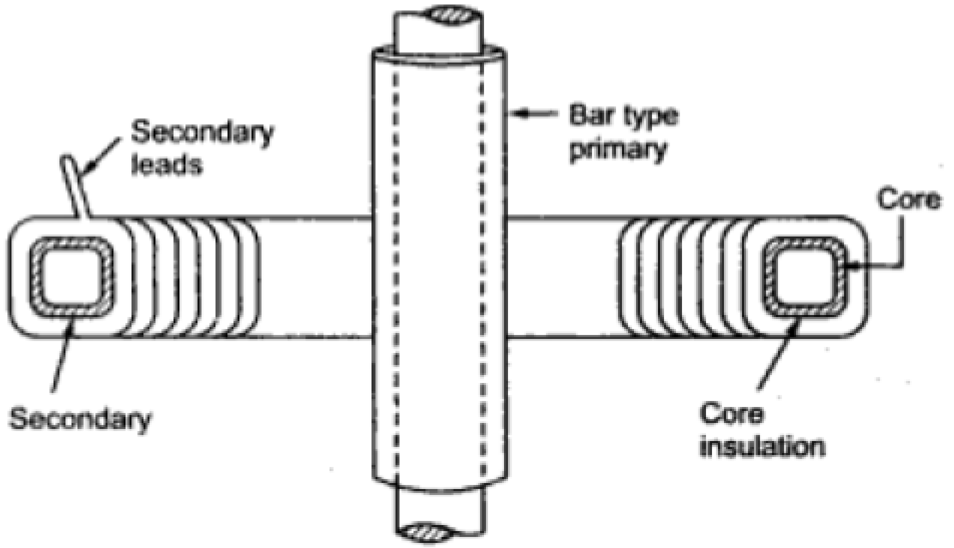
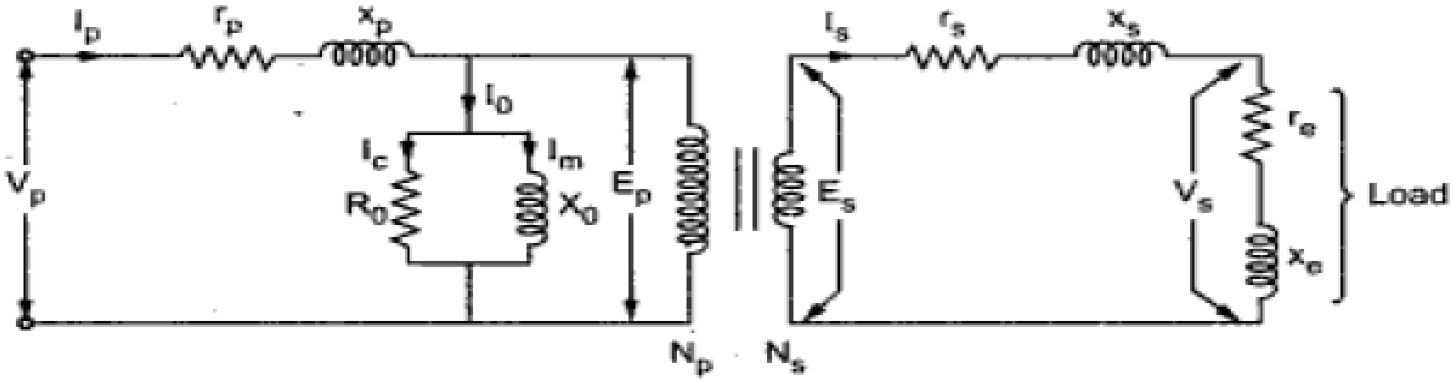


Fig. Bar type current transformer

Relationships in current Transformer

. Consider the equivalent circuit of a current transformer as shown in the along with the load.



Equivalent circuit of current transformer

The various symbols are,

n = Turns ratio = $\dfrac{\text{Secondary turns}}{\text{Primary turns}} = \dfrac{N_s}{N_p}$

r_p = Resistance of primary winding

x_p = Reactance of primary winding

r_s = Resistance of secondary winding

x_s = Reactance of secondary winding

r_e = Resistance of external burden i.e. load on secondary

x_e = Reactance of external burden i.e. load on secondary

E_p = Primary induced voltage

E_s = Secondary induced voltage

V_s = Secondary terminal voltage

I_p = Primary current

I_s = Secondary current

I_0 = No load current or exciting current

I_c = Core loss component of I_0 i.e. $I_0 \cos\phi_0$

I_m = Magnetising component of I_0 i.e. $I_0 \sin\phi_0$

ϕ = Working flux of transformer

δ = Angle between E_s and I_s

= Phase angle of total impedance of secondary including burden

$= \tan^{-1}\left(\dfrac{x_s + x_e}{r_s + r_e}\right)$

θ = Phase angle of transformer

Δ = Phase angle of load or burden i.e. $r_e + j\,x_e$

$= \tan^{-1}\dfrac{x_e}{r_e}$

α = Angle between I_0 and working flux ϕ.

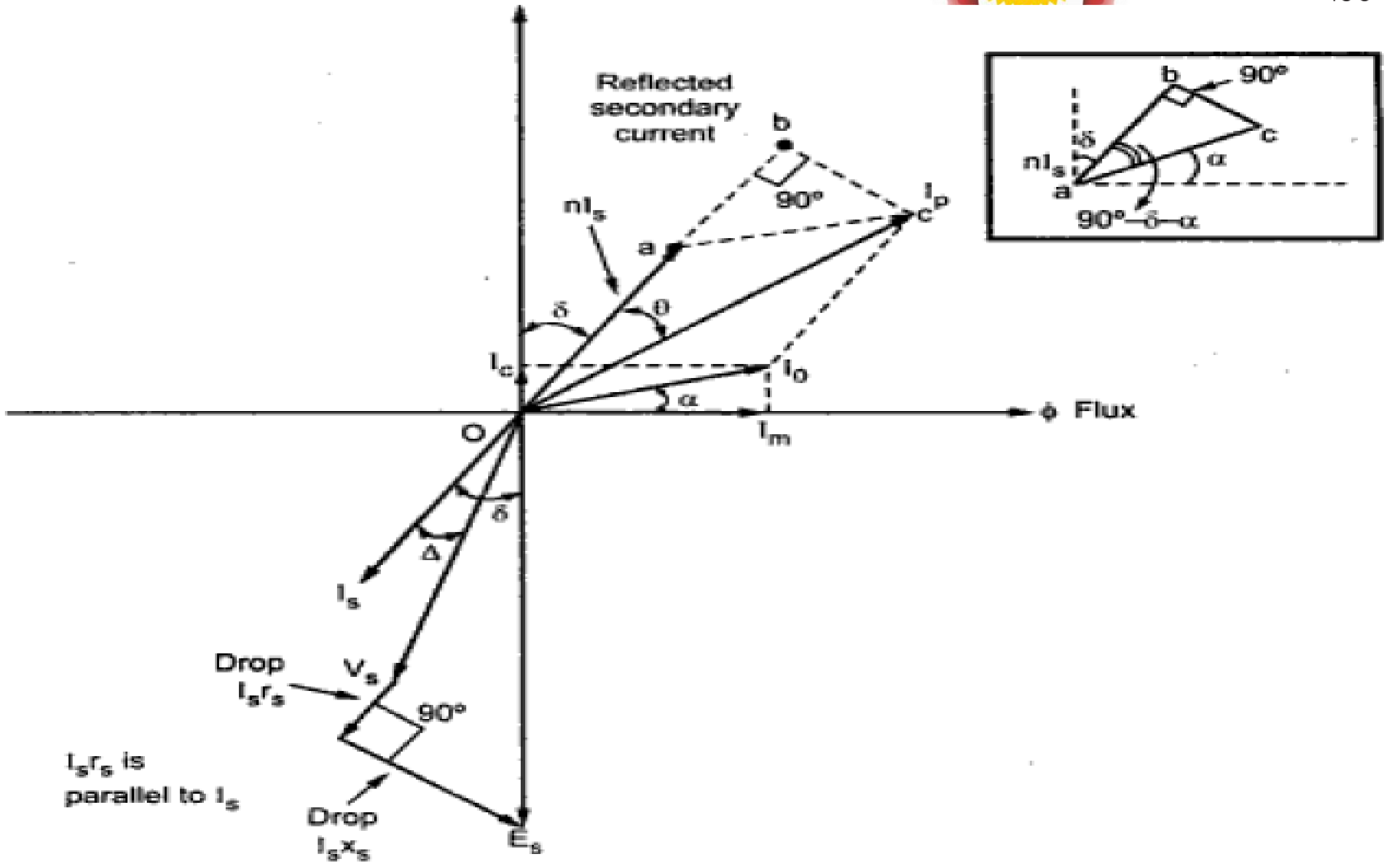


Fig. Phasor diagram of current transformer

Consider $\angle$ bac as shown in the small section which is,

$$\angle bac = 90° - \delta - \alpha, \quad ac = I_0, \quad Oa = n\,I_s, \quad Oc = I_p$$

$$\therefore \quad bc = ac\sin(90° - \delta - \alpha) = I_0 \sin[90° - (\delta + \alpha)] = I_0\cos(\delta + \alpha)$$

$$\therefore \quad ab = ac\cos(90° - \delta - \alpha) = I_0\cos[90° - (\alpha + \delta)] = I_0\sin(\delta + \alpha)$$

From right angle triangle Obc,

$$(Oc)^2 = (Ob)^2 + (bc)^2 = (Oa + ab)^2 + (bc)^2$$

$$= [n\,I_s + I_0\sin(\delta + \alpha)]^2 + [I_0\cos(\delta + \alpha)]^2$$

$$= n^2\, I_s^2 + 2n\,I_s\,I_0\sin(\delta + \alpha) + I_0^2\sin^2(\delta + \alpha) + I_0^2\cos^2(\delta + \alpha)$$

i.e. $$I_p = \sqrt{n^2\, I_s^2 + 2n\,I_s\,I_0\sin(\delta + \alpha) + I_0^2} \quad \ldots (1)$$

$$\therefore \quad \text{Actual ratio} = R = \frac{I_p}{I_s} \quad \ldots \text{As per definition}$$

$$\therefore \quad R = \frac{\sqrt{n^2\, I_s^2 + 2n\,I_s\,I_0\sin(\delta + \alpha) + I_0^2}}{I_s} \quad \ldots (2)$$

Practically for properly designed transformer $I_0 << n\, I_s$,

$$\therefore \qquad R = \frac{\sqrt{n^2\, I_s^2 + 2n\, I_s\, I_0 \sin(\delta+\alpha) + I_0^2 \sin^2(\delta+\alpha)}}{I_s}$$

... Adjusting I_0^2 as $I_0^2 \sin^2(\delta+\alpha)$

$$\therefore \qquad R = \frac{n\, I_s + I_0 \sin(\delta+\alpha)}{I_s} = n + \frac{I_0}{I_s}\sin(\delta+\alpha) \qquad \text{... (3)}$$

This is approximate value of actual ratio but practically very close to actual result. The equation (3) can be further expanded as,

$$R = n + \frac{I_0}{I_s}[\sin\delta\cos\alpha + \cos\delta\sin\alpha]$$

But $I_0 \cos\alpha = I_m$ and $I_0 \sin\alpha = I_c$

$$\therefore \qquad R = n + \frac{I_m}{I_s}\sin\delta + \frac{I_c}{I_s}\cos\delta$$

$$\therefore \qquad \boxed{R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_s}} \qquad \text{... (4)}$$

Note that δ is positive for lagging p.f. load while negative for leading p.f. load.

Derivation of Phase Angle (teta) of Current Transformer

The phase angle θ is defined as the angle between reversed secondary current phasor i.e. reflected secondary current phasor and the primary current.

Sign convention : θ is positive if reflected secondary current leads primary current. θ is negative if secondary current lags primary current.

$$\therefore \qquad \theta = n I_s \wedge I_p$$

From the phasor diagram,

$$\tan\theta = \frac{bc}{Ob} = \frac{bc}{Oa + ab} = \frac{I_0 \cos(\delta + \alpha)}{n I_s + I_0 \sin(\delta + \alpha)}$$

Now $\tan\theta \approx \theta$ as θ is very small.

$$\therefore \qquad \theta = \frac{I_0 \cos(\delta + \alpha)}{n I_s + I_0 \sin(\delta + \alpha)} \text{ radians} \qquad \ldots (5)$$

But $I_0 << n I_s$ hence neglecting from denominator,

$$\theta = \frac{I_0 \cos(\delta + \alpha)}{n I_s} = \frac{I_0 [\cos\delta \cos\alpha - \sin\delta \sin\alpha]}{n I_s}$$

$$\therefore \qquad \theta = \frac{I_m \cos\delta - I_c \sin\delta}{n I_s} \text{ radians} \qquad \ldots (6)$$

Converting to degrees,

$$\boxed{\theta = \frac{180°}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{n I_s}\right] \text{ degrees}} \qquad \ldots (7)$$

Errors in Current Transformer

For an instrument transformers, it is necessary that the transformation ratio must exactly equal to turns ratio and phase of the secondary terms (voltage and current) must be displaced by exactly 10 from that of the primary terms (voltage and current). Two types of errors affect characteristics of an instrument transformer which are.

1. Ratio error
2. Phase angle error

Ratio Error:

- In practice it is said that current transformation ratio I1/I2 is equal to the turns ratio NI / N2. But actually it is not The current ratio is not equal to turns ratio because of magnetizing and core loss components of the exciting current. It gets affected due to the secondary current and its power factor. The load current is not a constant fraction of the primary current.
- Similarly in of potential transformers, voltage ratio V2 / VI is also not exactly equal to N2 / NI due to the factors.
- Thus the transformation ratio is not constant but depends on the load current, factor Of load and exciting current Of the Due to this fact, large error is introduced in the measurements done by the instrument transformers. Such an error is called ratio error.

The ratio error is defined as,

$$\%\ \text{Ratio error} = \frac{\text{nominal ratio} - \text{actual ratio}}{\text{actual ratio}} \times 100$$

$$\boxed{\%\ \text{Ratio error} = \frac{K_n - R}{R} \times 100}$$

Phase Angle Error: it is denoted by an angle Ө by which the phase difference between primary and secondary is different from 180. but actually is not. Therefore the error introduced due to this fact is phase angle error

The phase angle error is given by,

$$\boxed{\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{n\, I_s}\right] \text{ degrees}} \qquad \dots (9)$$

Approximate results : In practice, the loads are inductive and δ is positive and very small.

$\therefore \quad \sin\delta \approx 0 \quad$ and $\quad \cos\delta = 1$ hence the equations (4) and (7) becomes,

$$R = n + \frac{I_c}{I_s} \qquad \dots (10\ (a))$$

and

$$\theta = \left(\frac{180}{\pi}\right)\left(\frac{I_m}{n\, I_s}\right) \text{ degrees} \qquad \dots (11\ (a))$$

Interms of I_p, these can be written using $n = \frac{I_p}{I_s}$.

$\therefore$

$$R = n + \frac{n\, I_c}{I_p} \qquad \dots (10\ (b))$$

and

$$\theta = \left(\frac{180}{\pi}\right)\left(\frac{I_m}{I_p}\right) \text{ degrees} \qquad \dots (11\ (b))$$

Cause of Errors in Current Transformer

Due to following reasons:

- There is some exciting mmf required by the primary winding to produce flux. Therefore the transformer draws an Im (Magnetizing current).
- The flux density in the core is not a linear function of the magnetizing force.ie.., The transformer core becomes saturated.
- There is a magnetic leakages and consequently the primary flux linkages are not equal to the secondary flux linkages
- Due to the flow of no load current, The transformer input must have a component which supplies the core losses eddy current and hysteresis losses and I^2 R losses of transformer winding.

Reduction of Errors in CT

- Phase Angle depends on magnetizing current (Im) and Actual Ratio, turns Ratio depends on loss component (Ic). It is obvious that the turns ratio and phase angle is to be small and Ic, Im must be small as compared to Ip.
- There are some method or design features which helps us to minimize the errors they are.
- **Core:** To minimize the errors the Im and Ic must be kept low. So that core must have low reluctance and low core loss. By using materials of high permeability, short magnetic paths, large cross section of the core and low flux densities, there will be reduction of reluctance of flux path.
- The number of joints in building up ores should be minimum as possible because joints produce air gaps which offers high reluctance for the flux. The mmf consumed by the joints can be reduced by properly lapping the joints and tightly binding the core.

- The core loss is reduced by choosing materials having low hysteresis and low eddy current losses. Magnetic materials used in CT can be hot rolled silicon steel. Cold rolled grain oriented silicon steel and nickel iron Alloys.
- Two winding primary and secondary should be close together to reduce the secondary winding leakage reactance (Xp and Xs)
- Use of ring shaped core and toroidal winding of uniformly distributed leads to low leakage reactance's.
- Secondary winding current is too large, it may be reduced by a shunt placed across the primary or secondary. This method makes an exact correction for particular value and type of burden) it also reduces the phase angle errors.
- Turns compensation (To decrease ration Error)
- Ex: Let us consider1000/5A CT with loss component equal to 0.6% of primary winding current

Ex:- Let us consider 1000/5A CT with loss component equal to 0.6% of primary winding current

⇒ w.k.t Ratio Error = $\frac{\text{Nominal Ratio} - \text{Actual Ratio}}{\text{Actual Ratio}}$

given:- $K_n = 1000/5A = 200 \longrightarrow (1)$

$I_c = \frac{0.6}{100} * \text{Primary Current} = \frac{0.6}{100} * 1000 = 6A$

→ Let us consider the primary turn $N_p = 1$

→ if turns Ratio(n) = Nominal Ratio $\langle n = K_n \rangle$

$\frac{N_s}{N_p} = K_n$

$\boxed{N_s} = K_n * N_p = 200 * 1 = \boxed{200}$

→ Actual Ratio [R] = $n + \frac{I_c}{I_s}$

$= 200 + \frac{6}{5} = 201.2$

→ ~~Let~~ Instead of 200 secondary winding turns. Let us considered 199 turns

→ Actual transformation Ratio with turns compensation

$R = n + \frac{I_c}{I_s} = 199 + \frac{6}{5} = 200.2 \longrightarrow (2)$

→ ∴ If we ~~to~~ reduce the secondary turns slightly actual transformation Ratio = Nominal Ratio (1) = (2) eqns (9)

R > Kn, so turn Ratio(n) is reduced by secondary turns. This makes actual Ratio (R) = Nominal Ratio (Kn). This is turns compensation for CT

Characteristics of Current Transformer

1. Effect of power factor of secondary circuit

The p.f. of the secondary circuit depends on the p.f. of the burden on Secondary. This directly affects the two errors of the transformer.

a. Ratio error : For all inductive loads, Is lags Es so that δ is positive. Hence actual ratio R is always greater than the tums ratio n (R>n) For capacitive burdens, Is leads Es so that δ is negative and Hence R is less than the turns ratio n (Approaching to -90%)

b. Phase angle error : When load is inductive and δ is small positive then θ is also positive. But as δ increases, As δ approaches to 90 (load become highly inductive) then θ becomes negative . For capacitive load, δ is negative and θ is always positive.

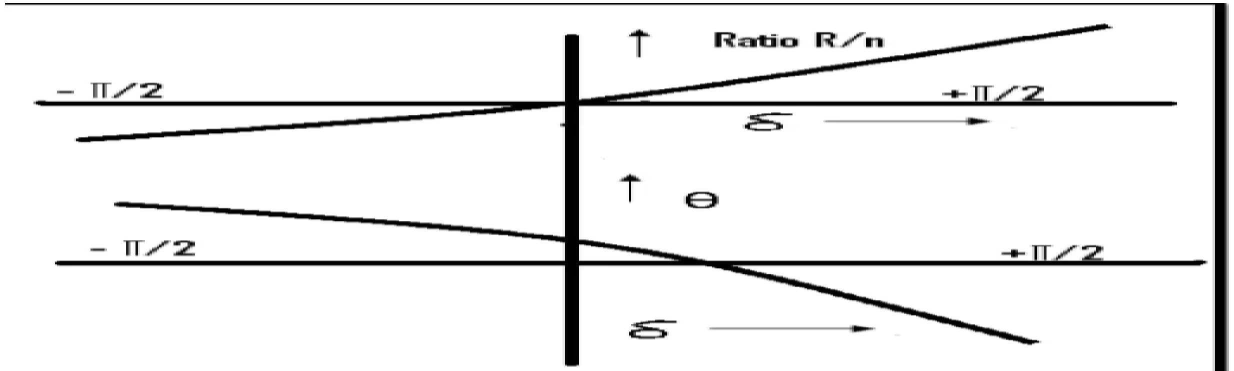


FIG.1:Variation of transformation ratio and phase exciting angle with p.f of secondary winding circuit

2. Effect of change of primary winding current

- If Ip changes Is changes proportionately.
- For low value of Ip , Io is dominating thus Im and Ic are also dominating parts of Ip, Thus errors are higher.
- As the current Ip increases, there is increase in Is also and there is a decreases in ratio error and phase angle. Thus errors are less.

3. Effect of change in burden on secondary

- The secondary winding circuit burden increases means volt- ampere rating increases. Due to increased Is , secondary flux increases which induces more voltage on secondary. Thus both Im and Ic increases to keep flux constant due to this, error also increases.

4. Effect of change in frequency:

- If Frequency is increased at constant and voltage then the flux and flux density decreases. Thus there is a reduction in Im and Ic and hence errors get reduced.

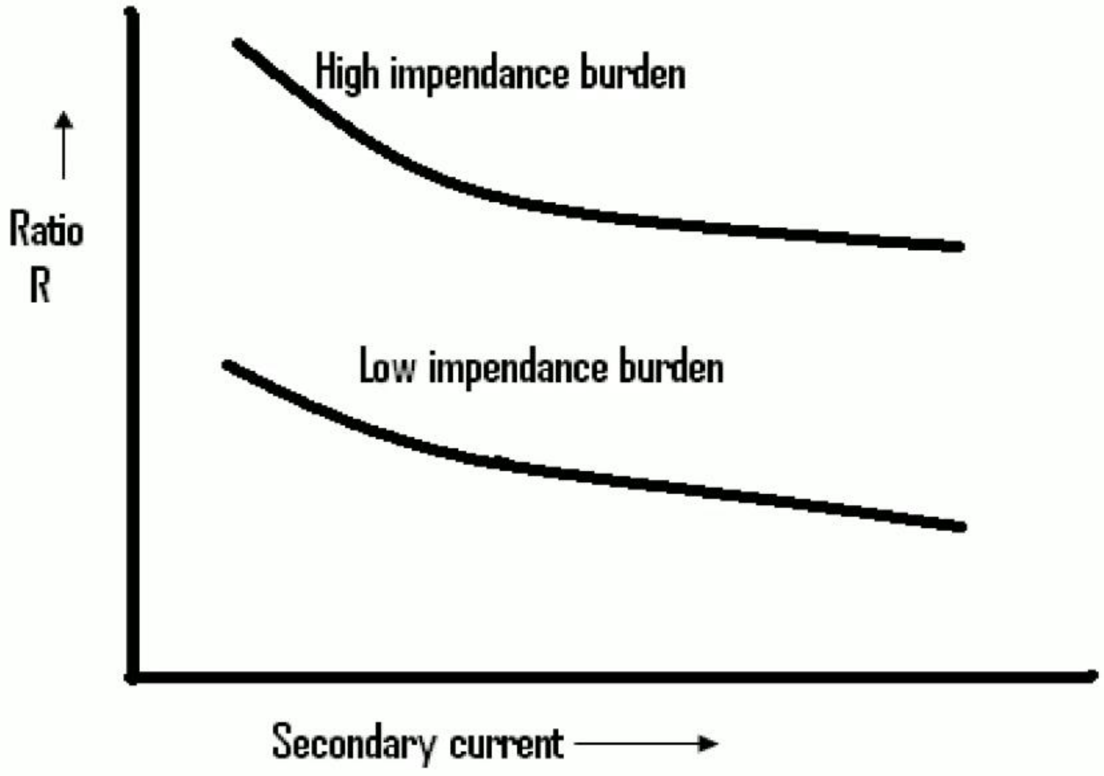


FIG.2:Variation of ratio R with secondary winding current

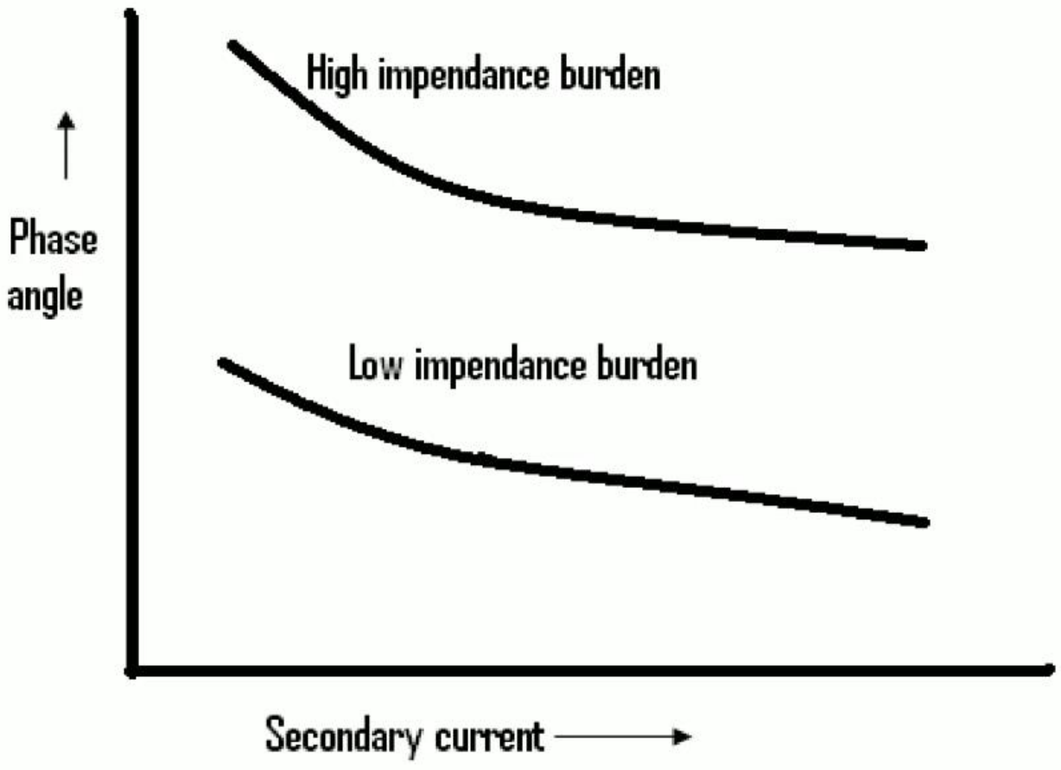


FIG.3:Variation phase angle with secondary winding current

Example 2.3 : *The no load current components of a current transformer are, magnetizing component = 102 A core loss component = 38 A. The current transformation ratio is 1000 / 5 A. Calculate the approximate ratio error at full load.*

Solution : $I_m = 120$ A, $I_c = 38$ A K_n = nominal ratio $= \frac{1000}{5} = 200$

At full load, $I_s = 5$ A

$$R = n + \frac{I_c}{I_s} \quad \text{... Using approximate results}$$

Now $\quad n$ = turns ratio $= \frac{N_s}{N_p} = \frac{I_p}{I_s} = \frac{1000}{5} = 200$

$$\therefore \quad R = 200 + \frac{38}{5} = 207.6$$

$$\therefore \quad \%\text{ ratio error} = \frac{K_n - R}{R} \times 100 = \frac{200 - 207.6}{207.6} \times 100 = -3.66\%$$

Example 2.4 : *A current transformer has a single turn primary and 400 secondary turns. The magnetizing current is 90 A while core loss current is 40 A. Secondary circuit phase angle is 28°. Calculate the actual primary current and ratio error when secondary carries 5 A current.*

Solution : $I_m = 90$ A, $I_c = 40$ A, $\delta = 28°$, $I_s = 5$ A.

$$n = \frac{N_s}{N_p} = \frac{400}{1} = 400$$

$$K_n = \frac{I_p}{I_s} = \frac{N_s}{N_p} = 400$$

$$R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_s}$$

$$= 400 + \frac{90 \sin 28° + 40 \cos 28°}{5} = 415.514$$

$$I_p = \text{actual primary current} = R\, I_s$$

$$= 415.514 \times 5 = 2077.5703 \text{ A}$$

$$\therefore \quad \% \text{ ratio error} = \frac{K_n - R}{R} \times 100 = \frac{400 - 415.514}{415.514} \times 100 = -3.733\%$$

Example 2.5 : *A current transformer has turns ratio 1:399 and is rated as 2000/5 A. The core loss component is 3 A and magnetizing component is 8 A, under full load conditions. Find the phase angle and ratio errors under full load condition if secondary circuit power factor is 0.8 leading.*

Solution : $I_c = 3$ A, $I_m = 8$ A, $\cos\delta = 0.8$ leading

$$\therefore \quad \delta = -36.8698^\circ, \quad \text{negative as leading}$$

$$n = \frac{N_s}{N_p} = \frac{399}{1}$$

$$K_n = \frac{I_p}{I_s} = \frac{2000}{5} = 400$$

$$R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_s} \quad \text{where} \quad I_s = 5 \text{ A} \quad \text{(full load)}$$

$$= 399 + \frac{8\sin(-36.869^\circ) + 3 \times 0.8}{5} = 398.52$$

$$\therefore \quad \% \text{ ratio error} = \frac{K_n - R}{R} \times 100 = 0.3713\%$$

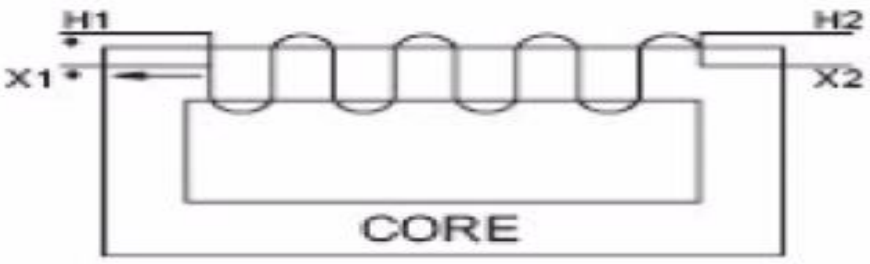
$$\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{nI_s}\right] \text{degrees}$$

$$= \frac{180}{\pi}\left[\frac{8 \times 0.8 - 3 \times \sin(-36.8698^\circ)}{399 \times 5}\right]$$

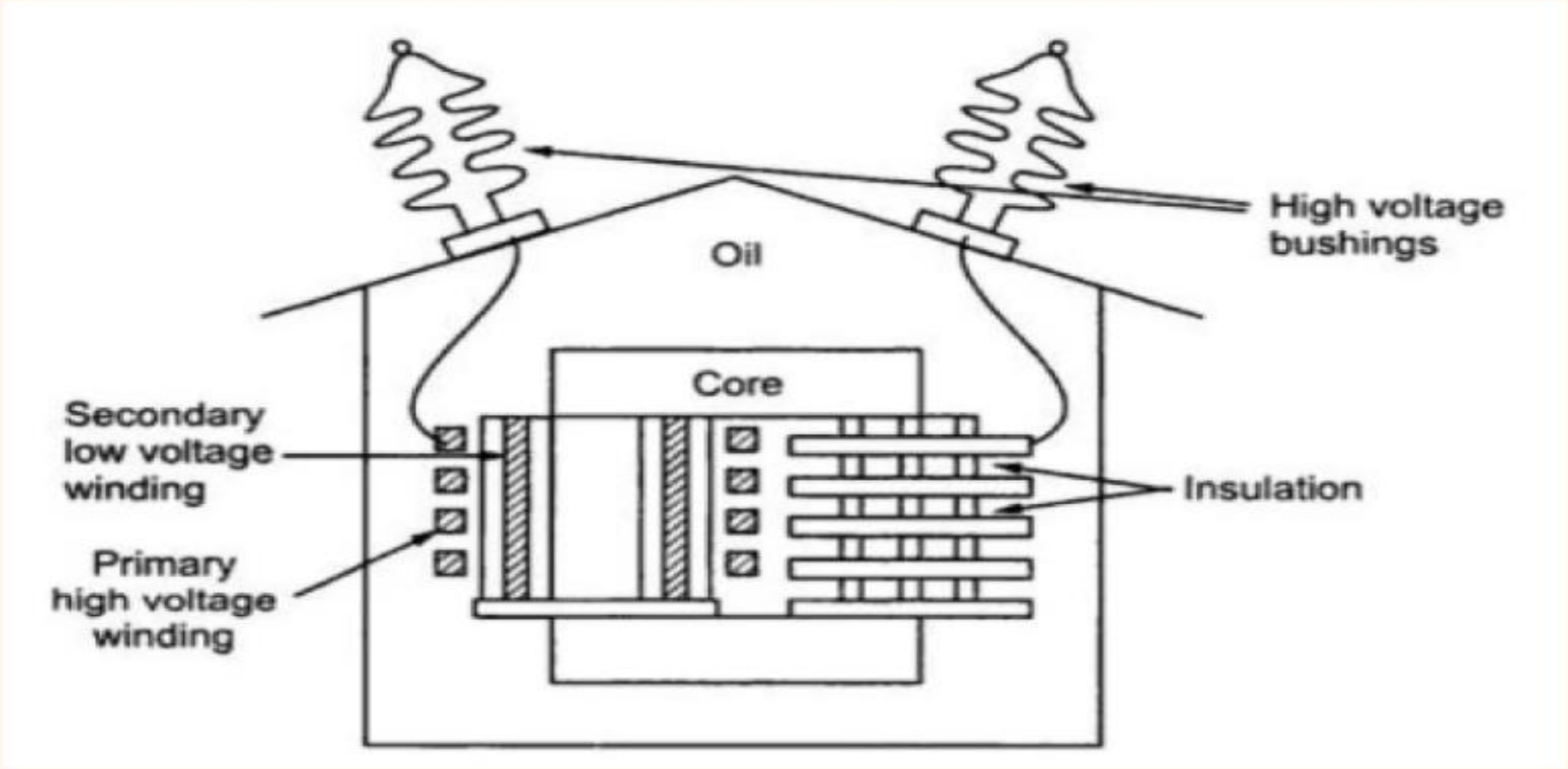
$$= 0.2355^\circ = 14.13'$$

Potential Transformer

Voltage Transformer



Voltage Example
Primary 7200 Volts
Ratio 60:1 or 7200:120 Volts


High voltage bushings
Oil
Core
Secondary low voltage winding
Insulation
Primary high voltage winding

Points to note about PT

- Secondary is connected voltmeter or Potential coil of the Wattmeter or Relay
- Design is similar to Power Transformer, but Potential Transformers are lightly loaded
- Secondary is usually rated for 110 V
- Should not be shorted

Construction of PT

- For the same power rating, Voltage transformer is costly than Power transformer (large core & conductor size)
- Output is small (and accurate), but size is large
- Can carry more load (2 to 3 times)
- Shell type core – Low voltage
- Co-axial windings

Construction of PT

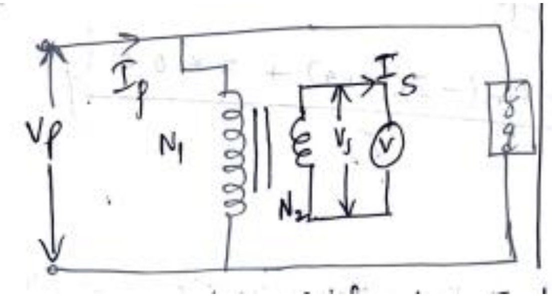
- Insulation: Cotton tape and varnished cambric as insulation for coil
- Oil immersed for more than 7 kV
- Oil filled bushing for oil filled transformer
- If one side of the primary winding is at neutral, one bushing is sufficient

Why PT??

A Large voltages which cannot be sensed or passed through normal voltmeter . Therefore Potential transformer are used to measure high voltage, for energizing the potential coil of low range wattmeter's and energy meter, relays and other protective devices.

A Potential Transformer/voltage Transformer :

- Primary winding consists of large number of turns while the secondary has less number of turns usually rated for 110V and irrespective of primary voltage rating.
- The primary is connected across high voltage line while secondary is connected to low range voltmeter coil.
- One end of the secondary is always grounded for safety purpose.
- Its ratio can be specified as Vp/Vs = N_p/N_s
- Primary voltage is fixed, EMF is induced in secondary . EMF divided by impedance of secondary winding results in production of current in secondary . According to flux produced by secondary, primary will take extra current to produce the required flux to compensate the secondary current



$$\frac{N_1}{N_2} = \frac{V_p}{V_s}$$

$$\therefore V_s = V_p\left[\frac{N_2}{N_1}\right]$$

Current Transformer	Potential Transformer
It can be treated **as series Transformer** under short circuit Condition	It can be treated as parallel transformer under open circuit Secondary
Secondary is connected to **ammeter**	**Secondary** is connected to **voltmeter**
Secondary works almost in **short** circuit **condition**	Secondary is nearly under **open** circuit **condition**
Primary current depends on **power** circuit current	**Primary current** depends on **secondary burden** or secondary circuit condition
Primary current and excitation vary over wide range	Primary current and excitation vary over limited range because line voltage is almost constant
Need only one bushing as two ends of primary winding are brought out through the same insulator .Hence there is saving in cost	Two bushing are required when neither side of the line is at ground potential
A Small voltage exists across its terminals	Full line voltage appears across its terminals
Winding carries full line current	Winding is impressed with full line voltage

Relationships in PT or Theory of Potential Transformer

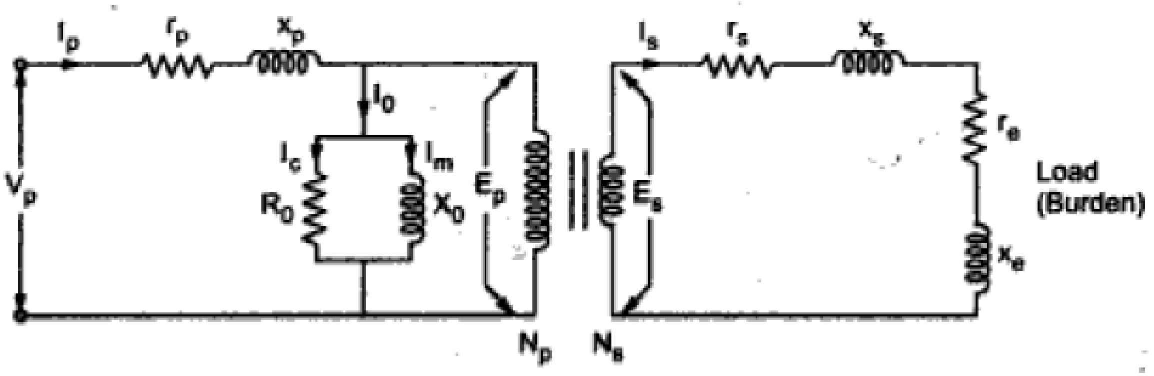


Fig. 2.9 Equivalent circuit of potential transformer

The various symbols are,

ϕ = Working flux

N_p = Primary turns

N_s = Secondary turns

I_p = Primary current

I_s = Secondary current

I_m = Magnetising component of I_0

I_c = Core less component of I_0

I_0 = No load current i.e. exciting current

r_s, x_s = Resistance and reactance of secondary winding

r_p, x_p = Resistance and reactance of primary winding

r_e, x_e = Resistance and reactance of burden

E_p = Primary induced voltage

E_s = Secondary induced voltage

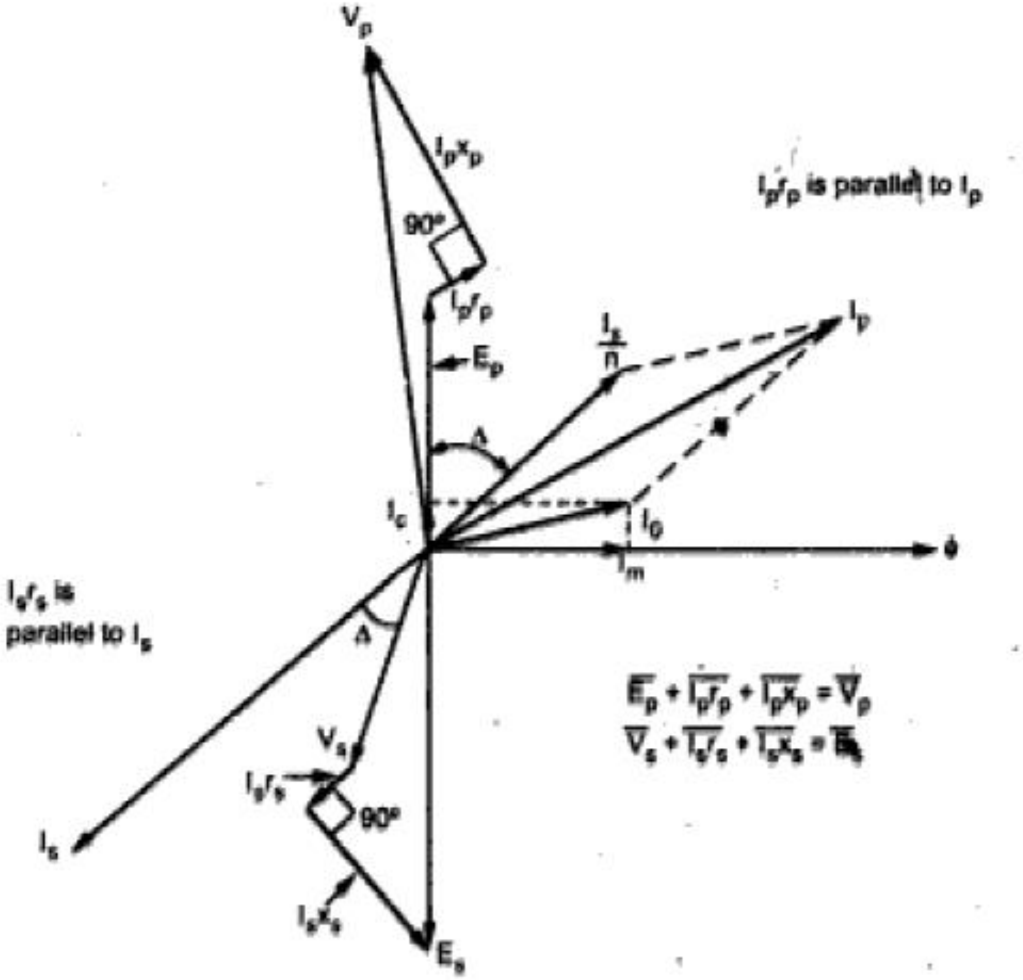
Δ = Phase angle of secondary load current = $\tan^{-1} \frac{x_e}{r_e}$

V_p = Primary applied voltage

V_s = Secondary terminal voltage

For P.T. $\boxed{n = \frac{N_p}{N_s} = \frac{E_p}{E_s}}$

The phasor diagram is shown in the Fig. 2.10.



Potential transformer is same as power transformer, the only difference is that, the loading of a PT is very less

$\boxed{V_s = E_s - I_s(r_s + jx_s)}$ (or) ~~$E_p = V_p + I_p(r_p + jx_p)$~~

$\boxed{E_s = V_s + I_s(r_s + jx_s)} \longrightarrow (1)$

→ Let us assuming I_s lagging V_s by angle "Δ"

$\boxed{E_p + I_p(r_p + jx_p) = V_p} \longrightarrow (3)$

$\boxed{I_p = I_0 + I_s'} \Rightarrow I_0 + \frac{I_s}{n} \longrightarrow (2)$

WKT turns Ratio $n = \frac{N_p}{N_s} = \frac{E_p}{E_s}$

⇒ Current will be transfered to the inverse proportional to the voltage

→ V_s to the primary side, this V_s taking 180° apart it becomes nV_s

→ I_s to the primary side ∴ $\frac{I_s}{n}$

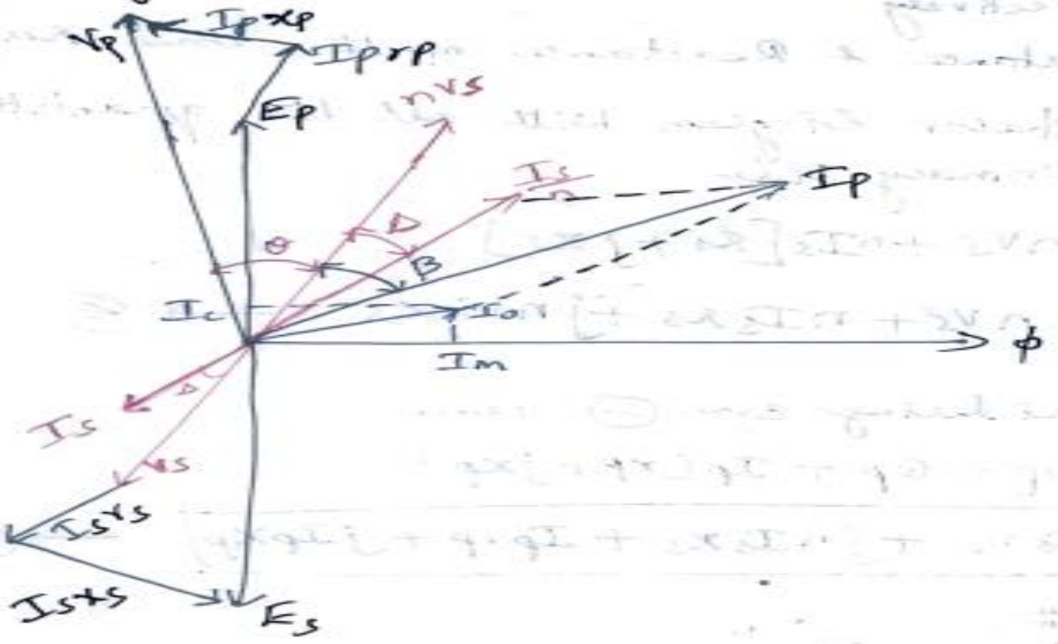
→ angle b/w nV_s & $\frac{I_s}{n}$ is Δ

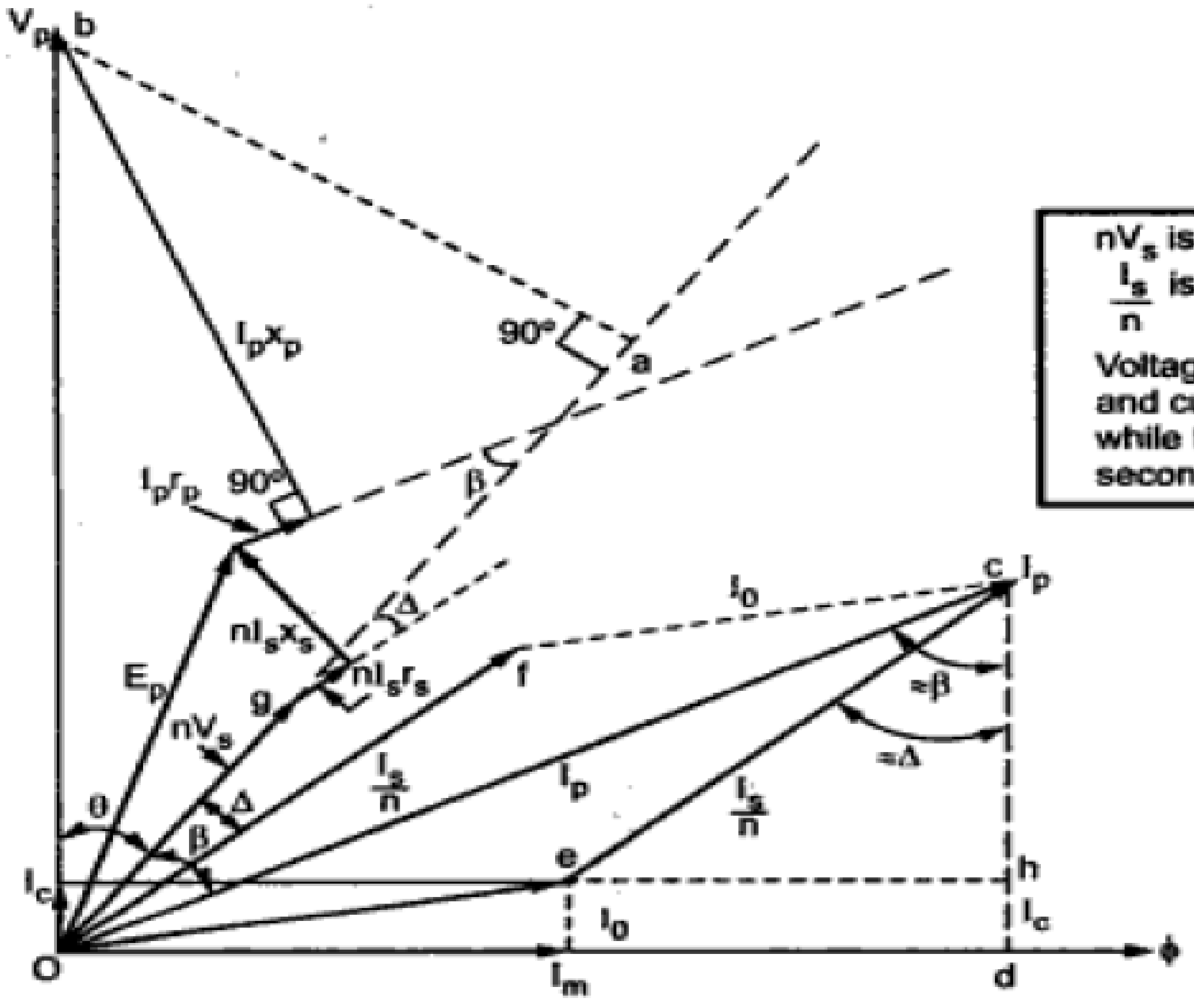
NOTE :- Voltages are multiplied by 'n' & currents divided by 'n' while transferring from secondary to primary

$\boxed{\Delta}$ = phase angle of secondary load current = $\tan^{-1}\left(\frac{x_e}{r_e}\right)$

→ angle b/w I_p & nV_s is represented by $\boxed{\beta}$

→ angle difference b/w nV_s & V_p is represented by $\boxed{\theta}$ phase angle of the transformer (power factor angle)





nV_s is V_s reversed
$\frac{I_s}{n}$ is I_s reversed.

Voltages are multiplied by n and currents divided by n while transferring from secondary to primary.

$Oe = I_0,\quad Oc = I_p,\quad Of = \frac{I_s}{n},\quad Og = n\,V_s,\quad Ob = V_p$

θ = Phase angle of transformer = $V_p \wedge V_s$ reversed

Δ = Phase angle of secondary load = $n\,V_s \wedge \frac{I_s}{n}$

β = Phase angle between I_p and V_s reversed

Oa is $n\,V_s$ extended and ba is perpendicular drawn from b on $n\,V_s$ extended.

$$\therefore \quad Oa = Ob\cos\theta = V_p\cos\theta \quad \text{... (1)}$$

Now Oa is made up of various components.

$$Oa = n\,V_s + n\,I_s\,r_s\cos\Delta + n\,I_s\,x_s\sin\Delta + I_p\,r_p\cos\beta + I_p\,x_p\sin\beta \quad \text{... (2)}$$

Equating (1) and (2)

$$\therefore \quad V_p\cos\theta = n\,V_s + n\,I_s(r_s\cos\Delta + x_s\sin\Delta) + I_p(r_p\cos\beta + x_p\sin\beta) \quad \text{... (3)}$$

For potential transformer the load is nothing but a voltmeter hence θ is very small hence both V_p as well as $n\,V_s$ can be assumed to be perpendicular to ϕ.

Thus approximately, $\angle$ Ocd $\approx \beta$ and $\angle$ ecd $\approx \Delta$

$$\therefore \qquad cd = I_p \cos\beta = ch + hd = \frac{I_s}{n}\cos\Delta + I_c \qquad \ldots (4)$$

$$\text{and} \qquad I_p \sin\beta = I_m + \frac{I_s}{n}\sin\Delta \qquad \ldots (5)$$

As θ is very very small, $\cos\theta \approx 1$

$$\therefore \qquad V_p \cos\theta = V_p \qquad \ldots (6)$$

Using in (3), all the results of (4), (5) and (6)

$$V_p = n\,V_s + n\,I_s(r_s\cos\Delta + x_s\sin\Delta) + r_p\left[\frac{I_s}{n}\cos\Delta + I_c\right] + x_p\left[I_m + \frac{I_s}{n}\sin\Delta\right]$$

$$= n\,V_s + I_s\cos\Delta\left(n\,r_s + \frac{r_p}{n}\right) + I_s\sin\Delta\left(n\,x_s + \frac{x_p}{n}\right) + I_c\,r_p + I_m\,x_p$$

$$\therefore \qquad V_p = n\,V_s + \frac{I_s}{n}\cos\Delta(n^2 r_s + r_p) + \frac{I_s}{n}\sin\Delta(n^2 x_s + x_p) + I_c\,r_p + I_m\,x_p \qquad \ldots (7)$$

Now $\qquad n^2 r_s + r_p = R_{1e}$ = equivalent resistance referred to primary

$\qquad n^2 x_s + x_p = X_{1e}$ = equivalent reactance referred to primary

$$\therefore \qquad V_p = n\,V_s + \frac{I_s}{n}[R_{1e}\cos\Delta + X_{1e}\sin\Delta] + I_c\,r_p + I_m\,x_p \qquad \ldots (8)$$

Thus the actual ratio is,

$$R = \frac{V_p}{V_s} = n + \frac{\frac{I_s}{n}[R_{1e}\cos\Delta + X_{1e}\sin\Delta] + I_c\, r_p + I_m\, x_p}{V_s} \quad \text{... (9)}$$

The result also can be derived interms of parameters referred to secondary. The equation of V_p can be written as,

$$V_p = n\,V_s + \frac{n^2}{n} I_s \cos\Delta\left(r_s + \frac{r_p}{n^2}\right) + \frac{n^2}{n} I_s \sin\Delta\left(x_s + \frac{x_p}{n^2}\right) + I_c\, r_p + I_m\, x_p$$

But $r_s + \frac{r_p}{n^2} = R_{2e}$ = equivalent resistance referred to secondary

$x_s + \frac{x_p}{n^2} = X_{2e}$ = equivalent reactance referred to secondary

$$\therefore \quad V_p = n\,V_s + n\,I_s[R_{2e}\cos\Delta + X_{2e}\sin\Delta] + I_c\, r_p + I_m\, x_p \quad \text{... (10)}$$

$$\therefore \quad \boxed{R = \frac{V_p}{V_s} = n + \frac{n\, I_s [R_{2e} \cos\Delta + X_{2e} \sin\Delta] + I_c\, r_p + I_m\, x_p}{V_s}} \quad \text{... (11)}$$

2.10.2 Derivation of Phase Angle θ

From the phasor diagram shown in the Fig. 2.11.

$$\tan\theta = \frac{ab}{Oa} = \frac{I_p\, x_p \cos\beta - I_p\, r_p \sin\beta + n\, I_s\, x_s \cos\Delta - n\, I_s\, r_s \sin\Delta}{n\, V_s + n\, I_s\, r_s \cos\Delta + n\, I_s\, x_s \sin\Delta + I_p\, r_p \cos\beta + I_p\, x_p \sin\beta}$$

In the expression of Oa, the terms other than nV_s are very small and can be neglected.

Similarly as θ is very small, $\tan\theta \approx \theta$.

$$\therefore \quad \theta = \frac{I_p\, x_p \cos\beta - I_p\, r_p \sin\beta + n\, I_s\, x_s \cos\Delta - n\, I_s\, r_s \sin\Delta}{n\, V_s}$$

$$= \frac{x_p \left[\frac{I_s}{n} \cos\Delta + I_c\right] - r_p \left[I_m + \frac{I_s}{n} \sin\Delta\right] + n\, I_s\, x_s \cos\Delta - n\, I_s\, r_s \sin\Delta}{n\, V_s}$$

$$= \frac{I_s \cos\Delta \left(\frac{x_p}{n} + n\, x_s\right) - I_s \sin\Delta \left(\frac{r_p}{n} + n\, r_s\right) + I_c\, x_p - I_m\, r_p}{n\, V_s}$$

$$= \frac{\frac{I_s \cos\Delta}{n}(x_p + n^2 x_s) - \frac{I_s \sin\Delta}{n}(r_p + n^2 r_s) + I_c x_p - I_m r_p}{n V_s}$$

Now $r_p + n^2 r_s = R_{1e}$ and $x_p + n^2 x_s = X_{1e}$

$$\therefore \quad \theta = \frac{\frac{I_s}{n} \cos\Delta\, X_{1e} - \frac{I_s}{n} \sin\Delta\, R_{1e} + I_c x_p - I_m r_p}{n V_s}$$

$$\therefore \quad \theta = \frac{\frac{I_s}{n}(X_{1e} \cos\Delta - R_{1e} \sin\Delta) + I_c x_p - I_m r_p}{n V_s} \text{ radians} \qquad \text{... (12)}$$

Interms of quantities referred to secondary,

$$R_{2e} = \frac{R_{1e}}{n^2} \quad \text{and} \quad X_{2e} = \frac{X_{1e}}{n^2}$$

$$\therefore \quad \theta = \frac{n I_s (X_{2e} \cos\Delta - R_{2e} \sin\Delta) + I_c x_p - I_m r_p}{n V_s}$$

$$\therefore \quad \boxed{\theta = \frac{I_s}{V_s}(X_{2e} \cos\Delta - R_{2e} \sin\Delta) + \frac{I_c x_p - I_m r_p}{n V_s} \text{ radians}} \qquad \text{... (13)}$$

It can be noted that the phase angle θ is treated **positive** when V_s reversed i.e. **n V_s leads the primary winding voltage V_p**. The θ is treated **negative when nV_s lags the primary winding voltage V_p.**

Once R and θ are obtained then the errors in potential transformers are,

$$\boxed{\%\text{ ratio error } = \frac{K_n - R}{R} \times 100}$$

and $\boxed{\text{Phase angle error } = \theta \text{ radians}}$

Errors in PT

Once R and teta are obtained then the errors in potential transformer are

The ratio error is defined as,

$$\% \text{ Ratio error} = \frac{\text{nominal ratio} - \text{actual ratio}}{\text{actual ratio}} \times 100$$

$$\boxed{\% \text{ Ratio error} = \frac{K_n - R}{R} \times 100}$$

Phase angle Error =

The phase angle error is given by,

$$\boxed{\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{n\, I_s}\right] \text{ degrees}}$$

Reduction of errors in PT

The ratio and phase angle errors can be minimized by following methods:

- Reducing the core loss and magnetizing components of I0:

The equation of ratio and phase angle errors depends on the core loss and magnetizing components of no load current I0 and the following precautions are taken to reduce Ic and Im

1. Choosing low reluctance Core
2. Using materials of high permeability
3. Providing smaller magnetic paths to the flux
4. Keeping flux density in the core to low value
5. Using large cross section of the core
6. Taking suitable precaution while designing the assembly and interleaving the core

- Reduction of resistance and leakage reactance

1. The equation of ratio and phase angle errors depends on the voltage drop which are in turn depends on the values resistance and leakage reactance.
2. Winding resistance can be reduced by increasing cross section of conductors and decreasing the length of mean turns
3. Leakage reactance can be reduced by keeping primary and secondary winding close to each other . Similarly keeping flux density as high as practicable, the number of turns required are less and hence leakage reactance get reduced.

- Providing turns compensation :

For potential transformer

$$R = \frac{n + \frac{I_s}{n}\left[R_p \cos\Delta + X_p \sin\Delta\right] + I_c r_p + I_m X_p}{V_s}$$

At No load, Secondary current $I_s = 0$ hence

$$R = n + \frac{I_c r_p + I_m X_p}{V_s}$$

Thus on NO load , Actual ratio exceed by $\frac{I_c r_p + I_m X_p}{V_s}$

Remedy for this is to reduce the primary turns or increasing the secondary turns.
At one particular load, Actual ratio can be made equal to nominal ratio. This reduces the ratio error this is called turns compensation however turns compensation does not affect the phase angle

Characteristics of PT

Effect of power factor of secondary circuit:

1. If the pf of secondary circuit depends on the pf of the secondary burden is reduced and is Δ increased. This makes Ip to shift towards Io.
2. This Vp and Vs come closer with Ep and ES respectively. Thus Vp become more compared to Ep. but as vp is constant as supply voltage, the result is the reduction in Ep.
3. Similarly Vs reduces compared to Es . Hence the transformation ratio increases and pf decreases
4. from the phasor diagram Vs is advanced in phase and Vp is reduced in phase due to which phase angle is negative when secondary reversed voltage nvs lags the primary voltage Vp and phase angle is reduced with decrease in power factor.

Effect of change in burden on secondary:

1. If we increase the secondary burden, secondary current increases and hence the primary current increases both primary and secondary voltage drops increases (load,Is,Ip, Is(rs+jxs) and Ip(rp+jxp) increases.
2. For constant Vp (supply voltage) , Vs decreases and hence transformation ratio increases, which inturn Ratio Error increases. Due to increased voltage drop, Vp advances and Vs retards in phase , the phase angle between Vp and Vs increases.

Effect of change in frequency :

1. At constant voltage, if the frequency is increased, the flux gets reduced. Hence Im and IC are decreased, hence Voltage ratio decreases and errors reduces
2. Increase in frequency increases the leakage reactance increasing voltage drops this increase the ratio and ratio errors Thus these two effects are opposite to each other and the resultant effects depends on value of Io and the leakage reactance while phase angle increase due to increase in leakage reactance as well as decreases in Io.

Effect of primary voltage:

1. Vp is practically constant and there is a significant changes in it and hence there is no significant changes in error

Example 2.9 : *A potential transformer has a ratio 2000/100 V and has following parameters :*

Primary resistance = 105 Ω, *Secondary resistance = 0.7 Ω*

Primary reactance = 75.2 Ω, *Secondary reactance = 0.087 Ω*

No load current is 0.03 A at 0.36 p.f. lagging. Find

i) Phase angle error on no load

ii) Phase angle error on a load of 5 A at 0.92 lag p.f.

iii) Burden in VA at unity p.f. to have zero phase angle.

Solution : $r_p = 105\ \Omega,\ r_s = 0.7\ \Omega,\ x_p = 75.2\ \Omega,\ x_s = 0.087\ \Omega$

$$n = \frac{E_p}{E_s} = \frac{2000}{100} = 20 \quad \text{(for P.T.)}$$

$I_0 = 0.03$ A, $\cos\phi_0 = 0.36$, $\sin\phi_0 = 0.9329$

$$\therefore \quad I_c = I_0 \cos\phi_0 = 0.03 \times 0.36 = 0.0108 \text{ A}$$

$$I_m = I_0 \sin\phi_0 = 0.03 \times 0.9329 = 0.02798 \text{ A}$$

i) On no load, $I_s = 0$

$$\therefore \quad \theta = \frac{I_c x_p - I_m r_p}{n V_s} = \frac{0.0108 \times 75.2 - 0.02798 \times 105}{20 \times 100}$$

$$= -1.062 \times 10^{-3} \text{ radians} = -0.0608° = \mathbf{-3.65'}$$

ii) $I_s = 5$ A, $\cos\Delta = 0.92$, $\sin\Delta = 0.3919$

$$\theta = \frac{\frac{I_s}{n}[X_{1e}\cos\Delta - R_{1e}\sin\Delta] + I_c x_p - I_m r_p}{n V_s} \text{ radians}$$

$$X_{1e} = x_p + n^2 x_s = 75.2 + (20)^2 \times 0.087 = 110\ \Omega$$

$$R_{1e} = r_p + n^2 r_s = 105 + (20)^2 \times 0.7 = 385\ \Omega$$

$$\therefore \quad \theta = \frac{\frac{5}{20}[110 \times 0.92 - 385 \times 0.3919] + 0.0108 \times 75.2 - 0.02798 \times 105}{20 \times 100}$$

$$= -7.273 \times 10^{-3} \text{ radians} = -0.4167° = \mathbf{-25'}$$

iii) At unity p.f., $\cos\Delta = 1$, $\sin\Delta = 0$, $\theta = 0$ required.

$$\therefore \quad 0 = \frac{\frac{I_s}{20}[110 - 0] + 0.0108 \times 75.2 - 0.02798 \times 105}{20 \times 100}$$

$$\therefore \quad I_s = 0.3864 \text{ A}$$

$\therefore$ Burden in $V_A = V_s I_s = 100 \times 0.3864 = \mathbf{38.64\ VA}$

Example 2.12 : *A single phase potential transformer has a turns ratio of 3810/63. The nominal secondary voltage is 63 V and the total equivalent resistance and reactance referred to the secondary side are 2 Ω and 1 Ω respectively. Calculate tl and phase angle errors when the transformer is supplying a burden of 100 + j 20*

Solution : $R_{2e} = 2\ \Omega, \quad X_{2e} = 1\ \Omega,\ V_s = 63\ V$

$$n = \frac{3810}{63} = 60.4761$$

Neglecting no load component of current,

$$R = n + \frac{nI_s[R_{2e}\cos\Delta + X_{2e}\sin\Delta]}{V_s}$$

$$\text{Burden} = r_e + jx_e = 100 + j\,200\ \Omega$$

$$\therefore \quad \Delta = \tan^{-1}\frac{x_e}{r_e} = 63.434948^\circ$$

$$\therefore \quad R = 60.4761 + \frac{60.4761\,[2\times\cos\Delta + \sin\Delta]}{\frac{V_s}{I_s}}$$

$$\text{Now} \quad \frac{V_s}{I_s} = Z_s = \sqrt{100^2 + 200^2} = 223.6067\ \Omega$$

$$\therefore \quad R = 60.9599 \text{ and } K_n = \text{Nominal ratio} = n = 60.4761$$

$$\therefore \quad \%\text{ ratio error} = \frac{K_n - R}{R}\times 100 = -0.799\ \% \approx -0.8\ \%$$

$$\theta = \frac{I_s}{V_s}[X_{2e}\cos\Delta - R_{2e}\sin\Delta] \text{ in radians}$$

$$= \frac{1}{223.6067}[\cos 63.43 - 2\sin 63.43]$$

$$= -5.9\times 10^{-3}\text{ rad} = \frac{-5.9\times10^{-3}\times 180^\circ}{\pi}\text{ degrees}$$

$$= -0.338^\circ \quad \text{... Phase angle error}$$

Example 2.6 : *A potential transformer has a ratio 1000/100 V and has following parameters :*

Primary resistance = 96 Ω, Secondary resistance = 0.88 Ω

Primary reactance = 67.2 Ω, Total equivalent reactance = 115 Ω.

No load current is 0.03 A at 0.4 power factor lagging.

Calculate, i) Phase angle error at no load.

ii) Burden in VA at unity p.f. at which the phase angle will be zero.

Solution : $r_p = 96\ \Omega,\ r_s = 0.88\ \Omega,\ x_p = 67.2\ \Omega,\ X_{1e} = 115\ \Omega.$

Now $\quad n = \dfrac{E_p}{E_s} = \dfrac{1000}{100} = 10$

i) $$\theta = \frac{\frac{I_s}{n}(X_{1e}\cos\Delta - R_{1e}\sin\Delta) + I_c\,x_p - I_m\,r_p}{n\,V_s}$$

On no load, $I_s = 0$

$$\therefore\quad \theta = \frac{I_c\,x_p - I_m\,r_p}{n\,V_s}$$

$$\cos\phi_0 = 0.4,\quad I_0 = 0.03\ \text{A}$$

$$I_c = I_0\cos\phi_0 = 0.012\ \text{A}$$

$$I_m = I_0\sin\phi_0 = 0.02749\ \text{A}$$

$$\therefore\quad \theta = \frac{0.012\times 67.2 - 0.02749\times 96}{10\times 100}\ \text{rad}$$

$$= -1.8326\times 10^{-3}\ \text{radians} = -0.105^\circ = -\mathbf{6.3'}$$

ii) At unity p.f. $\cos\Delta = 1,\ \sin\Delta = 0$

$$\therefore\quad \theta = \frac{\frac{I_s}{n}X_{1e}\cos\Delta + I_c\,x_p - I_m\,r_p}{n\,V_s}$$

$$\therefore\quad 0 = \frac{\frac{I_s}{10}\times 115 + 0.012\times 67.2 - 0.02749\times 96}{10\times 100}$$

$$\therefore\quad I_s = 0.1593\ \text{A}$$

$$\therefore\quad \text{Load in } V_A = V_s\,I_s = 100\times 0.1593 = \mathbf{15.93\ VA}$$

Magnetic Measurements

Introduction:

- The operating Characteristics of electrical machines, Apparatus, equipment and instruments are greatly influenced by the properties of ferro magnetic materials used for this construction so magnetic measurements and characteristics of the magnetic and electrical material plays a vital role designing and manufacturing electrical equipment.

- The principal requirements in magnetic measurements are

- The measurement of the magnetic field strength in air (H)
- Determination of B-H curve and hysteresis loop for soft ferro magnetic materials.
- Determination of eddy current and hysteresis losses of soft ferro-magnetic materials subjected to alternating magnetic fields
- The testing of permanent magnets

- Magnetic Measurements have some inaccuracies due to which the measured values depart from true value. The inaccurate are due to following reasons:-

- The magnetic materials are not homogeneous
- There is no uniformity between different batches of test specimens even if such batches are of same composition .
- The actual conditions in the magnetic specimen under test are different from the condition that were assumed in calculations.

Types of Tests

Many methods of testing magnetic materials have been developed, with the aim of reducing inaccurate and improving precision . They are

Ballistic Test:

Generally employed for the determination of **BH curve and hysteresis loops of ferro –magnetic materials**

A **ballistic galvanometer** or flux meter is employed for the measurement of flux density, Ballistic method do not directly measure the value flux density in a magnetic materials corresponding to a particular value of the magnetizing force. But measures the change in flux by changes in magnetic force.

AC Testing : These tests may be carried at power, Audio or radio frequencies. They give information about eddy current and hysteresis losses

Steady State Tests: These are performed to obtain the steady value flux density existing in the air gap of the magnetic circuit.

A ballistic galvanometer is a sensitive instrument used to measure the quantity of charge passed through it, typically for short-duration electrical events.

Measurement of Flux Density / Ballistic Tests:

- The measurement of flux density inside a ring specimen can be done by winding a search coil over the specimen, Search coil is known as B coil. This search coil is then connected to a ballistic galvanometer/ Flux meter.
- Let us consider that we have to measure the flux density in a ring specimen
- The Ring Specimen is wound with a magnetizing winding which carries a current I and A search coil of convenient number of turns is wound on the specimen and connected through a resistance and calibrating coil, to a ballistic galvanometer.
- Firstly current I is flowing through magnetizing winding , flux linked with B coil and then by reversing switch change the direction of current flowing through the magnetizing winding. Therefore flux linkage of search coil changes and induce an emf in to it . Whatever the emf induced in B coil or search coil sends a current through the ballistic galvanometer which shows the deflection.
- Whatever flux linked with the circuit changes , an emf is induced in it called faraday's laws.
- A ballistic galvanometer is a type of sensitive galvanometer; commonly a mirror galvanometer.

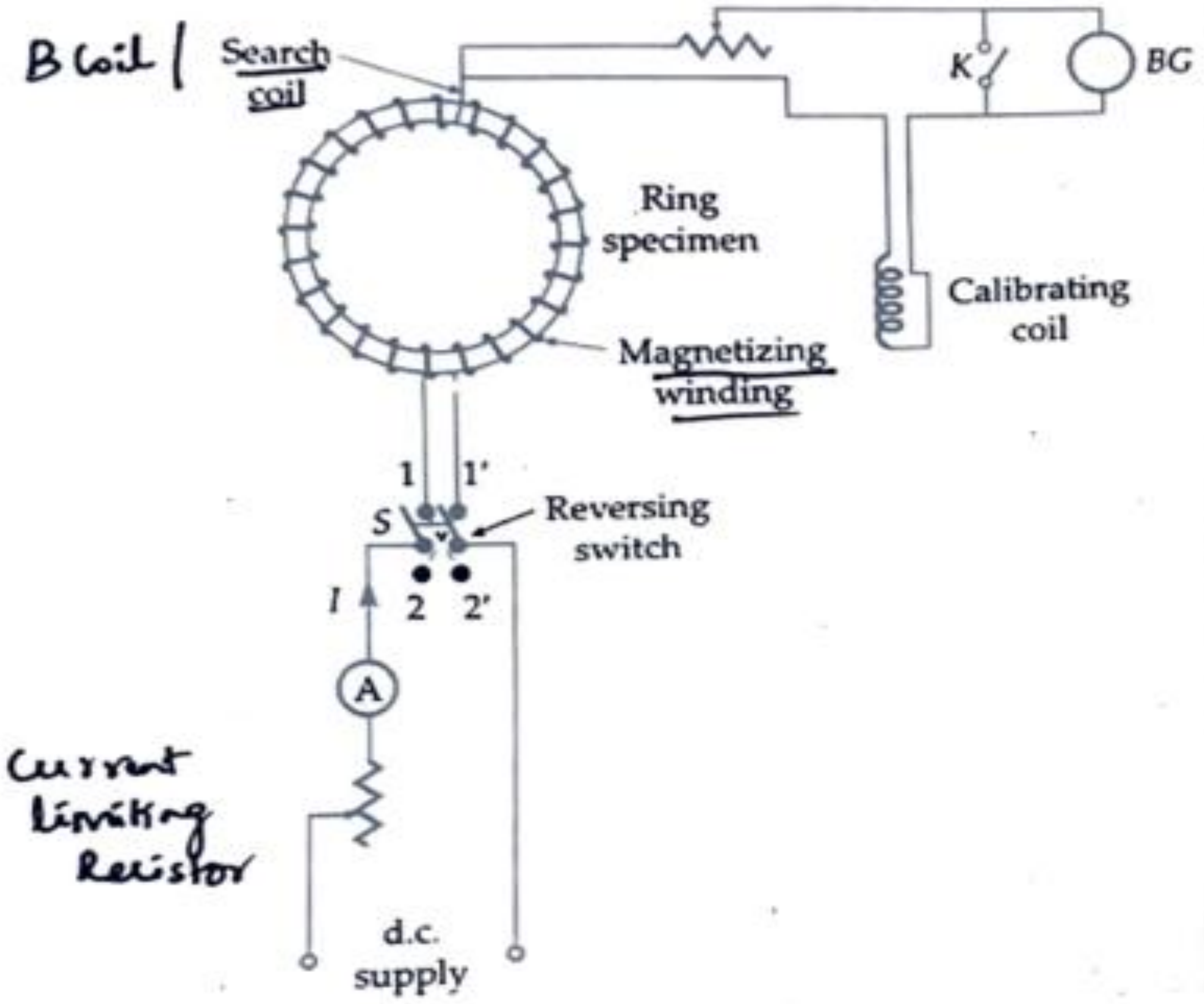


fig Measurement of flux density in Ring specimens

Let ϕ = flux ~~linkage~~ linking the search coil

R = Resistance of the ballistic galvanometer circuit

N = Number of turns in the search coil

t = time taken to reverse the flux

$I \propto \phi \propto e$

∴ → Average Emf induced in the search coil

WKT $e = \frac{N d\phi}{dt}$

$\boxed{e = 2N\frac{\phi}{t}}$ ← Avg emf induced in the search coil, due to reversal of current direction

→ Average current through the ballistic galvanometer is

$V = IR$

$i = \frac{V}{R} = \frac{e}{R}$

$\boxed{i = 2N\frac{\phi}{Rt}}$

→ charge $Q = i * t$

$Q = 2N\frac{\phi}{R\cancel{t}} * \cancel{t}$

$\boxed{Q = 2N\frac{\phi}{R}}$

$\frac{d\phi}{dt}$ = change in flux

$d\phi = \phi_2 - \phi_1$ (or) $\phi_1 - \phi_2$

$\Rightarrow$: $\phi_1 - (-\phi_1)$

Let $\boxed{\phi_2 = -\phi_1}$

← Reversing position Magnitude fixed direction changes

$\boxed{d\phi = 2\phi}$

$\boxed{dt = t}$

(a) Swing of the Galvanometer

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→ Let θ_1 be the first throw of the galvanometer & K_q be the constant of the galvanometer expressed in coulomb/unit deflection.

→ Charge should be expressed in coulomb by multiplying θ_1 deflection & K_q constant.

→ charge indicated by ballistic galvanometer

$$Q = \theta_1 K_q$$

$$= \frac{2N\phi}{R} = \theta_1 K_q$$

$$= \text{flux} \quad \boxed{\phi = \frac{\theta_1 K_q R}{2N}}$$

→ ~~In a uniform field~~ flux density is defined as $B = \frac{\text{flux}}{\text{Area}}$

Area = Ring specimen Area = A_s

$$\boxed{B = \frac{\phi}{A_s} = \frac{\theta_1 K_q R}{2N A_s}}$$

Observed value of flux (or) flux linking with search coil = True value of flux in the specimen + flux in the airgap between specimen & search coil

$$\rightarrow \quad B' A_s = B A_s + \mu_0 H [A_c - A_s] \longrightarrow (1)$$

$\div$ Eqn (1) by A_s

$$\rightarrow \quad \frac{B' A_s}{A_s} = \frac{B A_s}{A_s} + \mu_0 H \left[\frac{A_c}{A_s} - \frac{A_s}{A_s}\right]$$

$$\rightarrow \quad B' = B + \mu_0 H \left[\frac{A_c}{A_s} - 1\right]$$

$$\rightarrow \quad \boxed{B = B' - \mu_0 H \left[\frac{A_c}{A_s} - 1\right]} \longrightarrow \text{True value of flux density}$$

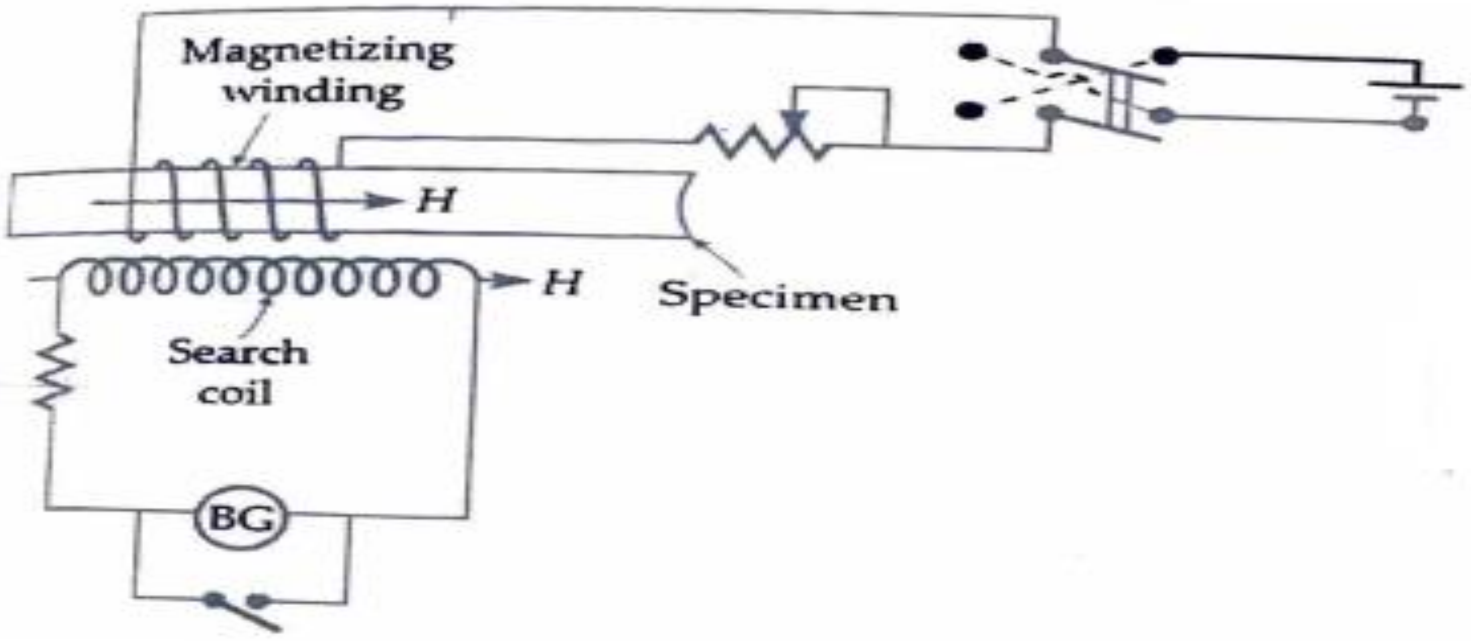
Where B' = observed (or) apparent value of density Wb/m^2

B = True value of flux density in specimen Wb/m^2

A_s = Area of cross-section of specimen ; m^2

A_c = Area of cross-section of coil ; m^2

Magnetising Force (H)



Determination of magnetising force *H*.

Magnetising Force =H
= B0/M0 A/M

Magnetizing Force (H)

- The Magnetomotive force per unit length is called the magnetizing force (H) = mmf/l = NI/l At/m
- To determine the magnetizing force in the airgap, can be use ballistic galvanometer and a search coil positioned
 directly in the air gap.
- To Determine the value of magnetizing force (H) inside a specimen requires either from calculations based on data obtained from the magnetizing coil and the specimen or from measurements made outside the specimen
- To determine the magnetizing force within the specimen, when testing the ferromagnetic materials by measuring the magnetizing force at its surface. This Is possible because of tangential components of magnetic field have equal magnitudes on both sides of the interface.
- The search coil positioned in fig measures the value of flux densities (B0)in air and is called H coil.
- However when testing iron, there is no trouble in getting good sensitivity by using H coil. This is challenging for 2 reasons

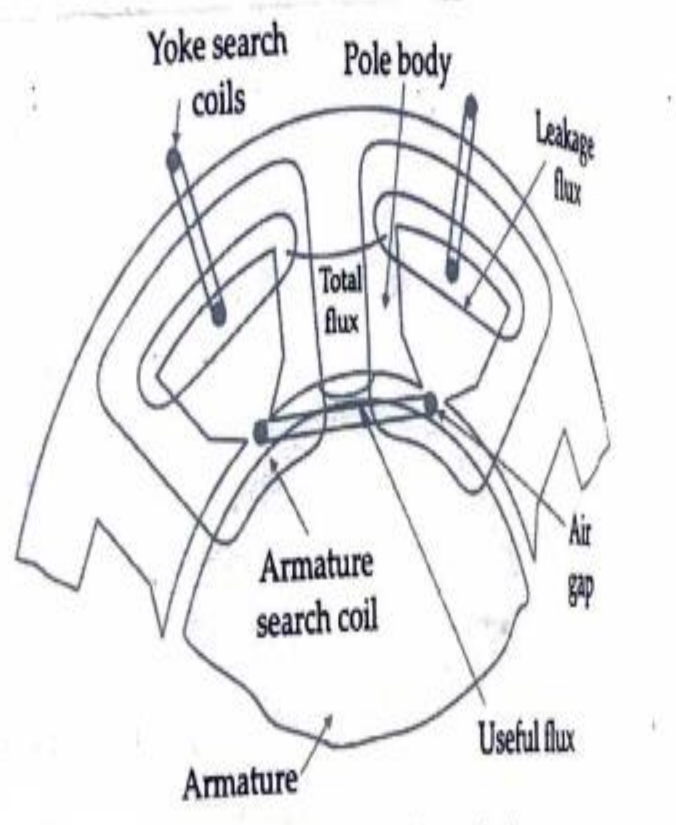
1. Cross sectional Area of magnetizing winding H coil is much smaller than the coil surrounding the specimen [Search coil / B coil] and then H is not constant across the section.

This cause difficulties in achieving adequate sensitivity when measuring flux densities in iron.

2. The permeability iron is very large as compared to that of air and flux densities in search coil is very small compared to that in specimen. The value of flux densities in H coil is measured in a similar way for the determination of B coil in the specimen

Measurement of leakage factor with Flux meter:

- Leakage factor is defined as total flux / useful flux in Weber's
- Useful flux = Flux in the armature (flux crossing the air gap) in wb
- Total flux=Flux in the pole bodies =useful flux + leakage flux existing in the pole body at its root in Weber's
- The Flux measurements are done by the flux meter. A ballistic galvanometer cannot be used here as the field winding of electric machine are highly inductive and the flux changes very slowly when the voltage is impressed across the field winding.
- Yoke carries half of the total flux , therefore it is possible to measure the total flux per pole by using two search coil on the yoke and connecting them in series across the flux meter.
- The armature is kept stationary and the search coil is connected with the flux meter and the useful flux is measured.
- The leakage factor can be calculated from two reading of the flux meter
- Search coil of one turn are used so that the flux meter reading gives the flux directly.
- In Large machines, the value of the flux is quite large and therefore it becomes necessary to use a shunt along with the flux meter in order that its range may be increased.



Measurement of leakage factor.

Numerical on magnetic measurements

(1) An Iron ring of $350\ mm^2$ cross-sectional area with a mean length of 1m is wound with a magnetising winding of 100 turns. A secondary coil with 200 turns of wire is connected to a ballistic galvanometer having a constant of $1\ \mu C$ per scale division. The total resistance of the secondary circuit being $2000\ \Omega$. On reversing a current of 10A in the magnetising winding, the galvanometer shows a deflection of 100 scale division. Calculate the flux density in the specimen and the value of permeability at this flux density.

Flux density in the Specimen = ?

permeability of Specimen = ?

given, Mean length $l = 1\,m$; Area = $350\,mm^2$

→ Magnetising Winding $N_1 = 100$ turns

→ Secondary coil (or) Search coil $N_2 = 200$ turns

→ Constant $K_q = 1\,\mu C$ / Scale division

→ $R = 2000\,\Omega$

→ $I_1 = 10A$ [Current in Magnetising Winding]

→ $\theta_1 = 100$ Scale division

⇒ Suppose ϕ is the flux through the ring.

→ flux linkage of Secondary (or) Search coil

$$\boxed{\psi = N_2 \phi = 200\phi}$$

→ change in flux linkage of search coil $(\Delta\psi)$, due to reversal of current is given by

WKT $d\phi = 2\phi$

$$\boxed{\Delta\psi = 2\psi}$$

$$\boxed{\Delta\psi = 2 * 200\phi = 400\phi}$$

→ Average emf induced in the Search coil

$$\boxed{e = \frac{\Delta\psi}{\Delta t} = \frac{400\phi}{\Delta t}}$$

Where Δt - time of Reversal

∴ Current through Search coil

$$\boxed{i = \frac{e}{R} = \frac{400\phi}{\Delta t * R}}$$

→ Charge through the search coil circuit

$$Q = i * t = i * \Delta t = \frac{400\phi}{\Delta t * R} * \Delta t$$

$$Q = \frac{400\phi}{2000}$$

$$\boxed{Q = 0.2\phi} \rightarrow (1)$$

→ But charge through the galvanometer is given by

$$\boxed{Q = K_q \theta_1 = 1 * 100 = 100\,\mu C} \rightarrow (2)$$

where $K_q = 1\,\mu C$

→ Substitute (2) in (1)

$$100 * 10^{-6}\,C = 0.2\phi$$

$$\phi = \frac{100 * 10^{-6}}{0.2}$$

$$\boxed{\phi = 500 * 10^{-6}\,Wb}$$

→ ∴ flux density in the specimen

$$B = \frac{flux}{Area} = \frac{500 * 10^{-6}}{350 * 10^{-6}} = 1.429\,Wb/m^2$$

→ permeability of Specimen $\mu = \frac{B}{H} = \frac{1.429}{H} \rightarrow ?$

→ Magnetising force $H = \frac{N_1 I_1}{l}$

→ Total mmf of the coil $= N_1 I_1 = 100 * 10 = 1000\,A$

$$H = \frac{N_1 I_1}{l} = \frac{1000}{1} = 1000\,A/metre$$

$$\therefore \mu = \frac{1.429}{1000} = 1.429 * 10^{-3} \qquad \mu = \frac{B}{H}$$

→ Relative permeability of Specimen

$$\mu_r = \frac{\mu}{\mu_0} = \frac{1.429 * 10^{-3}}{4\pi * 10^{-7}} = 1137$$