Instrument Transformers

Books:

1) Electrical Measurements & Measuring Instruments
   (U.A. Bakshi, A.V. Bakshi, K.A. Bakshi) 1st Edition (2007)

2) Electrical & Electronic Measurements & Instrumentation
   (A.K. Sawhney)

Week # 09 (EE-223 I&M Spring, 22)

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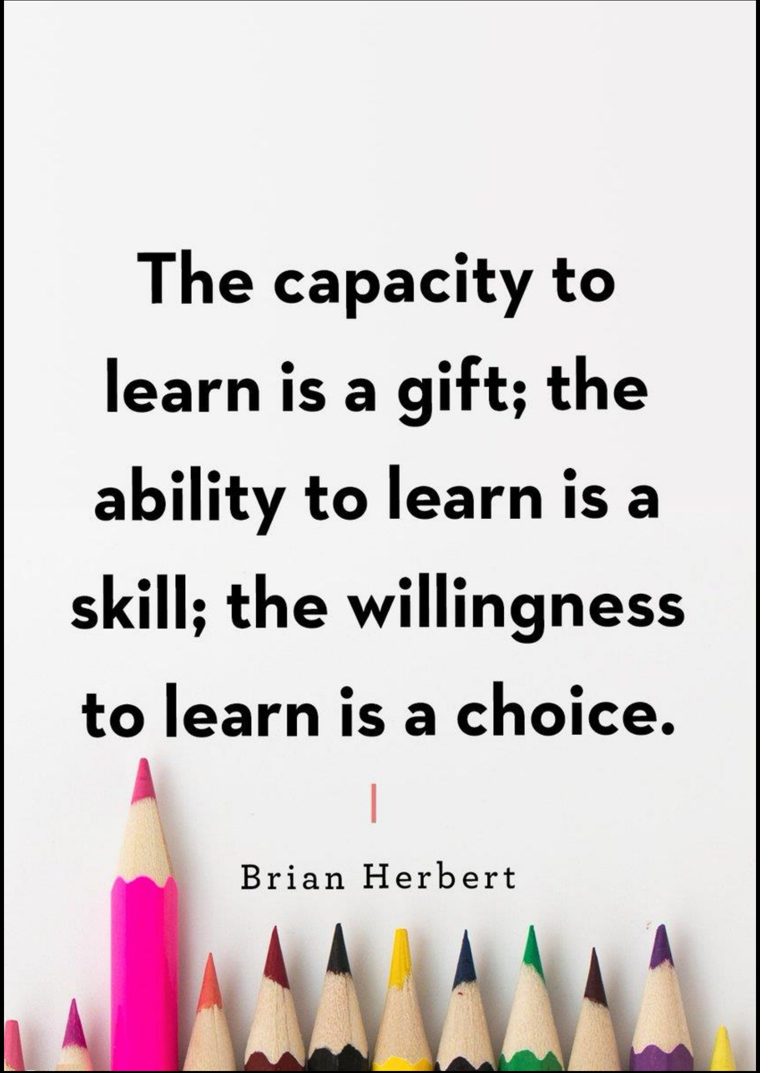

The capacity to learn is a gift; the ability to learn is a skill; the willingness to learn is a choice.
Brian Herbert

Introduction & Rationale

Possible approaches for measurement of **high voltage and currents (in kV and kA) for the power systems (e.g. high tension wires)**

1) Use shunts and multipliers with small scale measuring instruments (Galvanometer) and convert them for higher ranges

   Disadvantages:

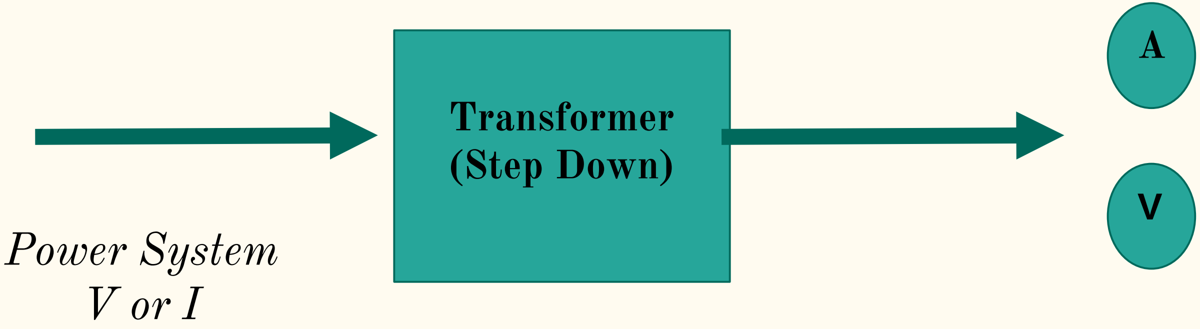
- Limited ranges
- Power consumption across multipliers
- No isolation between measuring and power circuit
- Insulation needed for high voltage levels
- **Direct measurement is therefore at times not even possible**

Introduction & Rationale

Possible approaches for measurement of **high voltages and currents in power systems**

2) Step down the voltages and currents at a lower level and then measure

Use **INSTRUMENT TRANSFORMERS**



Instrument Transformers

The transformers used in conjunction with the measuring instruments for measurement purpose are called “**instrument transformers**”.

These find wide application in power systems protection circuits also for operation of protective relays like over current, under voltage relays.

1. **Current Transformer (C.T)**: The instrument transformer used for measurement of current
2. **Voltage or Potential Transformer (P.T**): The instrument transformer used for measurement of voltage.

Instrument Transformers

Advantages:

- **Standard size** and **low power measuring instruments** (voltmeters and ammeters) can be used for measurement of high voltage and current in power systems as the CTs and PTs have standard ratios
- Provide **isolation** between measuring circuit and actual high-tension circuit
- Measuring instruments can be easily connected at switch-board or panels without any requirement of **high insulations**
- Ensure **safety** for the operating personnel
- Easily extend the range of measuring instruments

Transformer (Ratios)

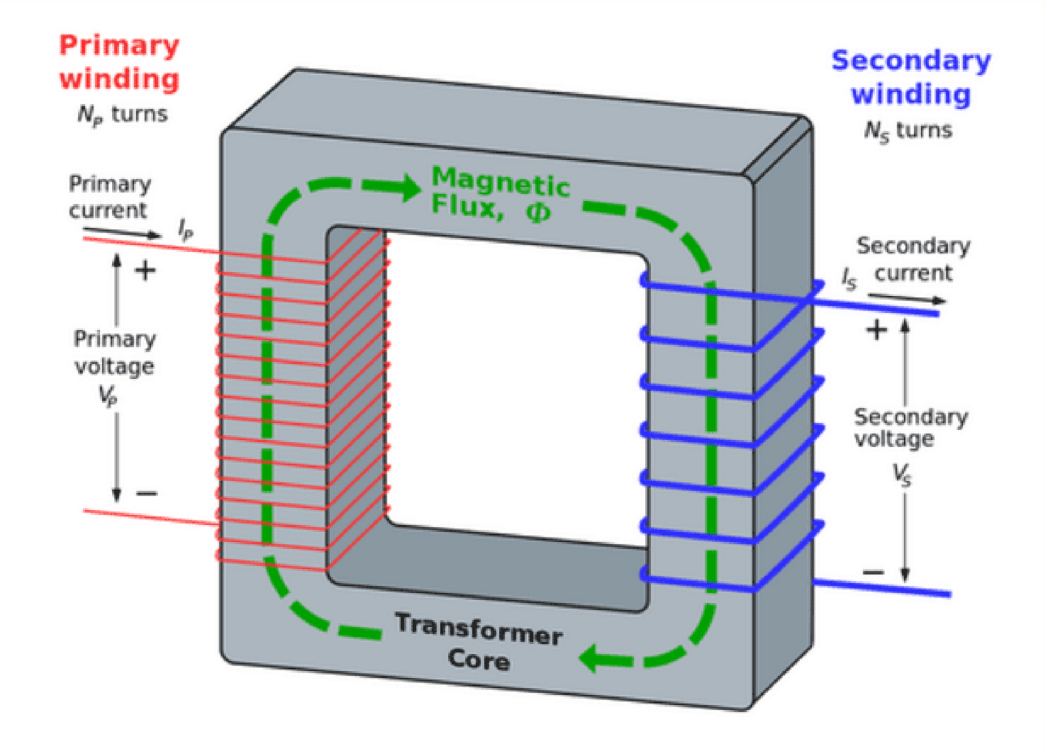
- Device consisting of Primary and Secondary windings that transforms voltage and current levels

$P_{\text{input}} = P_{\text{output}}$

$IpVp = IsVs$

Turns Ratio: Np/Ns

$Np/Ns = Vp/Vs = Is/Ip$



Current Transformer (C.T)

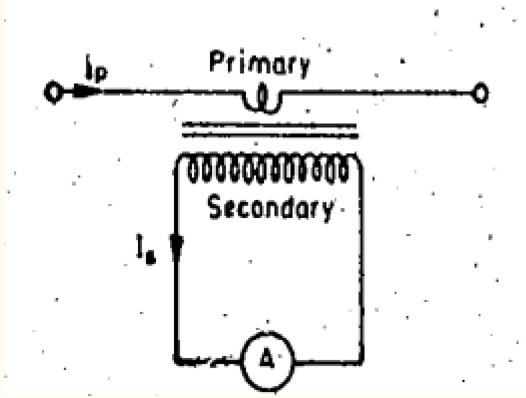
- The instrument transformer used for the measurement of current with an ammeter
- Connection: **In Series (**Primary current is the current to be measured)
- Construction: Np $<$Ns

The primary coil with high cross-sectional area

has a fewer no. of turns than secondary coil.

Therefore, $Is < Ip$.

$$\boldsymbol{Ip / Is = Ns / Np}$$



- It’s a voltage step-up (current step-down) transformer.
- Common CTs have secondary current rated at 1A, 5A
- NOTE: Primary current is not dependent on secondary load. It is always equal to the line current (to be measured) irrespective of secondary current

Current Transformer (C.T. Ratio)

For CTs, the **current ratio** is usually specified as Ip: Is e.g. 500: 5 shows a CT that transforms the primary to secondary current by a ratio 500 to 5.

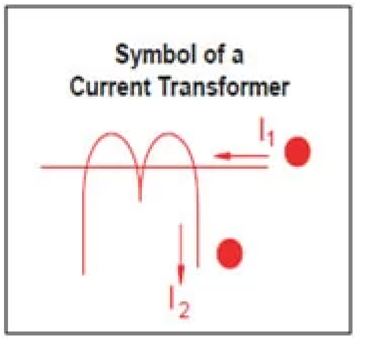
Knowing this current ratio and the meter reading at secondary, the line current can be estimated.

Example: A 250: 5 CT is used with an ammeter. If the ammeter reading is 2.7A, estimate the line current.

CT Ratio; $Ip/Is = 250/5 = Ns/Np$

For Is of 2.7A,

$$Ip = (Ns/Np) * Is = 135A \text{ (Line current required)}$$



Types of C.Ts (Construction-wise)

1) Wound-Type (Primary has a fewer no. of turns wound on a core).

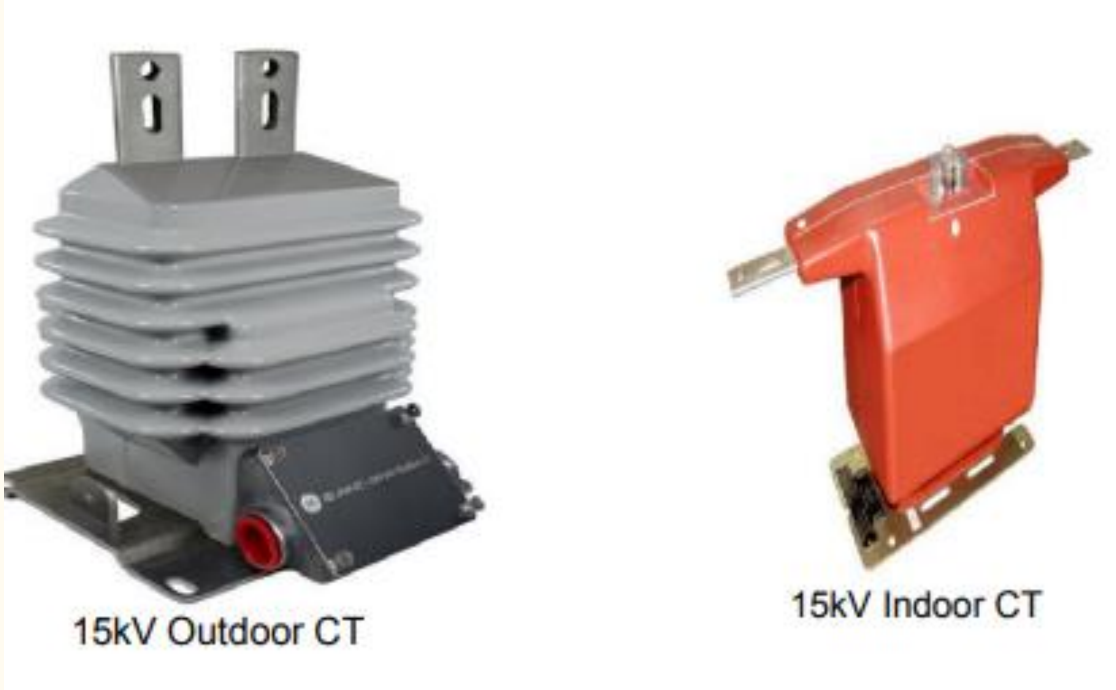
2) Window Type/ Ring /Donut-Type /Through Type (Have an opening where the conductor carrying the primary load is passed. The primary conductor constitutes the primary winding of the CT - one pass through the window is one turn on the primary).

   No need to break the circuit for series connection.

3) Bar Type (Primary is simply a bar - a fixed primary conductor mounted in the window which has standard terminal bar connections to attach cables.) **Np is 1.**

Types of C.Ts (Construction-wise)

Indoor and Outdoor CTs



Types of C.Ts according to Application

- Measuring C.T.

  The secondary of this C.T. is connected with an Ammeter

  Used for accurate current measurement

- Protection C.T.

  The secondary is connected with a relay (like over-current relay)

  Used in protection circuits for sending current information to the relay that controls a Circuit Breaker

Voltage or Potential Transformer (P.T.)

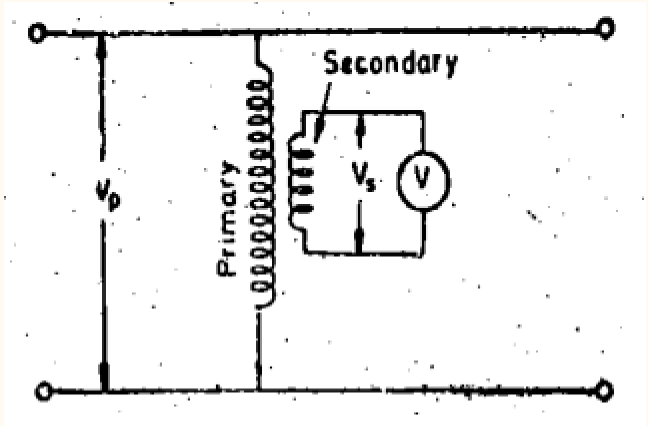
- The instrument transformer used for the measurement of voltage with a voltmeter
- Connection: **In Parallel (to the high tension line)**
- Construction: Np $>$ Ns

  The primary coil has higher no. of turns than

  the secondary coil.

  Therefore, $Vs < Vp$.

  $\boldsymbol{Vp/Vs = Np/\ Ns}$

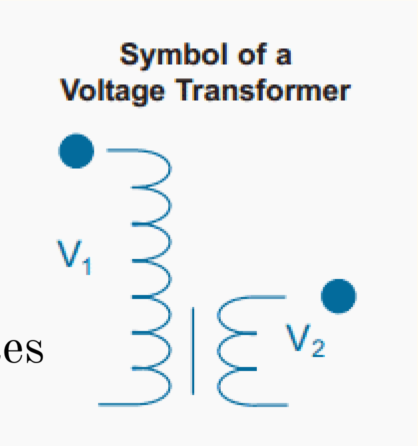


- It's a voltage step-down transformer with accurate ratio.
- Common PTs have secondary voltage ratings ranging from 100-120V.

Voltage or Potential Transformer (P.T. Ratio)

- It works like a normal power transformer, the ratio is specified as Vp:Vs e.g. 10kV/100V which means the P.T. transforms a primary voltage of 10kV to 100V at the secondary side.
- Knowing the voltage ratio of P.T and the voltmeter's

(connected at the secondary) reading, one can estimate the line voltage.



Example: A 11000:110 P.T. is used with a voltmeter that indicates 87.5V. Estimate the value of line voltage.

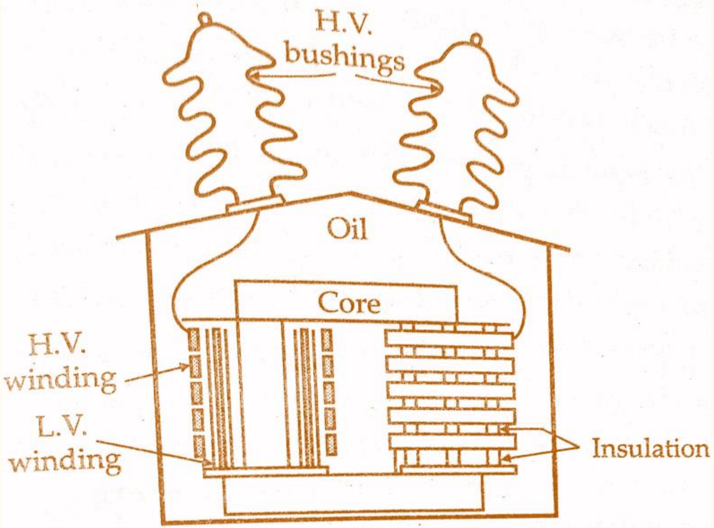
For the given P.T; Vp/Vs=Np/Ns = 11000/110

Therefore for Vs of 87.5V; Vp = (11000/110)*87.5 = 8750V

(Actual line voltage being measured).

Voltage or Potential Transformer

- Construction wise they are similar to power transformers.



Ratios of Instrument Transformers

- ✓ **Actual Ratio or Transformation Ratio [R]:** *Ratio of the magnitude of actual primary phasor to the corresponding magnitude of actual secondary phasor*

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

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

Ratios of Instrument Transformers

- ✓ **Nominal Ratio [Kn]:** *Ratio of the rated primary quantity to the rated secondary quantity. (Given by manufacturer)*

$$Kn = \frac{Rated\ primary\ current}{Rated\ secondary\ current} = \frac{Ip\_rated}{Is\_rated} \quad For\ C.T.$$

$$Kn = \frac{Rated\ primary\ voltage}{Rated\ secondary\ voltage} = \frac{Vp\_rated}{Vs\_rated} \quad For\ P.T.$$

Ratios of Instrument Transformers

- ✓ **Turns Ratio [n]:**

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

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

- ✓ **Ratio Correction Factor [RCF]:** *Ratio of transformation ratio (actual ratio) to the nominal ratio*

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

$$R = RCF * Kn$$

Burden of Instrument Transformers

- The **permissible load across the secondary winding** expressed in volt-amperes at the rated secondary winding voltage or current, such that **errors do not exceed the limit**

- The secondary load effects secondary current, power factor and magnetizing and core loss components of current and therefore, affects error

- The term “burden” is used to distinguish it from actual load of power circuit.

- This burden includes impedance of the instruments / components connected at secondary side (e.g. voltmeter, ammeter, relays) and the wires connecting them.

Burden of Instrument Transformers

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

$$Burden = \frac{(V_{sec})^2}{Z_{sec}} = (I_{sec})^2 Z_{sec}$$

(If winding impedance is not considered)

$$Burden = \frac{(V_{sec})^2}{Z_{load}} = (I_{sec})^2 Z_{load}$$

Errors of Instrument Transformer

1) Ratio Error:

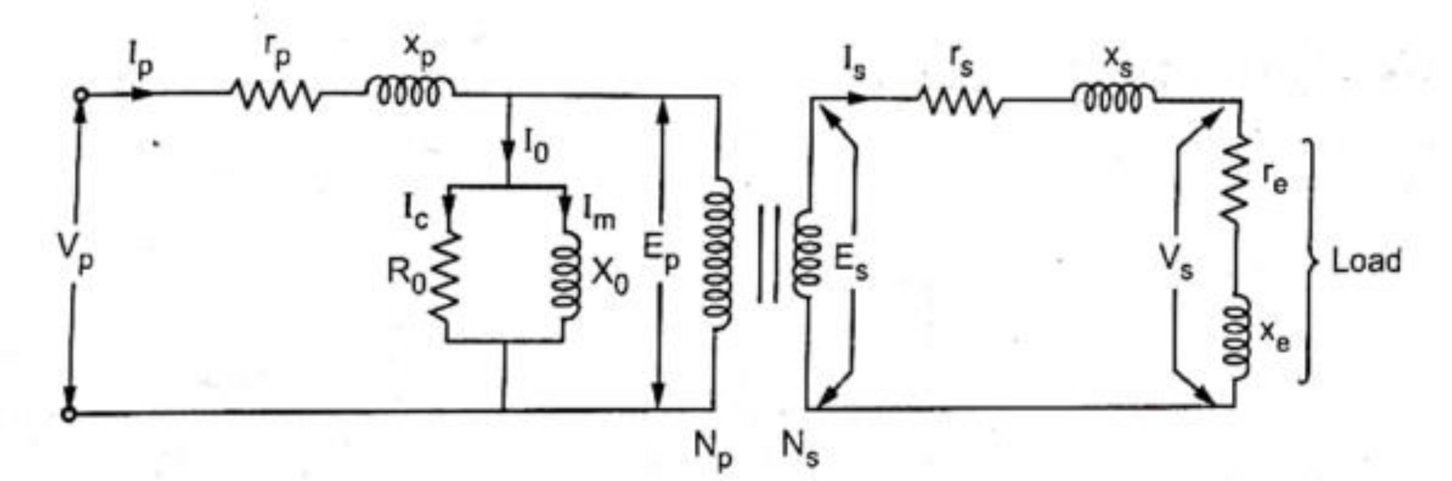
Practically, the ratio of primary to secondary current (and secondary to primary voltage) is not equal to the ratio of secondary to primary no. of turns.

The excitation current, load current, load power factor cause this deviation in the actual (transformation ratio) from the nominal ratio. The error introduced is called **ratio error**.

$$\%\, Ratio\ Error = \frac{Nominal\ ratio - Actual\ ratio}{Actual\ ratio} \times 100 = \frac{Kn - R}{R} \times 100$$

Errors of Instrument Transformer

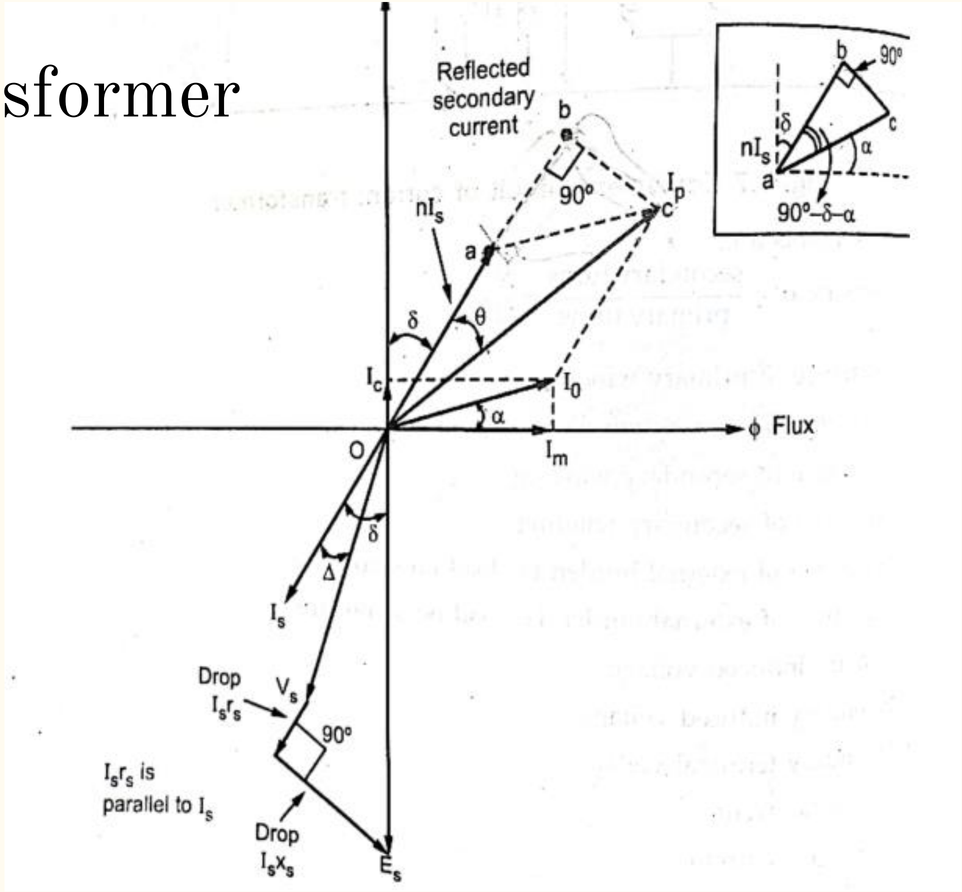
1) Ratio Error:



Equivalent Circuit of Transformer

Errors of Instrument Transformer

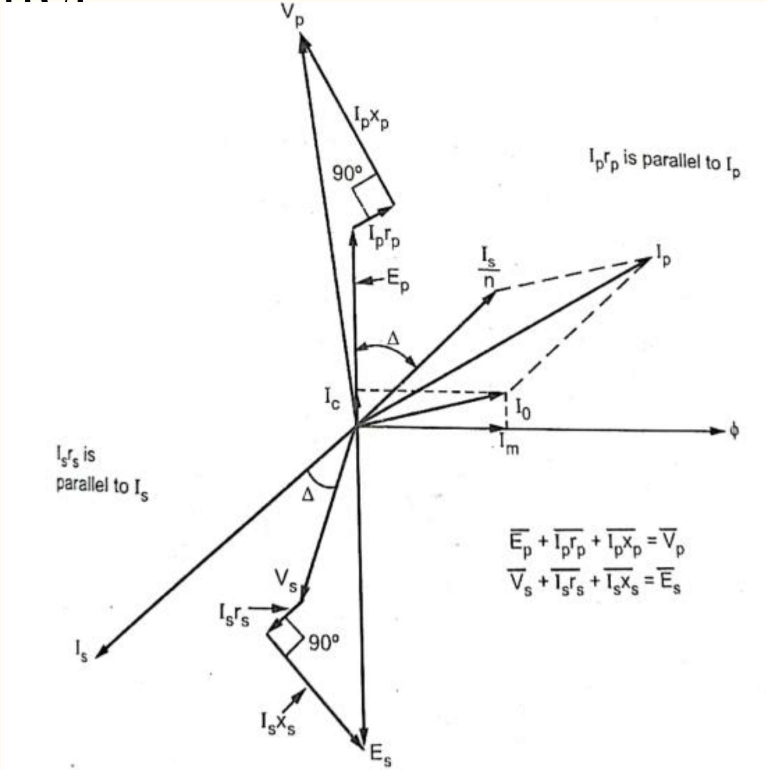
- n=turns ratio
- rp, xp = resistance and reactance of primary winding
- rs, xs,= resistance and reactance of secondary winding
- re, xe = resistance and reactance of secondary load (burden)
- Ep, Es= primary and secondary induced voltage
- Ip, Is= primary and secondary current
- Io= excitation current
- Ic = core loss component of Io (Ic=Io sin α)
- Im= magnetizing component of Io (Im= Io cos α)
- ϕ =transformer working flux
- δ = angle between Es and Is
- Θ = transformer angle
- Δ = phase angle of load or burden re+jxe => [arc tan (xe/re)]
- α = angle between Io and flux= 90 - (p.f. angle of excitation current or no load current)



Phasor Diagram of C.T.

Errors of Instrument Transformer

- n=turns ratio
- rp, xp = resistance and reactance of primary winding
- rs, xs,= resistance and reactance of secondary winding
- re, xe = resistance and reactance of secondary load (burden)
- Ep, Es= primary and secondary induced voltage
- Ip, Is= primary and secondary current
- Io= excitation current
- Ic = core loss component of Io (Ic=Io sin α)
- Im= magnetizing component of Io (Im= Io cos α)
- ϕ =transformer working flux
- Θ = transformer angle
- Δ = phase angle of load or burden re+jxe => [arc tan (xe/re)]
- Vp= primary applied voltage
- Vs= secondary terminal voltage



Phasor Diagram of P.T.

Errors of Instrument Transformer

1) Ratio Error:

Actual Ratio (R) For C.T.	Actual Ratio (R) For P.T.
Formula $$R = n + \frac{I_m \sin\delta + I_c \cos\delta}{I_s}$$ Approximate Relation $$R = n + \frac{nI_c}{I_p}$$	**In terms of parameters referred to primary side parameters** $$R = \frac{V_p}{V_s} = n + \frac{\frac{I_s}{n}[R_{1e}\cos\Delta + X_{1e}\sin\Delta] + I_c r_p + I_m x_p}{V_s}$$ *Referred to primary*: $R_{1e} = n^2 r_s + r_p \quad X_{1e} = n^2 x_s + x_p$ **In terms of parameters referred to secondary side parameters** $$R = \frac{V_p}{V_s} = n + \frac{nI_s[R_{2e}\cos\Delta + X_{2e}\sin\Delta] + I_c r_p + I_m x_p}{V_s}$$ *Referred to secondary:* $R_{2e} = r_s + \frac{r_p}{n^2} \quad X_{2e} = x_s + \frac{x_p}{n^2}$

$$\%\,Ratio\ Error = \frac{Nominal\ ratio - Actual\ ratio}{Actual\ ratio} \times 100 = \frac{Kn - R}{R} \times 100$$

Errors of Instrument Transformer

2) Phase Error:

In power measurements, it is considered that the secondary current is 180 degrees out of phase from primary current. Similarly, the secondary voltage is 180 degrees out of phase from the primary voltage. Practically it is not.

The angle by which the secondary current (or voltage), when reversed, differs in phase from the primary current (or voltage in case of P.T.) is called **phase angle** of the transformer.

Phase Angle Error = Phase Angle θ

It should be clear that while measuring voltage, ratio error is only important while for power measurements both ratio and phase angle errors are involved.

Errors of Instrument Transformer

2) Phase Error:

For C.T.	For P.T.
$\theta = \frac{180}{\pi}\left[\frac{I_m \cos\delta - I_c \sin\delta}{nI_s}\right]$ degrees $\theta = \left(\frac{180}{\pi}\right)\left(\frac{I_m}{I_p}\right)$ degrees	**In terms of parameters referred to primary side** $\theta = \frac{\frac{I_s}{n}(X_{1e}\cos\Delta - R_{1e}\sin\Delta) + I_c\, x_p - I_m\, r_p}{n\, V_s}$ radians **In terms of parameters referred to sec side** $\theta = \frac{I_s}{V_s}(X_{2e}\cos\Delta - R_{2e}\sin\Delta) + \frac{I_c x_p - I_m r_p}{nV_s}$ radians

Phase Angle Error = Phase Angle θ

Accuracy of Instrument Transformers

- There are several classes of accuracy for instrument transformers defined by the IEEE, CSA, IEC, and ANSI standards.
- IEEE C57.13 has recognized 0.3% as a reasonable error limit and has designated this as **“Accuracy Class 0.3.”.** 0.6 and 1.2 Classes have the permissible errors of (0.6%) and (1.2%), respectively.
- An **accuracy classification** for an instrument metering transformer includes the standard burden as well as the maximum percent error limits.
- A typical CT classification might be **0.3 B0.5** where the 0.3 is the percent allowable error and the B0.5 is the secondary burden in ohms impedance which may be connected to its secondary without causing a metering error greater than specified by its accuracy classification.

Reference: https://www.gegridsolutions.com/products/brochures/ititechinfo.pdf

Accuracy of Instrument Transformers

- Similarly, accuracy classes of P.T. are well defined.

Accuracy class	Permissible voltage ratio error (%)	Permissible phase angle error (min)	Application
0.1	± 0.1	± 5	Measurement
0.2	± 0.2	± 10	Measurement
0.5	± 0.5	± 20	Measurement
1.0	± 1.0	± 40	Measurement
3P	± 3.0	± 120	Protection
6P	± 6.0	± 240	Protection

Reference: https://engineeringnotesonline.com/potential-transformers/

Practice Problems

Example 3.3 **(U.A. Bakshi)**

The no-load current components of a 1000/5 CT are, magnetizing component (102 A) and core-loss component (38A). Calculate the approximate ratio error at full-load.

Solution : $I_m = 120$ A, $I_c = 38$ A

$$K_n = \text{nominal ratio} = \frac{1000}{5} = 200$$

At full load, $I_s = 5$ A

$$R = n + \frac{I_c}{I_s}$$

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

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

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

$$= -3.66\%$$

Practice Problems

Example 3.4 **(U.A. Bakshi)**

A CT with single turn primary and 400 turns secondary 90 A magnetizing current and 40A core loss current. Secondary circuit phase angle is 28 degrees. Calculate the actual primary current and ratio error when secondary carries 5A.

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

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

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

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

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

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

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

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

$$= -3.733\%$$

Practice Problems

Example 3.5 **(U.A. Bakshi)**

A CT rated at 2000/5 A has turns ratio of 1:399. The core loss component is 3A and magnetizing component is 8A, at full load. Find CT errors under full load condition if the secondary power factor is 0.8 leading.

$I_c = 3\text{ A},\quad I_m = 8\text{ A},\quad \cos\delta = 0.8 \text{ leading}$

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

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

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

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

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

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

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

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

$$= 0.2355^\circ = \mathbf{14.13'}$$

Practice Problems

Example 3.6 (U.A. Bakshi)

A 1000/100 V PT has following parameters: Primary resistance and reactance: 90 and 67.2 Ohms, Secondary resistance: 0.88 Ohms, Total equivalent resistance: 115 Ohms. No load current is 0.03A at 0.4 pf lagging.

Calculate: a) phase angle error at no load

b) Burden in VA at unity p.f. at which phase angle will be 0

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

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

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, $I_s = 0$

Practice Problems

Example 3.6 (U.A. Bakshi) (Cont.)

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

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

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

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

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

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

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

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

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

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

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

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

Practice Problems

Example 3.8 (U.A. Bakshi)

A bar type CT has 300 secondary turns. The secondary winding carries a burden of ammeter with resistance 1Ohms and inductive reactance of 0.53 Ohms while secondary winding resistance is 0.25 Ohms and reactance 0.35 Ohms. The magnetizing mmf required is 85 A-turns and core loss component of current is 50 A. Find, i) Primary current when secondary current is 5A ii) the ratio error.

Answers: 1589.8 A, -5.65 %

Practice Problems

Example 3.9 (U.A. Bakshi)

A 2000/100 V P.T has primary resistance and reactance of 105 and 75.2 Ohms and secondary resistance and reactance of 0.7 and 0.087 Ohms. No load current is 0.03A a 0.36 p.f. lagging. Find:

i) Phase angle error at no load

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

iii) Burden in VA at unity p.f. to have 0 phase angle

Answers: -0.0608 degrees, -0.4167 degrees, 38.64 VA

Practice Problems

Example 3.10 (U.A. Bakshi)

A ring core 500/5 A CT with a bar primary has secondary resistance of 0.5Ohms and negligible reactance. The total excitation current at full load secondary current of 5A in a non-inductive burden of 1 Ohms is 3A at 0.4 p.f. Calculate the true ratio and phase angle error of transformer at full-load.

Answers: R=100.24 , 0.314 degrees

Practice Problems

Example 3.11 (U.A. Bakshi)

A CT with 5 primary turns has secondary burden consisting of 0.16 Ohms resistance and 0.12 Ohms inductive reactance, when the primary current is 200A, the magnetizing current is 1.5A and the iron loss current is 0.4A. Find the no. of secondary turns needed to make the true current ratio 100.1 and phase angle.

Answers: n= 99.4893, Ns=497.44, 0.276 degrees

Practice Problems

Example 3.12 (U.A. Bakshi)

A single phase P.T. has a turns ratio of 3810/63 V. The nominal secondary voltage is 63V and the total equivalent resistance and leakage reactance referred to the secondary side are 2 and 1 Ohms, respectively. Calculate the ratio and phase angle errors when the transformer is supplying a burden of $100 + j200$ Ohms.

Neglect the no load component of current (excitation current).

Answers: -0.8%, -0.338 degrees

Practice Problems

- The excitation current of a ring core current transformer, of ratio 1000/5A, when operating at full primary current and with a secondary burden of non-inductive resistance of 1 Ohms, is 1 A at a power factor of 0.4. Calculate the C.T. ratio and phase angle errors.

Answers: -0.04%, ~ 3 degrees

- For a 1000/5 CT, at purely resistive burden, the magnetizing component of excitation current is almost negligible whereas the core loss component is 37.5A. Calculate the ratio error.

Answer: -3.61 %

Knowledge is having the right answer.

Intelligence is asking the right question.

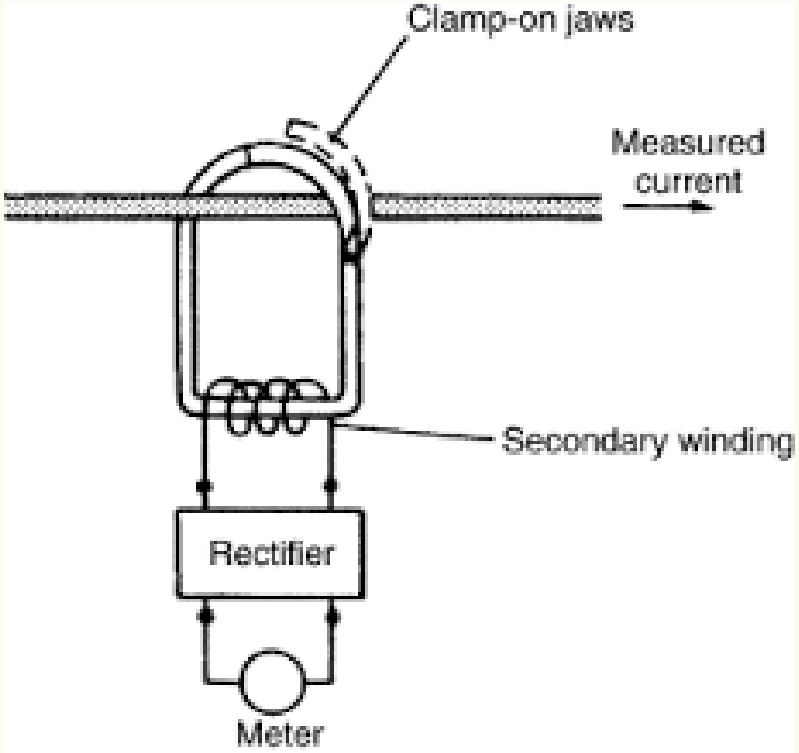
Dig-Up!!

- Why C.T. Secondary is not kept open or C.T. is never operated at open circuit conditions?
- Why P.T. Secondary is never operated at short circuit condition?
- Can instrument transformers be used for measurement of HVDC (High Voltage DC) system’s voltage and current?
- Wattmeter’s range can be extended using the instrument transformers. Think about the connection of C.T. and P.T. with wattmeter coils.

Clamp-meter or Clamp-on Ammeter

A current transformer with a single conductor is used in combination with a bridge rectifier and a DC milli-ammeter to produce a very useful service meter. **The core of the transformer can be split with the help of a trigger switch and therefore, the core can be clamped around a live conductor to measure the current. Thus this, arrangement avoids the necessity of breaking the circuit in order that a current measuring device be inserted in series with it to measure the value of current flowing.**

Clamp-meter or Clamp-on Ammeter



Clamp-meter or Clamp-on Ammeter

Interested in operation of clamp-meter, check this!

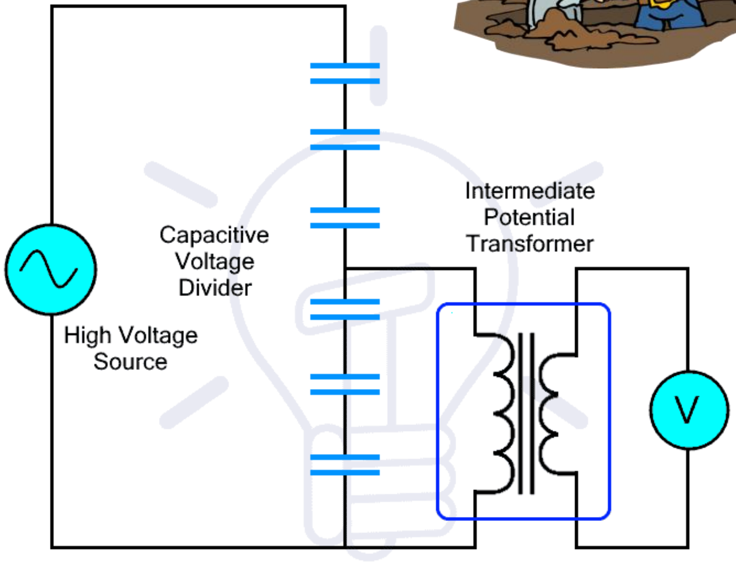
- Current Measurement for Appliances using Clamp-meter
- Clamp Meter Working (AC & DC Clamp Meters)

Does it mean there is a DC clamp-meter? How does it work?

- Hall Effect Current Sensor _ Basics for DC Clamp meter
- Hall-Effect

Capacitive Voltage Transformer (CVT)

- For measuring high voltage (above 100kV) the high insulated transformer is required. **The highly insulated transformer is quite expensive as compared to the normal transformer.** For reducing the cost, the capacitive potential transformer is used in the system.
- The capacitive potential divider is used in combination with the auxiliary transformer and the inductive element. The capacitive potential divider step-down the extra high voltage signals into a low voltage signal. The output voltage of the capacitive potential transformer is further step-down by the help of the auxiliary transformer.



Capacitive Potential Transformer

Successful people, in all callings, never stop acquiring specialized knowledge related to their major purpose, business, or profession.

Napoleon Hill