Unit -2

Polyphase Metering

Blondel’s Theorem

Blondel's theorem tells about the number of watt-meters required to measure three-phase power.

It states that, in order to measure power in a network with n number of lines. The total number of watt-meters required is equal to n, and total power is the sum of all the watt-meters readings. It is in such condition that, if current coils of each wattmeter are connected in each line and corresponding voltage coils are connected such that, one end to their respective line and other ends of all the voltage coils are connected together forming a common point.

Suppose, if the common point is to be taken on any one of the lines. Then the other end of the voltage coils is connected to that common line (i.e., common point). In such conditions, the power can be measured by (n-1) watt-meters. Thus for measuring 3-phase power, only 2 watt-meters are required, this is called Two Wattmeter Method.

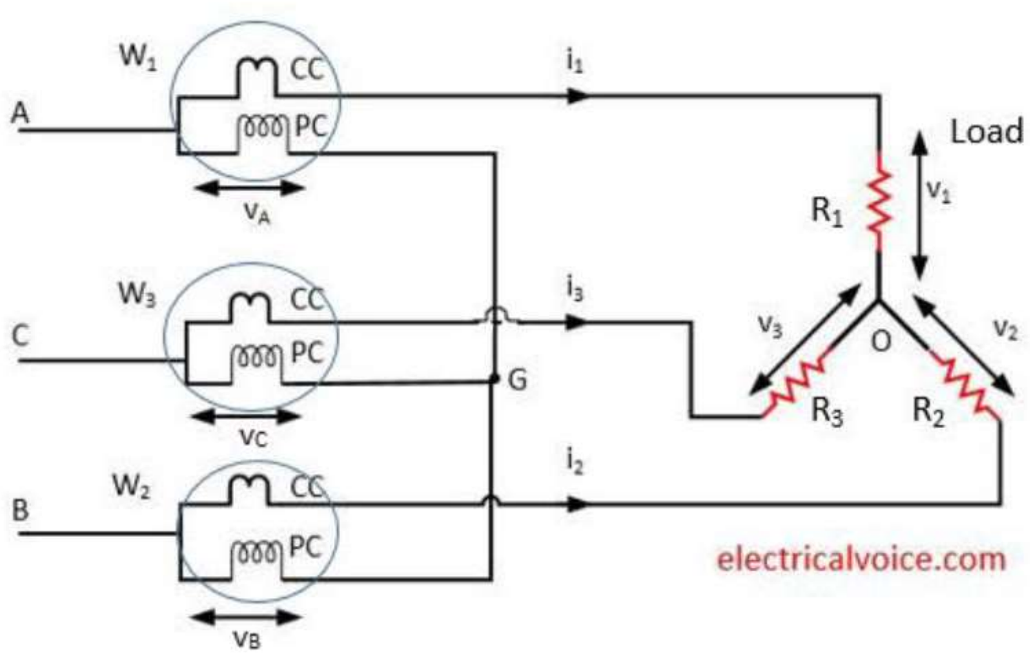


Fig. 1 Power measurement in a 3-phase, 3 wire system

The pressure coil of all the three wattmeters namely W_1, W_2 and W_3 are connected to a common terminal known as the **neutral point**. The product of the phase current and line voltage represents phase power and is recorded by an individual wattmeter.

The total power in a three wattmeter method of power measurement is given by the algebraic sum of the readings of three wattmeters. i.e.

$$\text{Total power } P = W_1 + W_2 + W_3$$

Where,

$W_1 = V_1I_1$

$W_2 = V_2I_2$

$W_3 = V_3I_3$

Except for 3 phase, 4 wire unbalanced load, 3 phase power can be measured by using only Two Wattmeter Method.

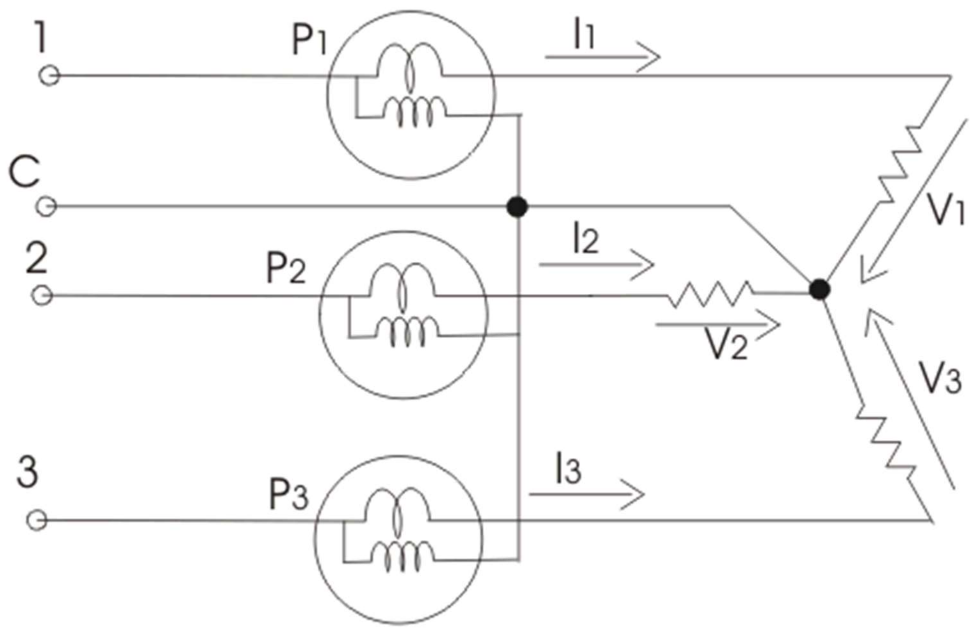
Measurement of Three Phase Power
Various methods are used for **measurement of three phase power** in three phase circuits on the basis of number of wattmeters used. We have three methods to discuss:

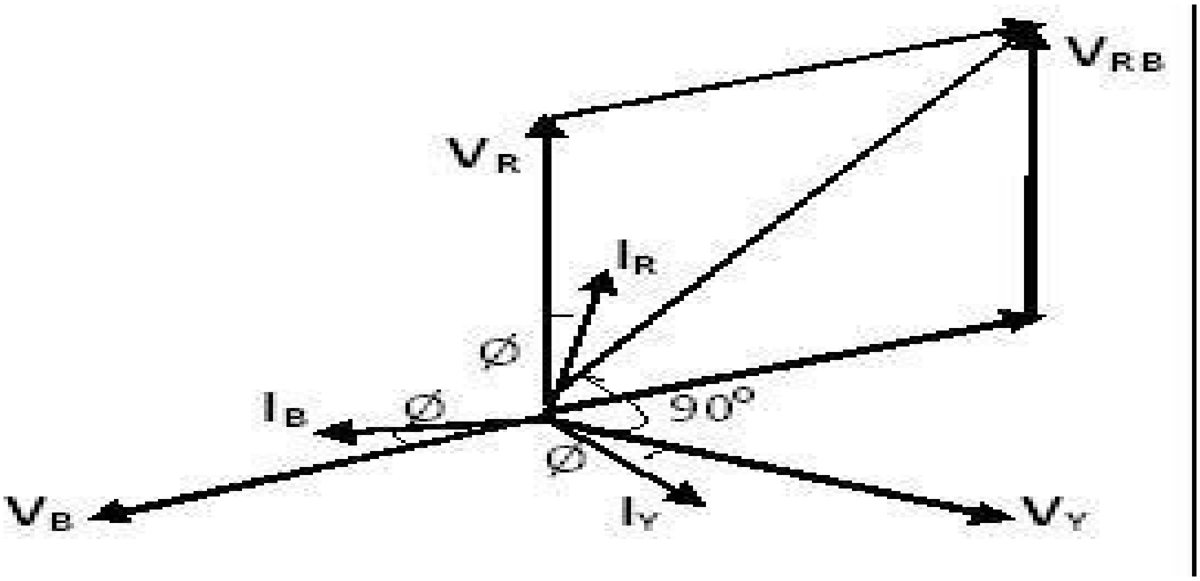
1. Three wattmeters method
2. Two wattmeters method
3. Single wattmeter method.

Let us discuss one by one each method in detail.

Measurement of Three Phase Power by Three Wattmeters Method

The circuit diagram is shown below-





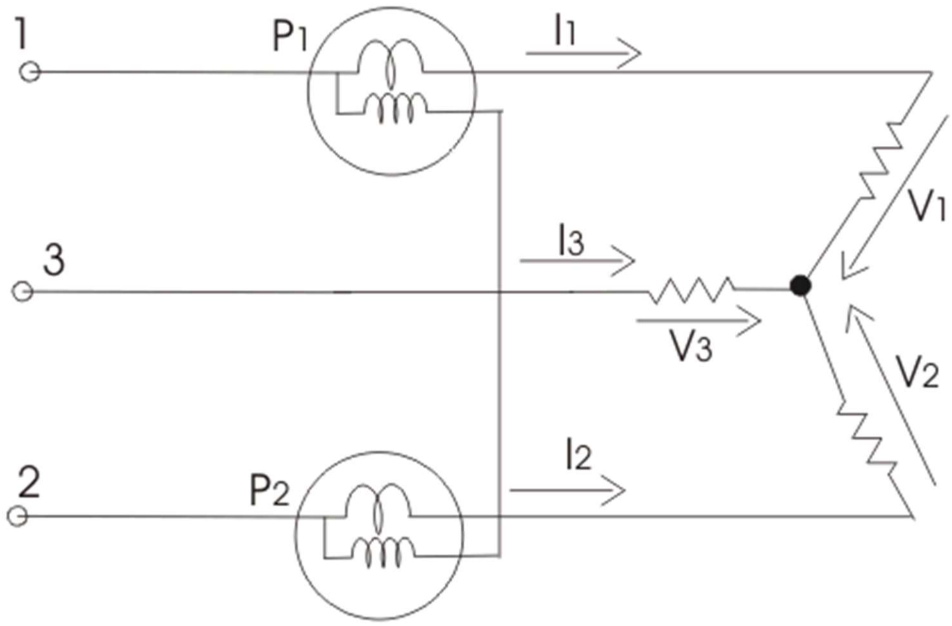
Here, it is applied to three phase four wire systems, current coil of all the three wattmeters marked as 1, 2 and 3 are connected to respective phases marked as 1, 2 and 3. Pressure coils of all the three wattmeters are connected to a common point at neutral line. Clearly each wattmeter will give reading as product of phase current and line voltage which is phase power. The resultant sum of all the readings of wattmeter will give the total power of the circuit. Mathematically we can write $P = P_1 + P_2 + P_3 = V_1 I_1 + V_2 I_2 + V_3 I_3$

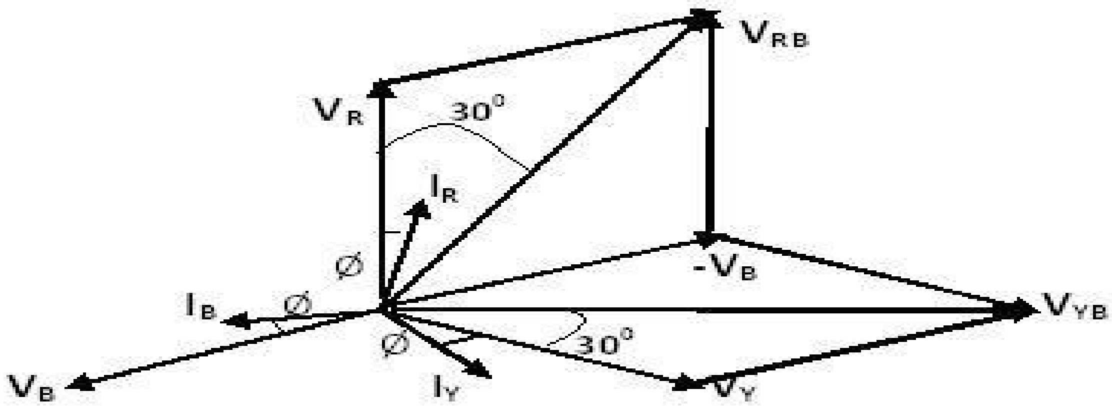
Measurement of Three Phase Power by Two Wattmeters Method

In this method we have two types of connections

1. Star connection of loads
2. Delta connection of loads.

When the load is star connected load, the diagram is shown in below-





Phasor diagram for real power measurements

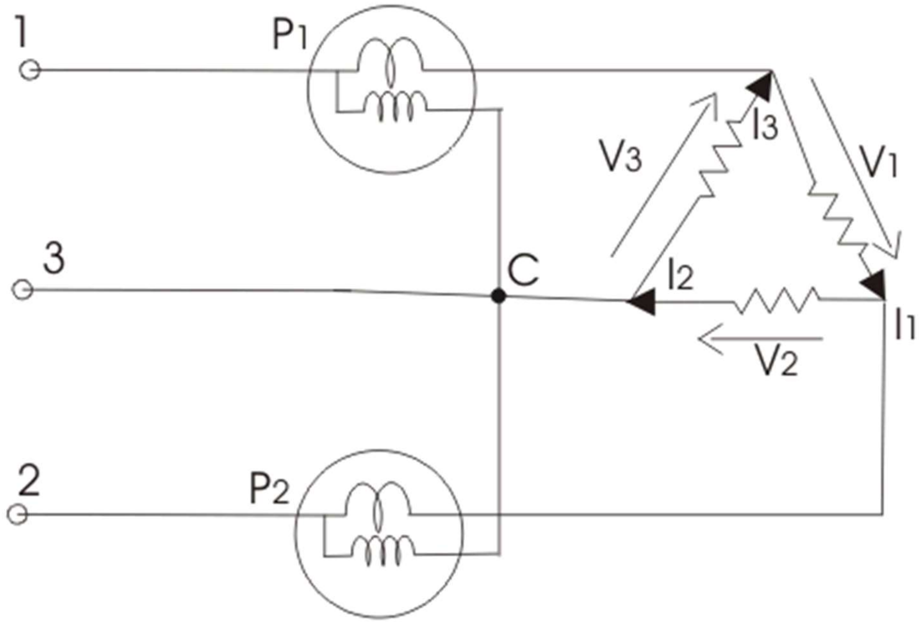
For star connected load clearly the reading of wattmeter one is product of phase current and voltage difference (V_2-V_3). Similarly the reading of wattmeter two is the product of phase current and the voltage difference (V_2-V_3). Thus the total power of the circuit is sum of the reading of both the wattmeters. Mathematically we can write

$$P = P_1 + + P_2 = I_1(\ V_1 + V_2\ ) + I_2(\ V_2 - V_3\ )$$

but we have , hence putting the value of .

We get total power as .

When delta connected load, the diagram is shown in below



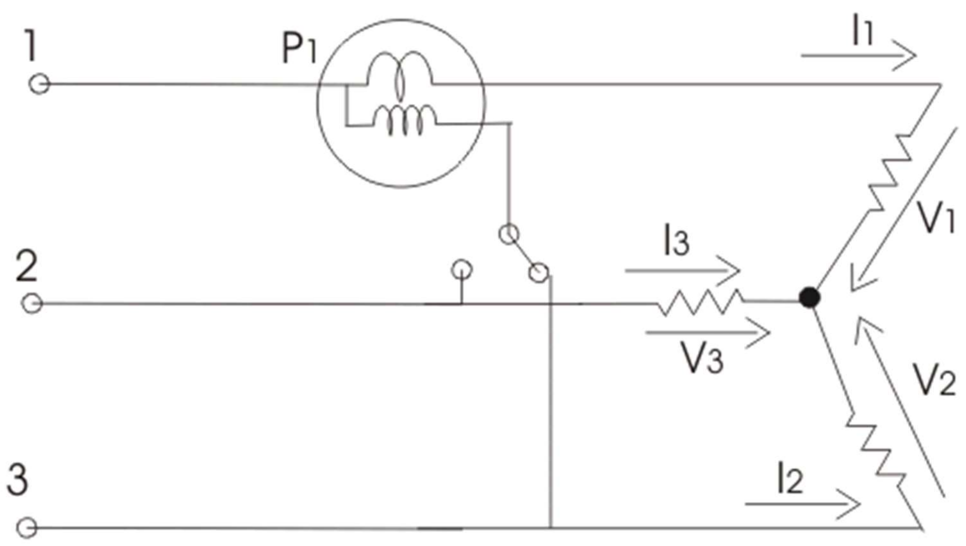
The reading of wattmeter one can be written as
$P_1 = -V_3(I_1 - I_3)$
and reading of wattmeter two is
$P_2 = -V_2(I_2 - I_1)$
$Total\ power\ is\ P = P_1 + P_2 = V_2I_2 + V_3I_3 - I_1(V_2 + V_3)$

but , hence expression for total power will reduce to .

Measurement of Three Phase Power by One Wattmeter Method

Limitation of this method is that it cannot be applied on unbalanced load. So under this condition we

have .
Diagram is shown below:



Two switches are given which are marked as 1-3 and 1-2, by closing the switch 1-3 we get reading of wattmeter as
$P_1 = V_{13} I_1 \cos(30 - \phi) = \sqrt{3} \times VI \cos(30 - \phi)$
Similarly the reading of wattmeter when switch 1-2 is closed is
$P_2 = V_{12} I_1 \cos(30 + \phi) = \sqrt{3} \times VI \cos(30 + \phi)$

$Total\ power\ is\ P_1 + P_2 = 3VI \cos\phi$

Variation of wattmeter readings with load PF (lag)

PF angle	PF	W_1	W_2	W3ph=W1+ W2	Remarks
φ (lag)	cos φ	$V_L I_L \cos(30-\varphi)$	$V_L I_L \cos(30+\varphi)$	$\sqrt{3} V_L I_L \cos\varphi$	Gen. Case (always $W_1 \geq W_2$)
0^0	UPF	$\sqrt{3}/2\ V_L I_L$	$\sqrt{3}/2\ V_L I_L$	$2W_1$ or $2W_2$	$W_1=W_2$
30^0	0.866	$V_L I_L$	$V_L I_L/2$	$1.5W_1$ or $3W_2$	$W_2=W_1/2$
60^0	0.5	$\sqrt{3}/2\ V_L I_L$	ZERO	W_1 alone	W_2 reads zero
$>60^0$	<0.5	W_1	W_2 reads negative	$W_1+(-W_2)$	For taking readings, the PC or CC connection of W_2 should be reversed) (LPF case)

Instrument Transformers:

Instrument Transformers Basics
Why instrument transformers?

In power systems, currents and voltages handled are very large.
Direct measurements are not possible with the existing equipments.
Hence it is required to step down currents and voltages with the help of instrument transformers so that they can be measured with instruments of moderate sizes

Instrument Transformers
Transformers used in conjunction with measuring instruments for measurement purposes are called "Instrument Transformers".
The instrument used for the measurement of current is called a "Current Transformer" or simply "CT".
The transformers used for the measurement of voltage are called "Voltage transformer" or "Potential transformer" or simply "PT".

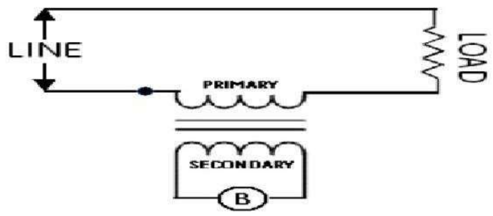


Fig 1. Current Transformer

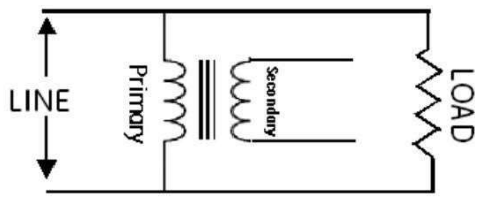


Fig 2. Potential Transformer

Fig 1. indicates the current measurement by a C.T. The current being measured passes through the primary winding and the secondary winding is connected to an ammeter. The C.T. steps down the current to the level of ammeter.
Fig 2. shows the connection of P.T. for voltage measurement. The primary winding is connected to the voltage being measured and the secondary winding to a voltmeter. The P.T. steps down the voltage to the level of voltmeter.
Merits of Instrument Transformers:

1. Instruments of moderate size are used for metering i.e. 5A for current and 100 to 120 volts for voltage measurements.
2. Instrument and meters can be standardized so that there is saving in costs. Replacement of damaged instruments is easy.
3. Single range instruments can be used to cover large current or voltage ranges, when used with suitable multi range instrument transformers.
4. The metering circuit is isolated from the high voltage power circuits. Hence isolation is not a problem and the safety is assured for the operators
5. There is low power consumption in metering circuit.
6. Several instruments can be operated from a single instrument

$$R = \frac{|\text{Primary phasor}|}{|\text{secondary phasor}|}$$

$$\frac{\text{Primary winding current}}{\text{Secondary winding current}} \quad \text{for a C.T.}$$

$$\frac{\text{Primary winding voltage}}{\text{secondary winding voltage}} \quad \text{for a P.T.}$$

Nominal Ratio: It is the ratio of rated primary winding current (voltage) to the rated secondary winding current (voltage).

$$K_n = \frac{\text{rated primary winding current}}{\text{rated secondary winding current}} \quad \text{for a C.T.}$$

$$= \frac{\text{rated primary winding voltage}}{\text{rated secondary winding voltage}} \quad \text{for a P.T.}$$

Turns ratio: This is defined as below

$$n = \frac{\text{number of turns of secondary winding}}{\text{number of turns of primary winding}} \quad \text{for a C.T.}$$

$$= \frac{\text{number of turns of primary winding}}{\text{number of turns of secondary winding}} \quad \text{for a P.T.}$$

Burden of an Instrument Transformer:

The rated burden is the volt ampere loading which is permissible without errors exceeding the particular class of accuracy.

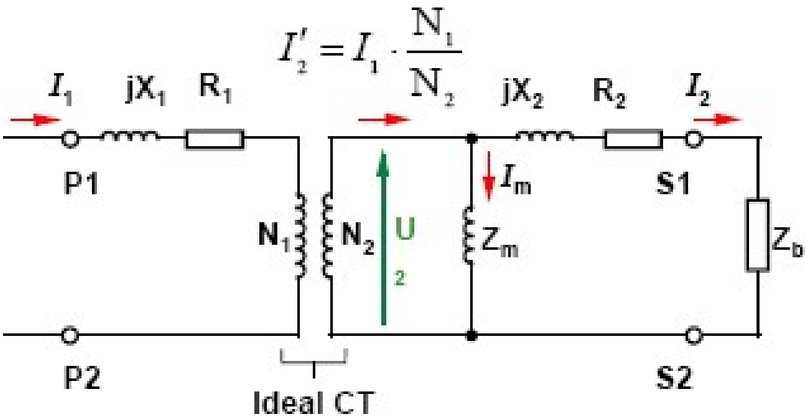
$$\text{Total secondary winding burden} = \frac{(\text{secondary winding induced voltage})^2}{(\text{impedance of secondary winding circuit including impedance of secondary winding})}$$

$$= (\text{secondary winding current})^2 \times (\text{impedance of secondary winding circuit including secondary winding})$$

$$\text{secondary winding burden due to load} = \frac{(\text{secondary winding terminal voltage})^2}{(\text{impendance of load on secondary winding})}$$

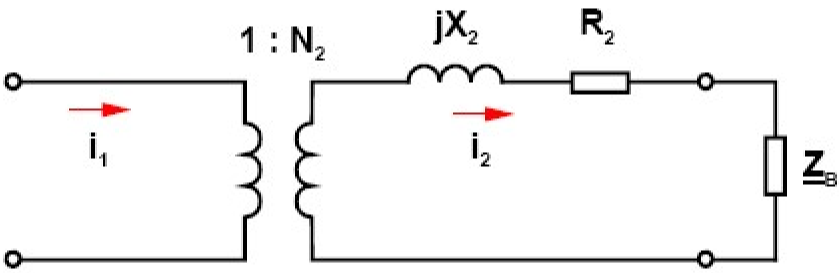
$$= (\text{secondary winding current})^2 \times (\text{impedance of load in the secondary winding circuit})$$

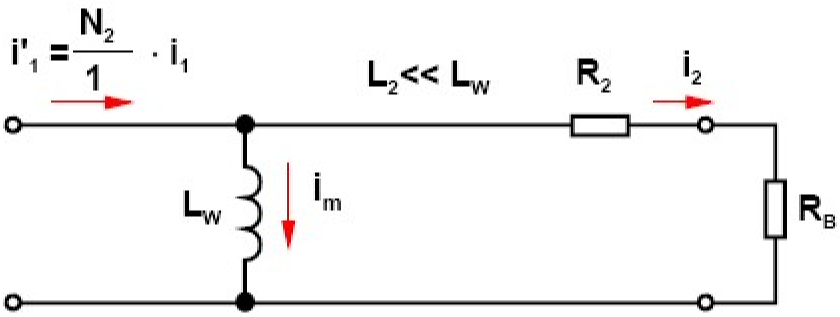
2.2. Current Transformer equivalent circuit:



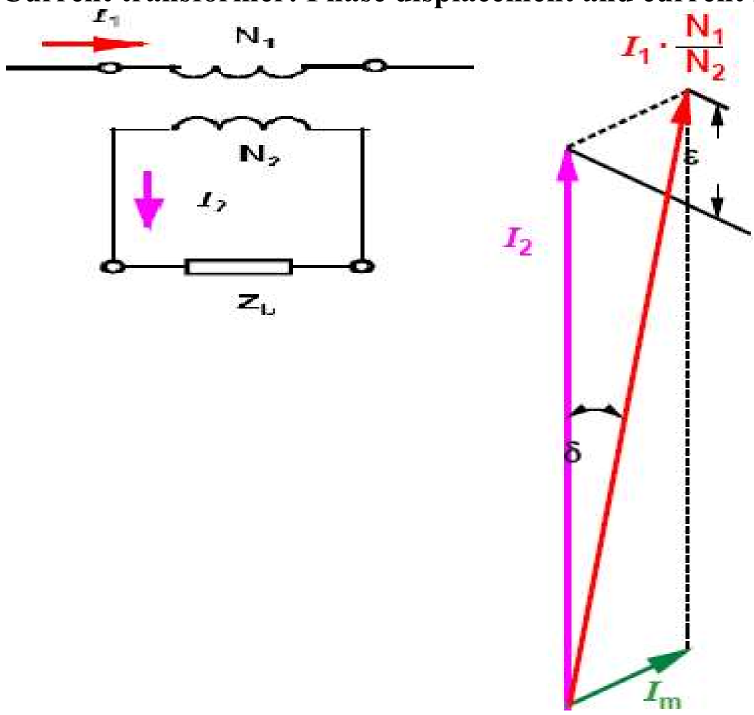
X1 = Primary leakage reactance
R1 = Primary winding resistance
X2 = Secondary leakage reactance
Z0 = Magnetizing impedance
R2 = Secondary winding resistance
Zb = Secondary load
Note: Normally the leakage fluxes X1 and X2 can be neglected

2.3. Current transformer, simplified equivalent circuit:





2.4. Current transformer: Phase displacement and current ratio error :



2.5. Construction of CT

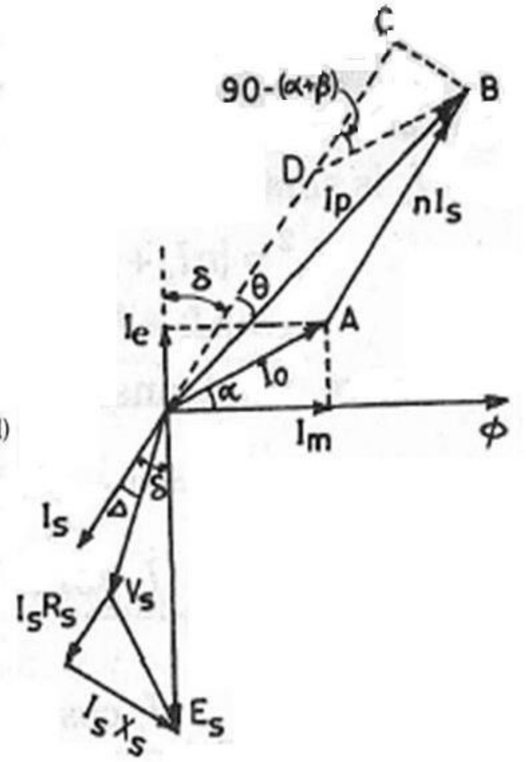
Construction of Current Transformer:

Current transformers are constructed in various ways. In one method there are two separate windings on a magnetic steel core. The primary winding consists of a few turns of heavy wire capable of carrying the full load current while the secondary winding consist of many turns of smaller wire with a current carrying capacity of between 5/20 amperes, dependent on the design. This is called the wound type due to its wound primary coil.

2.6. Wound Type

Phasor Diagram

E_s = open circuit secondary voltage
I_s = secondary current
V_s = secondary terminal voltage when current is I_s
R_s, X_s = secondary winding resistance and reactance
δ = angle between I_s and E_s
Δ = angle between I_s and V_s
I_p = primary current
I_o = exciting current
I_m = magnetizing component of I_o
I_e = loss component of I_o
θ = angle between the primary and secondary (reversed) currents, *i.e.* the phase angle of the transformer.
T_p = primary number of turns.
T_s = secondary number of turns.
n = turn ratio $= \dfrac{T_s}{T_p}$
ϕ = flux in the core
α = angle between ϕ and I_o.



Angle by which the reversed I_2 differs in phase from the I_1 vector
Ideally the I_2 should lag the I_1 by 180^0 and hence the phase angle is ZERO
In practice this angle is $< 180^0$ due to magnetizing and loss component of the I_1

The phase angle is considered to be positive if the secondary current (reserved) leads the primary current. ***For very low power factor the phase angle may be negative.***

$$\tan\theta = \frac{CB}{OC} = \frac{CB}{OD + DC}$$
$$= \frac{I_o \sin(90 - \alpha - \delta)}{nI_s + I_o \cos(90 - \alpha - \delta)}$$
$$= \frac{I_o \cos(\alpha + \delta)}{nI_s + I_o \sin(\alpha + \delta)}$$

Since θ is a small angle,

$$\theta \approx \tan\theta = \frac{I_o \cos(\alpha + \delta)}{nI_s + I_o \sin(\alpha + \delta)}$$

As $I_o \sin(\alpha + \delta) \ll nI_s$,

$$\theta = \frac{I_o \cos\alpha\cos\delta - I_o \sin\alpha\sin\delta}{nI_s}$$
$$= \frac{I_m \cos\delta - I_e \sin\delta}{nI_s}$$

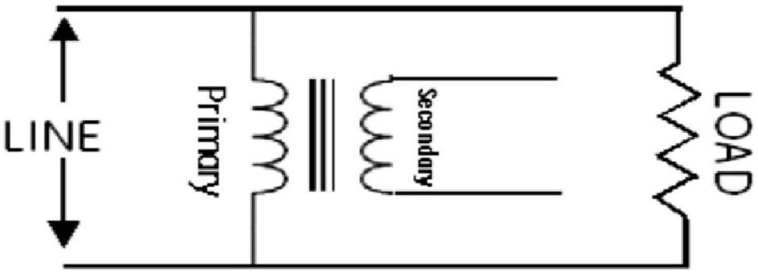
The angle δ being small, the expression for phase angle may be approximated as $\theta = \dfrac{I_m}{nI_s}$

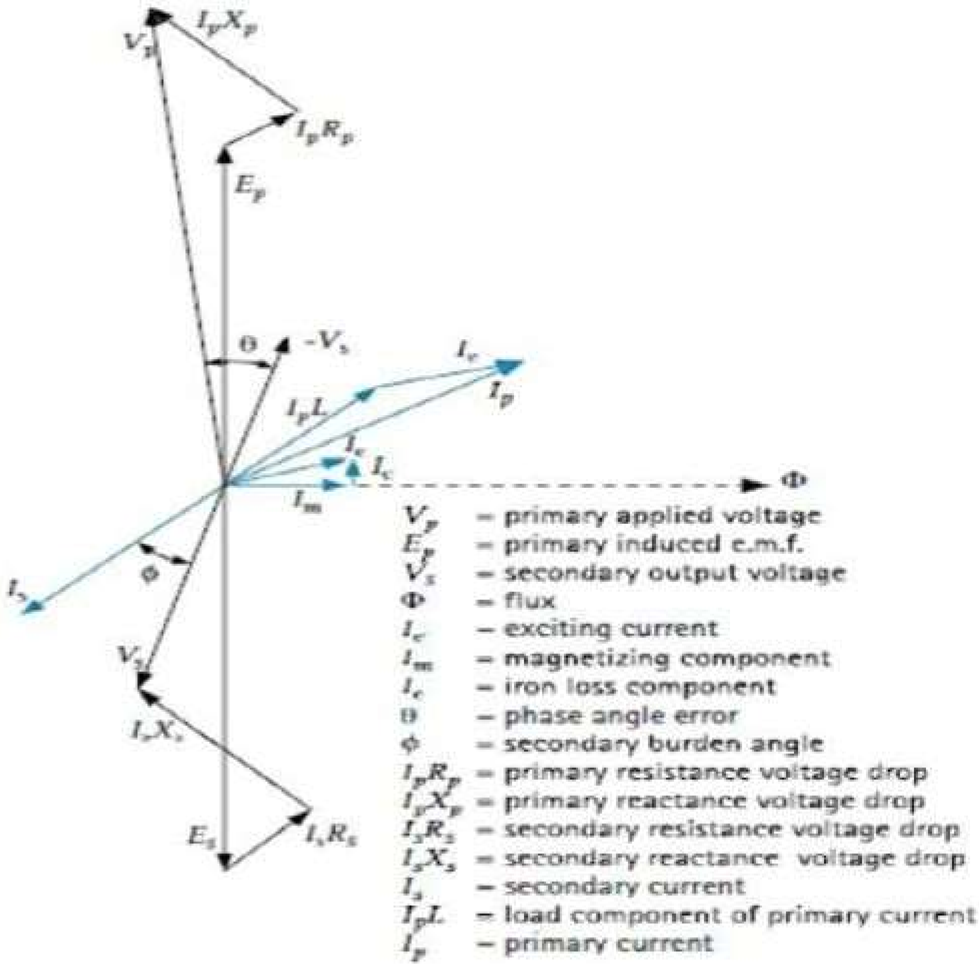
Potential Transformer Basics

Potential transformers are normally connected across two lines of the circuit in which the voltage is to be measured. Normally they will be connected L-L (line-to-line) or L-G (line-to-ground). A typical connection is as follows:

2.8. Phasor Diagram of Potential Transformer:

The theory of a potential transformer is the same as that of a power transformer. The main difference is that the power loading of a P.T. is very small and consequently the exciting current is of the same order as the secondary winding current while in a power transformer the exciting current is a very small fraction of secondary winding load current.





- **PTs** are widely used to scale down the line to neutral voltage Y system or the line-to-line voltage of a Delta system to the rated input scale of the meter (typically 110 V).
- Transformers can also be used in electrical instrumentation systems
- Due to t/fs ability to step up or step down voltage and current, and the electrical isolation they provide, they can serve as a way of connecting electrical instrumentation to high-voltage, high current power systems.
- They are used in the transmission lines for the purpose of voltage measurement, power metering, and the protection of the lines.
- The **PT** (like the **CT**) is used for the substation service