51- (3-ϕ AC circuits & Power & Energy Measurement).

Advantages of 3-ϕ AC Circuits :-

1> For a given size of the machine, 3-ϕ machine delivers larger output compared to 1-ϕ machine.
ex: A 3-ϕ Induction motor has rated output 1.5 times more than a 1-ϕ Induction motor of same size.

2> The power delivered by a single phase system is pulsating in nature, which will adversely affect the performance of motors connected to system. Ex:- 1-ϕ motors produce pulsating torque hence not steady in their operation. 3-ϕ motors produce uniform torque and operation is quite smooth.

3> The parallel operation of 1-ϕ alternators is not smooth but parallel operation of 3-ϕ alternators is smooth.

4> For same amount of power transmission, single phase system requires more conductor material than 3-ϕ system.

5> 1-ϕ Induction motors are not self starting but 3-ϕ Induction motors are self starting.

6> Single phase supply can be obtained from the three phase but three phase can not be obtained from single phase

7> Power factor of single phase motor is poor than the three phase motors of same rating.

Generation of Three phase Voltage :-

Consider a 3-phase alternator, there are three independent windings displaced by the angle 120° from each other, so that three separate voltages get developed. These windings terminals are named as R_1-R_2, Y_1-Y_2, and B_1-B_2 and all are mounted on same shaft.

When these three windings are rotated in the magnetic field they cut the magnetic flux and hence change in flux linking windings changes causing emf's induced in the three windings.

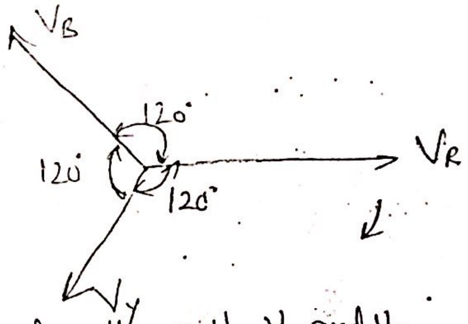
Let V_R, V_Y and V_B are the three independent voltages induced in windings $R_1 R_2$, Y_1-Y_2, and B_1-B_2 respectively.

All the voltages induced in windings have same magnitude and frequency as all are rotated with uniform speed. Hence all the voltages are also displaced with 120°.

These all three voltages together represent 3-φ voltages.

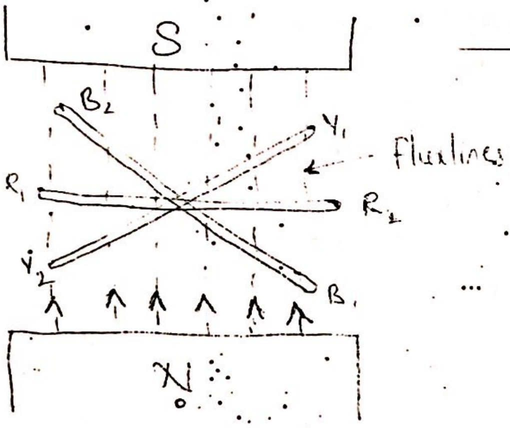
The equations for the voltages can be written as

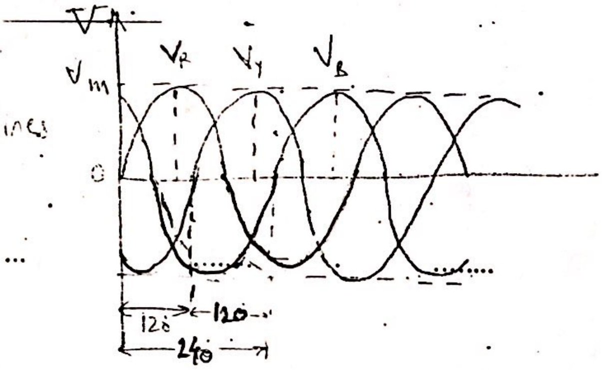
$$\boxed{\begin{aligned} V_R &= V_m \sin \omega t \\ V_Y &= V_m \sin(\omega t - 120°) \\ V_B &= V_m \sin(\omega t - 240°) \end{aligned}}$$



For a balanced System, the Vector Sum of voltages V_R, V_Y and V_B are equal to zero: i.e

$$\boxed{V_R + V_Y + V_B = 0}$$



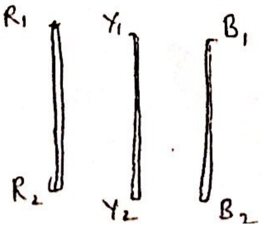


Star and Delta Connections :⟶

Need of star Delta:

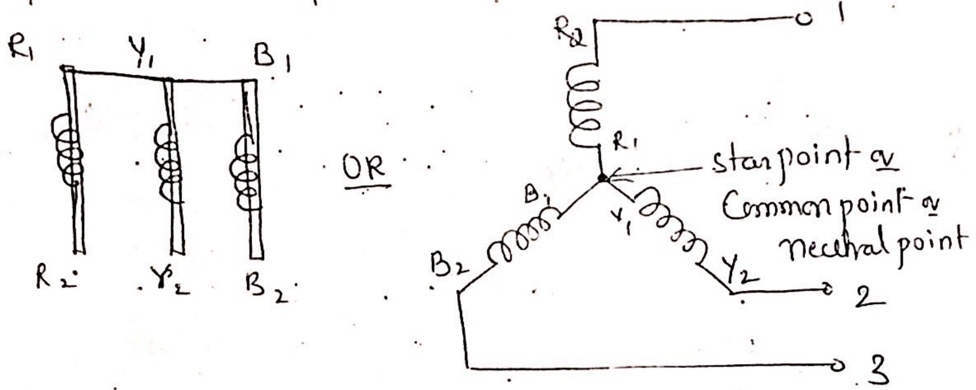
* In 3-φ Systems, there will be three set of windings having two terminals for each winding, hence totally there are six terminals are available from 3-set of windings. Under such case it would be difficult to use six terminals to connect load to 3-φ machine.

To reduce this six terminals of the windings to three star and delta connections are used.



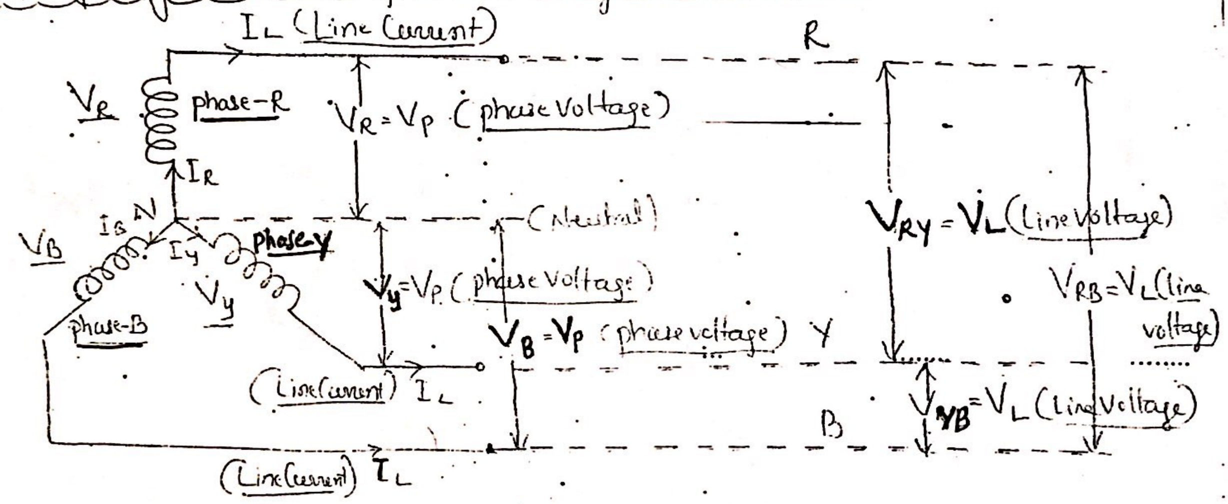
Star Connection :→

The Star Connection is obtained by connecting the similar ends (R_1, Y_1, B_1 or $R_2 Y_2 B_2$) to form a common point called as star point or neutral point.



* Thus by joining similar ends (star connection) of 3-φ windings the number of terminals are reduced from six to three.

Concept of Line and phase voltages and currents



Phase Voltage: Voltage measured across the phase is called phase voltage. But here in star connection phase voltage which is phase voltage across phase is the voltage measured between line and neutral.

V_R, V_Y, V_B are phase voltages across phases R Y B and V_p is the representation of phase voltage in general.

Line Voltage: Voltage measured between two lines is called line voltage.

Phase Current: Current through phase (R, Y, B) is called phase current.

Line Current: Current through line is called line current.

From the connections, it is clear that, in star connection, the line current is equal to phase current as the same current in phase pass through line. $\boxed{I_L = I_P}$

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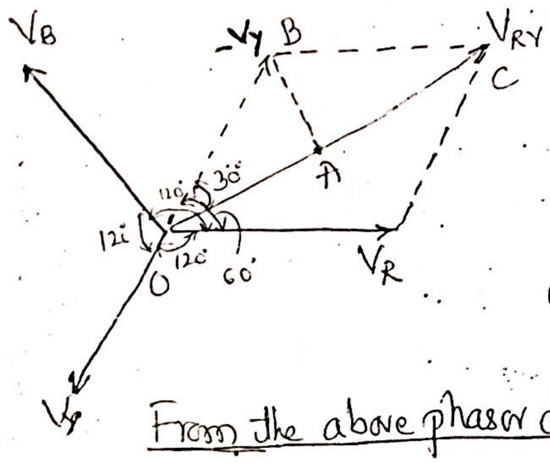
From the Connections, it is also clear that, voltage across phase (between line and neutral) is not equal to the line voltage (between two lines). Hence it is required to derive the relation between phase and line voltage in star connection.

Relation between Line and phase voltages in Star Connection:



Vector or Phasor diagram drawn to find out the resultant of two phase voltages (V_R and V_Y) and resultant obtained is V_{RY}.

From the above phasor diagram,

Consider Δ^{le} OAB, this triangle is formed by drawing a perpendicular from point B on line OC such that

OA = AC. From the Δ^{le} OAB, OA + AC = OC or OC = 2OA

$$\cos 30^\circ = \frac{OA}{OB}$$

$$\frac{\sqrt{3}}{2} = \frac{OC/2}{OB} = \frac{V_{RY}/2}{V_Y}$$

$$\frac{\sqrt{3}}{2} = \frac{V_{RY}}{2 \cdot V_Y}$$

$$V_{RY} = \sqrt{3}\, V_Y$$

$$\therefore \boxed{V_L = \sqrt{3}\, V_P}$$

Power Consumed in 3-φ System:

Power Consumed in One phase is given by = $V_P I_P \cos\phi$

$$P_{ph} = V_P I_P \cos\phi$$

Power Consumed in 3-φ is given by

$$P = 3 \cdot P_{ph} = 3 \cdot V_P I_P \cos\phi$$

$$\therefore P = 3 \cdot \frac{V_L}{\sqrt{3}} \cdot I_L \cos\phi$$

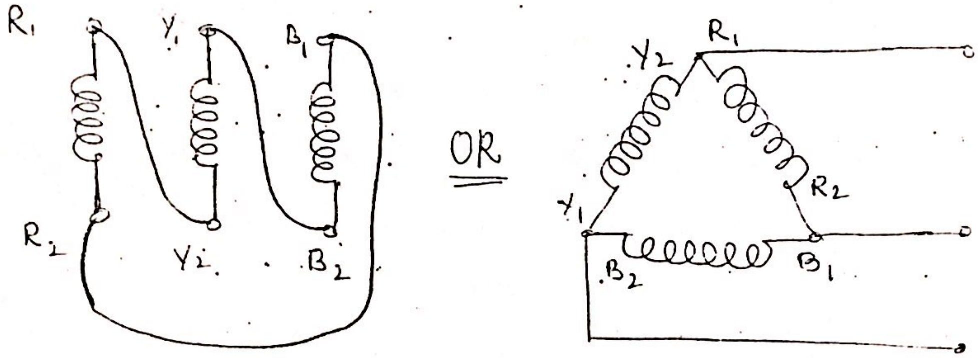
$$\therefore \boxed{P = \sqrt{3}\, V_L I_L \cos\phi}$$

Hence in Star Connected System, it is clear that

$\boxed{I_L = I_P}$ $\boxed{V_L = \sqrt{3}\, V_P}$ $\boxed{P = \sqrt{3}\, V_L I_L \cos\phi}$

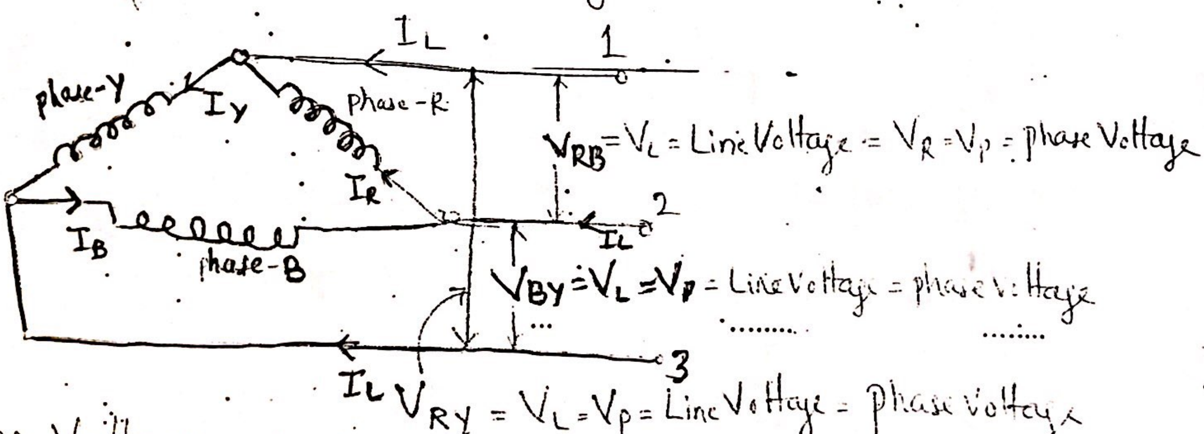
Delta Connection :→

The delta Connection is obtained by Connecting the Starting end of one set of winding (R_1) to ending end of other set of winding (Y_2) and is shown below.



Thus by joining starting end of one winding set to ending end of other winding set, the number of terminals are reduced from 6 to 3.

Concept of Line & Phase voltages and Currents :→



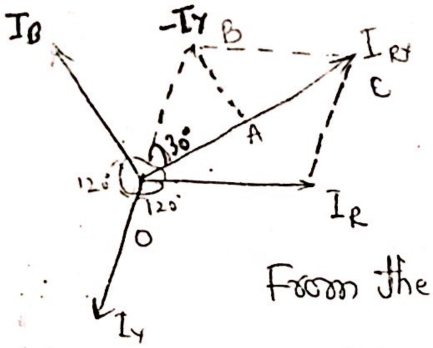
Phase Voltage: Voltage measured across the phase is Called phase voltage, but this voltage happens to be voltage between two lines. Hence $\boxed{V_R = V_{RY}} \Rightarrow \boxed{V_p = V_L}$

Phase Current: Current through phase is called phase Current.

From the Connections, it is clear that, Current through the phase is not equal to the current through line.

Hence it is required to derive the relation between line Current and phase Current in the delta Connections.

Relation between Line and Phase Currents in Delta Connection



Phasor diagram drawn to find out the resultant of two phase currents (I_R & I_Y)

From the above phasor diagram,

Consider Δ^{le} OAB, this triangle is formed by drawing a perpendicular from point B on the line OC such that $OA = AC$,

From Δ^{le} OAB,

$OA + AC = OC$ OR $OC = 2 \cdot OA$

$$\cos 30° = \frac{OA}{OB}$$

$$\frac{\sqrt{3}}{2} = \frac{OC/2}{OB} = \frac{I_{RY}/2}{I_Y}$$

$$\frac{\sqrt{3}}{\cancel{2}} = \frac{I_{RY}}{\cancel{2} \cdot I_Y}$$

$$I_Y = \sqrt{3} \cdot I_{RY}$$

$$\boxed{\therefore I_P = \sqrt{3} \cdot I_L}$$

Power Consumed in 3-ϕ System:

Power Consumed in one phase is given by: $P_{ph} = V_P I_P \cos\phi$

$$P_{ph} = V_P I_P \cos\phi$$

Power Consumed in 3-ϕ is given by:

$$P = 3 \cdot P_{ph} = 3 \cdot V_P I_P \cos\phi$$

$$\therefore P = 3 \cdot V_L \cdot \frac{I_L}{\sqrt{3}} \cdot \cos\phi$$

$$\boxed{\therefore P = \sqrt{3}\, V_L I_L \cos\phi}$$

Hence in delta Connected System, it is clear that,

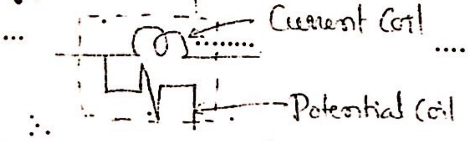
$$\boxed{I_L = \sqrt{3}\, I_P} \quad \boxed{V_L = V_P} \quad \boxed{P = \sqrt{3}\, V_L I_L \cos\phi}$$

Comparision between Star and Delta Connections:

Star Connection	Delta Connection
1) Star Connection is obtained by Connecting similar ends of 3-ϕ windings.	1) Delta Connection is obtained by Connecting **starting end** of one set of winding to the **ending end** of another set of winding.
2) Neutral point is present	2) Neutral point is absent
3) $I_L = I_P$	3) $I_L = \sqrt{3} \cdot I_P$
4) $V_L = \sqrt{3} V_P$	4) $V_L = V_P$
5) It is also Called as 3-ϕ, 4-wire System.	5) It is also Called as 3-ϕ, 3-wire System

Measurement of 3-ϕ Power Using Wattmeters:

Wattmeter: **Wattmeter** is an equipment used to **measure** power. Its **Symbolic** representation is shown below

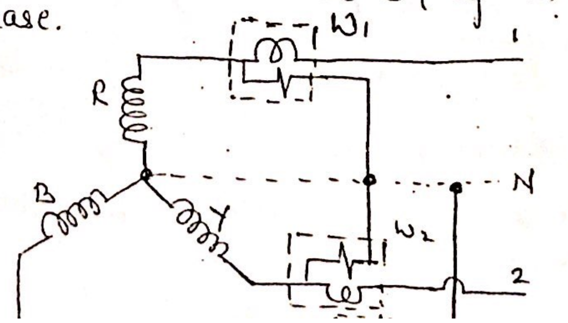


3-ϕ power can be measured using three methods and they are

1) Three wattmeter method
2) Two wattmeter method
3) Single wattmeter method

1) Three wattmeter method:

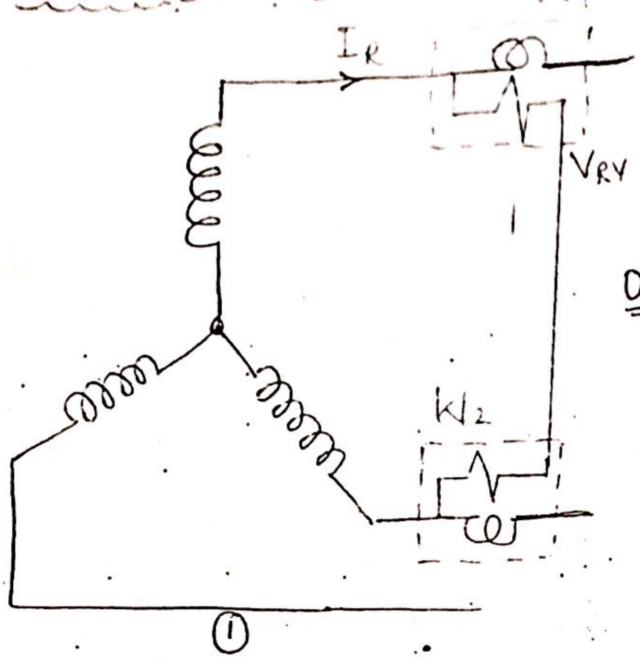
Three wattmeter are Connected to 3-ϕ System with one wattmeter Connected in every phase.



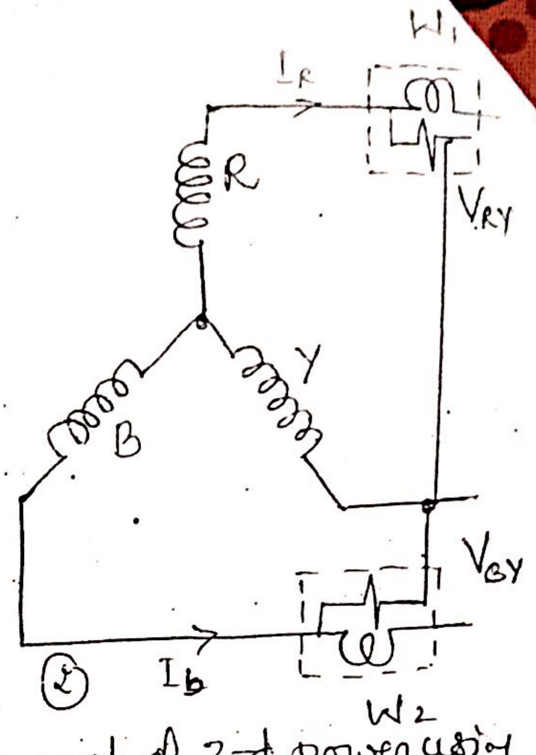
Total 3-ϕ power measured is given by

$$\boxed{W = W_1 + W_2 + W_3}$$

Q7 Two wattmeter method:

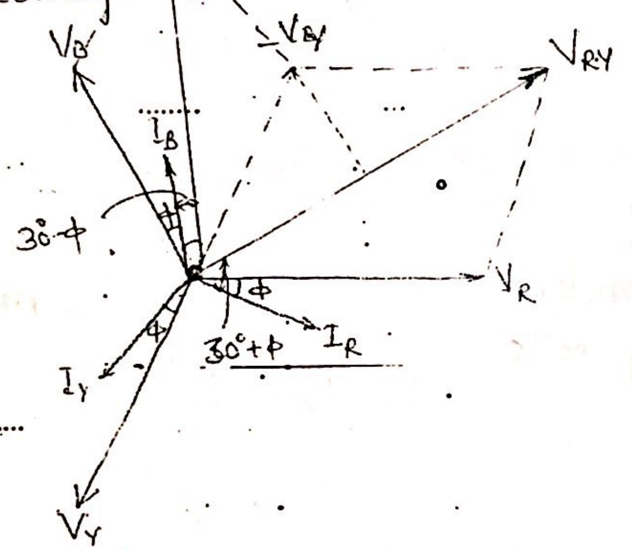


OR



Above two connection diagrams shows measurement of 3-ϕ power using two wattmeter method. Let us consider diagram (2).

In the circuit diagram (2) wattmeters are connected in phase 'R' and 'B' respectively.



Wattmeter W_1 measures voltage between line R & Y hence V_{RY} & measures current in line 'R' i.e I_R & phase angle between V_{RY} & I_R is $30°+\phi$ hence reading of wattmeter W_1 is given by.

$$W_1 = V_{RY} I_R \cos(30°+\phi)$$

$$= V_L I_P \cos(30°+\phi)$$

$$= (\sqrt{3} V_P) \cdot I_P \cos(30°+\phi)$$

$$\boxed{W_1 = \sqrt{3} V_P I_P \cos(30°+\phi)} \longrightarrow (1)$$

$$\therefore W_2 = V_L \cdot I_p \cos(30° - \phi)$$
$$= (\sqrt{3} V_p) \cdot I_p \cos(30° - \phi)$$
$$\therefore \boxed{W_2 = \sqrt{3}\, V_p I_p \cos(30 - \phi)} \longrightarrow (2)$$

Now Rewritting wattmeter W_1 & W_2 readings as

$$\boxed{\begin{aligned} W_1 &= \sqrt{3}\, V_p I_p \cos(30° + \phi) \longrightarrow (1) \\ W_2 &= \sqrt{3}\, V_p I_p \cos(30° - \phi) \longrightarrow (2) \end{aligned}}$$

Adding (1) & (2) or Total power measured is given by

$$W = W_1 + W_2$$
$$= \sqrt{3} V_p I_p \cos(30° + \phi) + \sqrt{3} V_p I_p \cos(30° - \phi)$$
$$= \sqrt{3} V_p I_p \left[\cos(30° + \phi) + \cos(30° - \phi) \right]$$
$$= \sqrt{3} V_p I_p \left[\cos 30° \cos\phi - \cancel{\sin 30° \sin\phi} + \cos 30° \cos\phi + \cancel{\sin 30° \sin\phi} \right]$$
$$= \sqrt{3} V_p I_p \left[2 \cdot \cos 30° \cdot \cos\phi \right]$$
$$= \sqrt{3} V_p I_p \left[\cancel{2} \cdot \frac{\sqrt{3}}{\cancel{2}} \cdot \cos\phi \right]$$
$$\boxed{W = W_1 + W_2 = 3 \cdot V_p I_p \cos\phi} \longrightarrow (3)$$

Thus two wattmeters are sufficient to measure 3-ϕ power.

Now (2) - (1) gives i.e $W_2 - W_1$ gives

$$W_2 - W_1 = \sqrt{3} V_p I_p \cos(30 - \phi) - \sqrt{3} V_p I_p \cos(30° + \phi)$$
$$= \sqrt{3} V_p I_p \left[\cos(30° - \phi) - \cos(30° + \phi) \right]$$
$$= \sqrt{3} V_p I_p \left[\cancel{\cos 30° \cos\phi} + \sin 30° \sin\phi - \cancel{\cos 30° \cos\phi} + \sin 30° \sin\phi \right]$$
$$= \sqrt{3} V_p I_p \left[2 \cdot \sin 30° \cdot \sin\phi \right]$$
$$= \sqrt{3} V_p I_p \left[\cancel{2} \cdot \frac{1}{\cancel{2}} \cdot \sin\phi \right]$$
$$\boxed{W_2 - W_1 = \sqrt{3} \cdot V_p I_p \sin\phi} \longrightarrow (4)$$

Now (4) ÷ (3) gives i.e $W_2 - W_1 / W_1 + W_2$

$$\frac{W_2 - W_1}{W_1 + W_2} = \frac{\sqrt{\cancel{3}}\, \cancel{V_p} \cancel{I_p} \sin\phi}{\cancel{3}\, \cancel{V_p} \cancel{I_p} \cos\phi}$$

$$\therefore \frac{W_2 - W_1}{W_1 + W_2} = \frac{1}{\sqrt{3}} \tan\phi$$

$$\therefore \tan\phi = \frac{\sqrt{3}\,(W_2 - W_1)}{(W_1 + W_2)}$$

$$\therefore \boxed{\phi = \tan^{-1} \frac{\sqrt{3}(W_2 - W_1)}{W_1 + W_2}}$$

Effect of power factor on Wattmeter readings (W_1 & W_2):

To study the effect of power factor on wattmeter readings W_1 & W_2, let us consider different cases as below.

Case 1) When $\cos\phi = 0$ or $\boxed{\phi = 90^\circ}$

Then wattmeter readings W_1 & W_2 are

$$W_1 = \sqrt{3}\, V_p I_p \cos(30^\circ + 90^\circ)$$

$$W_1 = \sqrt{3}\, V_p I_p \cos(120^\circ) \Rightarrow W_1 = -\frac{\sqrt{3}}{2} V_p I_p$$

$$W_2 = \sqrt{3}\, V_p I_p \cos(30 - 90^\circ)$$

$$W_2 = \sqrt{3}\, V_p I_p \cos(-60^\circ) \Rightarrow W_2 = \frac{\sqrt{3}}{2} V_p I_p$$

$\therefore$ W_1 & W_2 are equal but W_1 is negative & W_2 is positive

When wattmeter reads negative, the pointer kicks back below zero on the scale. Then current coil connections are changed (interchanged) to get pointer showing reading on scale but noted with -ve sign.

Case 2) When $\cos\phi$ is between $(60^\circ$ to $90^\circ)$ 0.5 to 0.

Then $W_1 = \sqrt{3}\, V_p I_p \cos(30^\circ + 70^\circ)$

$$\therefore W_1 = -0.3\, V_p I_p$$

$$W_2 = \sqrt{3}\, V_p I_p \cos(30^\circ - 70^\circ)$$

$$\therefore W_2 = 1.22\, V_p I_p$$

$\therefore$ W_1 & W_2 are not equal but W_1 is negative W_2 is positive

Then $W_1 = \sqrt{3} V_p I_p \cos 30^\circ$

$W_1 = 1.5 V_p I_p$

$W_2 = \sqrt{3} V_p I_p \cos 30^\circ$

$W_2 = 1.5 V_p I_p$

$\therefore$ W_1 & W_2 are both positive & equal.

- Finally the summary can be written as

Power factor $\cos\phi$	Range of ϕ	W_1 sign	W_2 sign
0	90°	$-$	+
0 to 0.5	90° to 60°	$-$	+
0.5	60°	Zero	+
0.5 to 1	60 to 0°	+	+
1	0°	+	+

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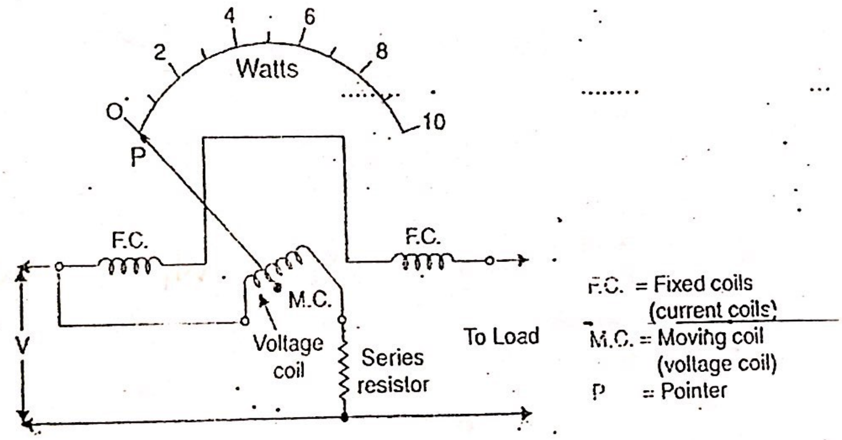
1. Explain the working principle of dynamometer type watt meter with necessary sketches of constructional details.

2. Explain the working of a single phase induction type energy meter with necessary sketches of constructional details.

Dynamometer type wattmeter

Permanent magnet moving coil (PMMC) instrument is the most accurate and useful for dc measurements. Dynamometer type moving coil instruments can be used both on dc as well as on ac. A wattmeter is essentially an inherent combination of an ammeter and a voltmeter and therefore consists of two coils, known as current coil and pressure coil. The fixed coil, which is divided into two equal portions in order to provide uniform field, is employed as current coil and the moving coil is used as pressure coil. The operation torque is produced due to interaction of fluxes on account of currents in current and pressure coils. The current coil is inserted in series with the line carrying current to be measured and the pressure coil, in series with a high non inductive resistance, is connected across the load or supply terminal. The wattmeter gives reading which is proportional to current through the current coil, pd across pressure coil and cosine of the phase angle between voltage and current.

The deflecting torque of dynamometer type wattmeter is determined by variations in either the fixed or the moving coil currents. Hence dynamometer type instrument is a versatile measuring device for various power measurements. Their calibration is the same for both dc as well as ac. Dynamometer type instruments are very similar to PMMC instruments except that the permanent magnetic field is replaced by a coil which carry the current to be measured or a definite fraction of it or proportional to the voltage to be measured. A high non inductive resistance is connected in series with the moving coil in order to limit the current. Figure shows the construction of a dynamometer type instrument.



Dynamometer type watt meter

The magnetic fields of the fixed and moving coils react on one another causing the moving coil to turn about its axis. The movement is controlled by hair springs which also lead the current into and out of the moving element. Damping is ... of the moving system about its final deflected