3^{rd} Semester

INSTRUMENTATION AND CONTROL ENGINEERING

SUBJECT: ELECTRICAL MACHINES

SUBJECT CODE : 181035

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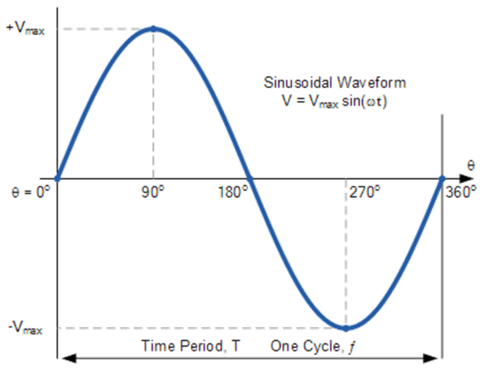
Single Phase AC System

The arrangement of the single phase system is simple and less complex in wiring construction. To complete the electrical connection, it requires **two wires** (one phase and one neutral) for completing the electrical circuit.

It has the single-phase voltage supply (230v) for the low or normal load. It is used as a domestic load.



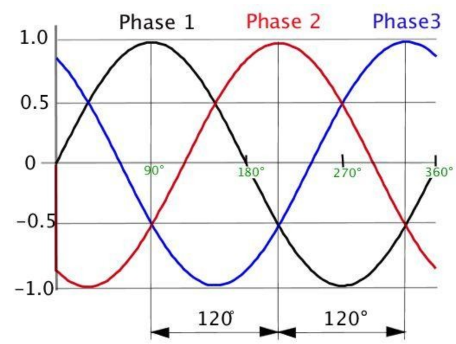


Figure1: Single Phase AC System

Figure2: Single Phase AC System

Three Phase AC System

Three phase system includes **four wires**– one neutral and three phases.

These three phases are separated by the equal magnitude and having a phase difference of 120º between each other. One of the benefits of this system is that the 3-phase AC power supply is constant. And it does not falls to zero at all. This property has various advantages in electrical engineering.

A three-phase system is generated by the three symmetrical coils. Based on the structure, the three-phase symmetrical power system can be divided into two class.

- Star Connection
- Delta Connection

As per the requirement, we can use either star or delta connection.

Advantage of three-phase system over single-phase system.

1. Operation in the System

Parallel operation of three phase system is easier than the single-phase system, especially in the alternator.

2. Delivering the Power Supply

In the single phase system, the instantaneous AC power varies sinusoidally from zero to the peak value. This pulsating nature of power is not good for the load system.

And In the three-phase power system, constant electrical AC power is obtained due to the balanced and cumulative three-phase system.

3. The Output of the System

The three-phase machine gives more output than the single phase machine.

4. Power Transmission Economics

Three phase system is more economical than the single-phase system for power transmission. The maximum amount of power is transferred through three phases as compared to single phase supply.

5. Working Role and Usage

Especially, the domestic application like the electric motors works on the three-phase system. For the proper working condition, three phases of the induction motor are better than the single phase of the induction motor. The three phases of the induction motor are self-starting.

6. Size of the Device

If comparing the same power rating machine, the size of the three-phase machine is smaller than the single phase machine.

7. Power Efficiency

In terms of power, the three-phase system is more efficient than the single phase system.

8. Power Factor

Three phase motors have higher power factor as compare to the single phase motor.

9. Reliability in Fault Condition

In the single phase system, if the fault occurs in the network, then the power supply completely fails. This is because it consists of only one phase.

In a three-phase system, the network has three phases. If the fault occurs on any one of the phases, the other two phases can continuously supply the power.

From this, it is clear, a three-phase system has good reliability than a single phase system, in case any failure occurs.

10. Rectifier System

For the rectifier service, three-phase AC is smoother than the single phase system. The three-phase voltage supply is easy to filter out the ripple components.

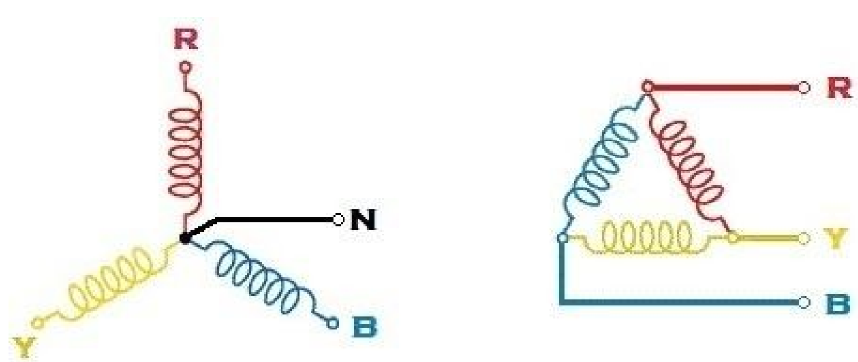
11. Maintainance

The three-phase supply requires less maintenance as compared to single phase supply.

Star Delta connections

Star and Delta Connections are the two types of connections in a 3 – phase circuits. A Star Connection is a 4 – wire system and a Delta Connection is a 3 – wire system.

Star (also called Y or Wye) and Delta (Δ). In a Star Connection, there are 4 wires: 3 phase wires and 1 neutral wire whereas in a Delta Connection, there are only 3 wires for distribution and all the 3 wires are phases (no neutral in a Delta connection). The following image shows a typical Star and Delta Connection.



Star Connection Figure:3 Delta Connection

Relationship of Line and Phase Voltages and Currents in a Star Connected System

To derive the relations between line and phase currents and voltages of a star connected system, we have first to draw a balanced star connected system.(Figure 4)

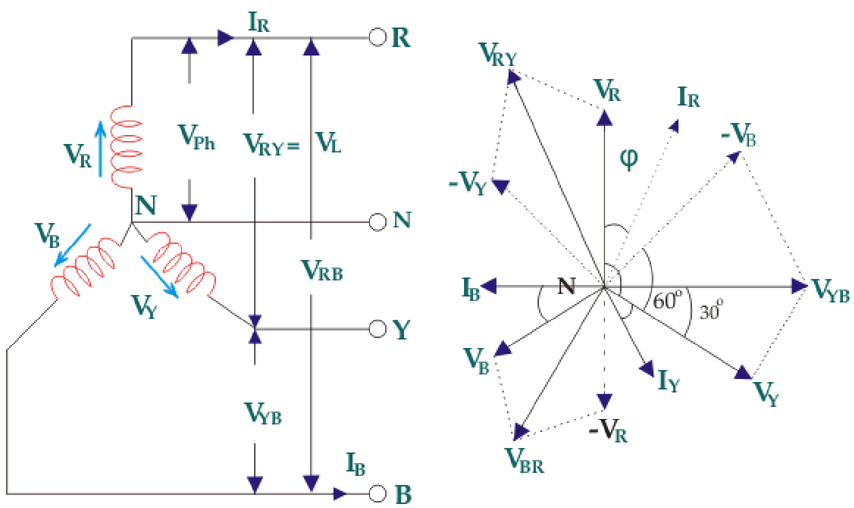


Figure 4

Suppose due to load impedance the current lags the applied voltage in each phase of the system by an angle ϕ. As we have considered that the system is perfectly balanced, the magnitude of current and voltage of each phase is the same. Let us say, the magnitude of the voltage across the red phase i.e. magnitude of the voltage between neutral point (N) and red phase terminal (R) is V_R.

Similarly, the magnitude of the voltage across yellow phase is V_Y and the magnitude of the voltage across blue phase is V_B.

In the balanced star system, magnitude of phase voltage in each phase is V_{ph}.

$\therefore V_R = V_Y = V_B = V_{ph}$

In the star connection,

Line current is same as phase current.

The magnitude of this current is same in all three phases and say it is I_L.

$\therefore I_R = I_Y = I_B = I_L$, Where, I_R is line current of R phase, I_Y is line current of Y phase and I_B is line current of B phase.

Again, phase current, I_{ph} of each phase is same as line current I_L in star connected system.

$\therefore I_R = I_Y = I_B = I_L = I_{ph}$.

Now, let us say, the voltage across R and Y terminal of the star connected circuit is V_{RY}.

The voltage across Y and B terminal of the star connected circuit is V_{YBBR}.

From the diagram, it is found that:

$V_{RY} = V_R + (- V_Y)$

Similarly, $V_{YB} = V_Y + (- V_B)$

And, $V_{BR} = V_B + (- V_R)$

Now, as angle between V_R and V_Y is 120°(electrical), the angle between V_R and $- V_Y$ is 180° – 120° = 60°(electrical).

$$V_L = |V_{RY}| = \sqrt{V_R^2 + V_Y^2 + 2V_R V_Y \cos 60^o}$$
$$= \sqrt{V_{ph}^2 + V_{ph}^2 + 2V_{ph} V_{ph} \times \frac{1}{2}}$$
$$= \sqrt{3} V_{ph}$$
$$\therefore V_L = \sqrt{3} V_{ph}$$

Thus, for the star-connected system line voltage = √3 × phase voltage.

Line current = Phase current

As, the angle between voltage and current per phase is φ, the electric power per phase is

$$V_{ph} I_{ph} cos\phi = \frac{V_L}{\sqrt{3}} I_L \cos\phi$$

So the total power of three phase system is

$$3 \times \frac{V_L}{\sqrt{3}} I_L \cos\phi = \sqrt{3} V_L I_L \cos\phi$$

Relationship of Line and Phase Voltages and Currents in a Delta Connected System

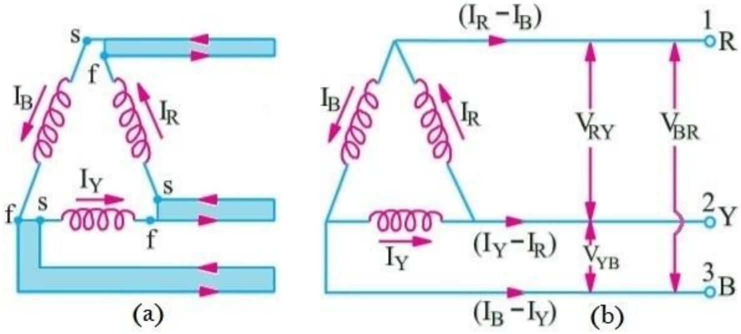


Figure 5: 3 Phase power, voltage and current values

In **Delta connection**, the three windings interconnection looks like a short circuit, but this is not true, if the system is balanced, then the value of the algebraic sum of all voltages around the mesh is zero in Delta connection.

When a terminal is open in Δ, then there is no chance of flowing currents with basic frequency around the closed mesh.

In Delta configuration, at any instant, the EMF value of one phase is equal to the resultant of the other two phases EMF values but in the opposite direction (as shown in Figure 5)

Line Voltages (V_L) and Phase Voltages (V_{Ph}) in Delta Connection

It is seen in figure 6 that there is only one phase winding between two terminals (i.e. there is one phase winding between two wires). Therefore, **in Delta Connection, the voltage between (any pair of) two lines is equal to the phase voltage of the phase winding** which is connected between two lines.

Since the phase sequence is R → Y → B, therefore, the direction of voltage from R phase towards Y phase is positive (+), and the voltage of R phase is leading by 120°from Y phase voltage. Likewise, the voltage of Y phase is leading by 120° from the phase voltage of B and its direction is positive from Y towards B.

If the line voltage between;

- Line 1 and Line 2 = V_{RY}

- Line 2 and Line 3 = V_{YB}
- Line 3 and Line 1 = V_{BR}

Then, we see that V_{RY} leads V_{YB} by 120° and V_{YB} leads V_{BR} by **120°**.

Let's suppose,

$V_{RY} = V_{YB} = V_{BR} = V_L$ .... (Line Voltage)

Then

$\mathbf{V_L = V_{PH}}$

i.e. **in Delta connection, the Line Voltage is equal to the Phase Voltage**.

Line Currents (I_L) and Phase Currents (I_{Ph}) in Delta Connection

It will be noted from the below (figure -6) that the **total current of each Line is equal to the vector difference between two phase currents in Delta connection** flowing through that line. i.e.;

- Current in Line 1= $I_1 = I_R - I_B$
- Current in Line 2 =$I_2 = I_Y - I_R$
- Current in Line 3 =$I_3 = I_B - I_Y$

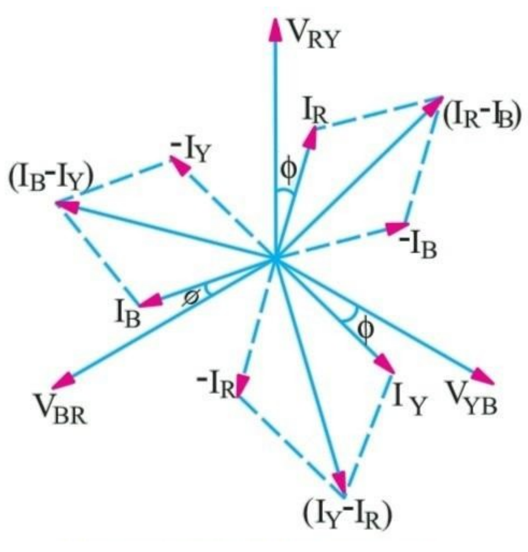


Figure 6: Line & Phase Current and Line & Phase Voltage in Delta Connection

The current of Line 1 can be found by determining the vector difference between I_R and I_B and we can do that by increasing the I_B Vector in reverse, so that, I_R and I_B makes a parallelogram. The diagonal of that parallelogram shows the vector difference of I_R and I_B which is equal to current in Line 1= I_1. Moreover, by reversing the vector of I_B, it may indicate as ($-I_B$), therefore, the angle between I_R and $-I_B$ (I_B, when reversed = $-I_B$) is 60°. If,

$\mathbf{I_R = I_Y = I_B = I_{PH}}$ …. The phase currents

Then;

The current flowing in Line 1 would be;

I_L or $I_1 = 2 \times I_{PH} \times \text{Cos}\ (60°/2)$

$= 2 \times I_{PH} \times \text{Cos}\ 30°$

$= 2 \times I_{PH} \times (\sqrt{3}/2)$ …… Since $\text{Cos}\ 30° = \sqrt{3}/2$

$\mathbf{I_L = \sqrt{3}\ I_{PH}}$

i.e. **In Delta Connection, The Line current is √3 times of Phase Current.**

Similarly, we can find the reaming two Line currents as same as above. i.e.,

$I_2 = I_Y - I_R$ … Vector Difference $= \sqrt{3}\ I_{PH}$

$I_3 = I_B - I_Y$ … Vector difference $= \sqrt{3}\ I_{PH}$

As, all the Line current are equal in magnitude i.e.

$\mathbf{I_1 = I_2 = I_3 = I_L}$

Hence

$\mathbf{I_L = \sqrt{3}\ I_{PH}}$

It is seen from the figure above that;

- The Line Currents are 120° apart from each other
- Line currents are lagging by 30° from their corresponding Phase Currents
- The angle Φ between line currents and respective line voltages is (30°+Φ), i.e. each Line current is lagging by (30°+Φ) from the corresponding line voltage.

Power in three-phase system

Since the phase impedances of a balanced star- or delta-connected load contain equal currents, the phase power is one-third of the total power. As a definition, the voltage across the load impedance and the current in the impedance can be used to compute the power per phase.

Let's assume that the angle between the phase voltage and the phase current is θ, which is equal to the angle of the impedance. Considering the load configurations given in Figure 7, the phase power and the total power can be estimated easily.

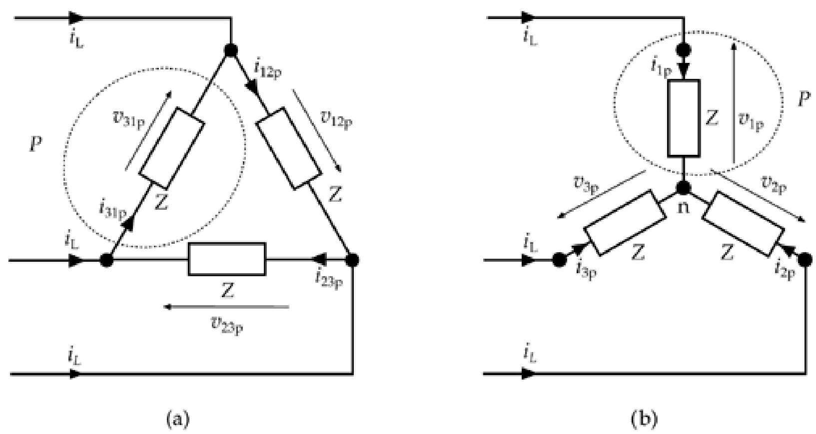


Figure 7:- Per-phase powers in (a) a delta-connected load and (b) a star-connected load.

In the case of Fig. 7 (a), the total active power is equal to three times the power of one phase.

$$P_1 = P_2 = P_3 = P = V_{\text{line}} I_{\text{phase}} \cos\theta$$ **Equation 1**

$$P_{\text{total}} = 3 \cdot P = 3V_{\text{line}} I_{\text{phase}} \cos\theta$$ **Equation 2**

$I_{\text{line}} = \sqrt{3} I_{\text{phase}}$ Since the line current in the balanced delta-connected loads, if this equation is substituted into equation 1, the total active load becomes

$$P_{\text{total}} = \sqrt{3} V_{\text{line}} I_{\text{line}} \cos\theta$$ **Equation 3**

In Figure 7(b), however, the impedances contain the line currents I_{line} (= phase current, I_{phase}) $V_{\text{phase}} (= V_{\text{line}} / \sqrt{3})$ and the phase voltages). Therefore, the phase active power and the total active power are

$$P_1 = P_2 = P_3 = P = V_{phase} I_{line} \cos\theta$$ **Equation 4**

$$P_{total} = 3 \cdot P = 3V_{phase} I_{line} \cos\theta$$ **Equation 5**

$V_{phase} = V_{line}/\sqrt{3}$ If the relationship between the phase voltage and the line voltage () is used, the total active power becomes identical to the equation developed in equation 3 This means that the total power in any balanced three-phase load (Δ- or Y-connected) is given by equation 3.

Similarly, the total reactive and the total apparent power in the three-phase balanced ac circuits can be given by

$$Q_{total} = \sqrt{3} V_{line} I_{line} \sin\theta$$ **Equation 6**

$$S_{total} = \sqrt{3} V_{line} I_{line}$$ **Equation 7**

Measurement of Power in three-phase system

One Wattmeter Method :

Power in 3-phase circuit can also be measured with one wattmeter but the circuit must be balanced 3-phase i.e. when I1=I2=I3 and V1=V2=V3 as shown in figure 8 . Power can not be measured in unbalanced 3-phase circuit with one wattmeter

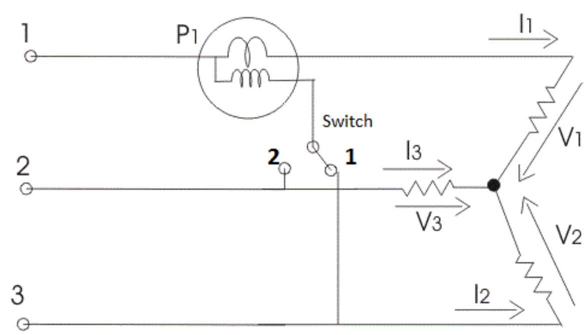


Figure :8

Two Wattmeter Method :

It can be employed to measure the power in a 3 phase, three-wire star or delta connected balanced or unbalanced load.

In two wattmeter method, the current coils of the wattmeter are connected with any two lines, say R and Y and the potential coil of each wattmeter is joined on the same line, the third line i.e. B as shown below in figure 9.

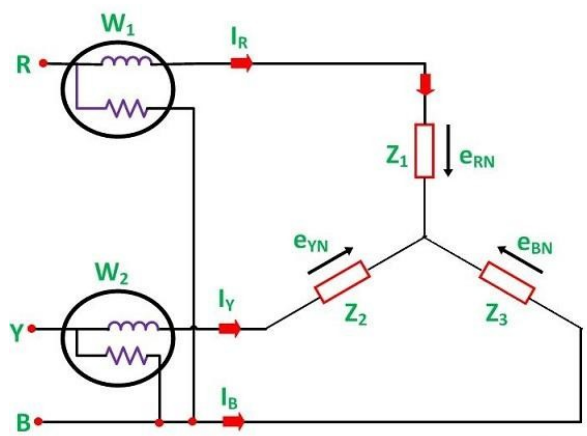


Figure 9

The total instantaneous power absorbed by the three loads Z_1, Z_2 and Z_3, is equal to the sum of the powers measured by the two wattmeters, W_1 and W_2.

Measurement of Power by Two Wattmeter Method in Star Connection

Considering the above figure 9 in which Two Wattmeter W_1 and W_2 are connected, the instantaneous current through the current coil of Wattmeter, W_1 is given by the equation shown below:

$$W_1 = i_R$$

The instantaneous potential difference across the potential coil of Wattmeter, W_1 is given as:

$$W_1 = e_{RN} - e_{BN}$$

Instantaneous power measured by the Wattmeter, W_1 is

$$W_1 = i_R (e_{RN} - e_{BN}) \;\ldots\ldots\ldots (1)$$

The instantaneous current through the current coil of Wattmeter, W_2 is given by the equation:

$$W_2 = i_Y$$

The instantaneous potential difference across the potential coil of Wattmeter, W_2 is given as:

$$W_2 = e_{YN} - e_{BN}$$

Instantaneous power measured by the Wattmeter, W_2 is:

$$W_2 = i_Y (e_{YN} - e_{BN}) \;\ldots\ldots\ldots..(2)$$

Therefore, the total power measured by the two wattmeters W_1 and W_2 will be obtained by adding the equation (1) and (2).

$$W_1 + W_2 = i_R (e_{RN} - e_{BN}) + i_Y (e_{YN} - e_{BN})$$

$$W_1 + W_2 = i_R e_{RN} + i_Y e_{YN} - e_{BN} (i_R + i_Y) \quad \text{or}$$

$$W_1 + W_2 = i_R e_{RN} + i_Y e_{YN} + i_B e_{BN} \quad (\text{i.e. } i_R + i_Y + i_B = 0)$$

$$W_1 + W_2 = P$$

Where, P – the total power absorbed in the three loads at any instant.

Measurement of Power by Two Wattmeter Method in Delta Connection

Considering the delta connected circuit shown in the figure 10 below

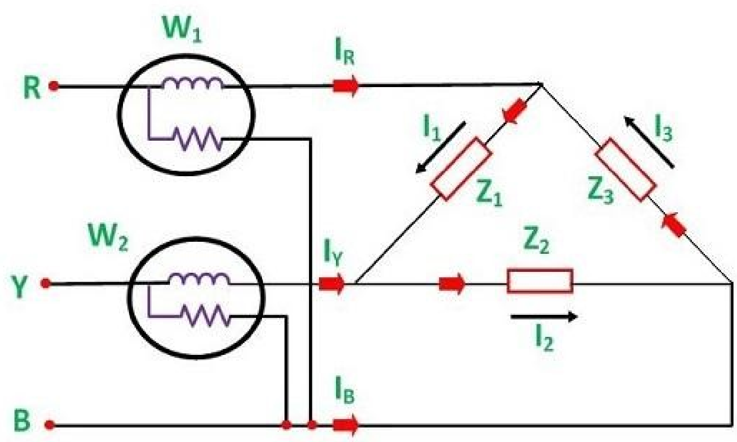


Figure 10

The instantaneous current through the coil of the wattmeter, W_1 is given by the equation:

$$W_1 = i_R = i_1 - i_3$$

Instantaneous power measured by the Wattmeter, W_1 will be:

$$W_1 = e_{RB}$$

Therefore, the instantaneous power measured by the wattmeter, W_1 will be given as:

$$W_1 = e_{RB}\,(i_1 - i_3) \;\ldots\ldots\ldots (3)$$

The instantaneous current through the current coil of the Wattmeter, W_2 is given as:

$$W_2 = i_Y = i_2 - i_1$$

The instantaneous potential difference across the potential coil of wattmeter, W_2 :

$$W_2 = e_{YB}$$

Therefore, the instantaneous power measured by Wattmeter, W_2 will be:

$$W_2 = e_{YB}\,(i_2 - i_1) \;\ldots\ldots\ldots (4)$$

Hence, to obtain the total power measured by the two wattmeter the two equations, i.e. equation (3) and (4) has to be added.

$$W_1 + W_2 = e_{RB}(i_1 - i_3) + e_{YB}(i_2 - i_1)$$

$$W_1 + W_2 = i_1 e_{RB} + i_1 e_{YB} - i_3 e_{RB} - i_1 e_{YB}$$

$$W_1 + W_2 = i_2 e_{YB} + i_3 e_{BR} - i_1(e_{YB} + e_{BR}) \quad (\text{i.e.} -e_{RB} = e_{RB})$$

$$W_1 + W_2 = i_1 e_{RY} + i_2 e_{YB} + i_3 e_{BR} \quad (\text{i.e } e_{RY} + e_{YB} + e_{BR} = 0)$$

$$W_1 + W_2 = P$$

Where P is the total power absorbed in the three loads at any instant.

The power measured by the Two Wattmeter at any instant is the instantaneous power absorbed by the three loads connected in three phases. In fact, this power is the average power drawn by the load since the Wattmeter reads the average power because of the inertia of their moving system.

<u>Three-Wattmeter Method</u>

Three Wattmeter method is employed to measure power in a 3 phase, 4 wire system. However, this method can also be employed in a 3 phase, 3 wire delta connected load, where power consumed by each load is required to be determined separately. The connections for star connected loads for measuring power by three wattmeter method is shown below in figure 11:

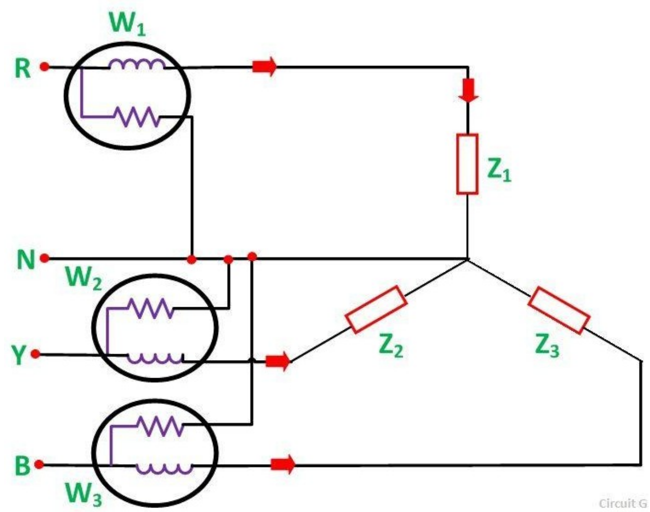


Figure 11

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.