Basic Electrical & Instrumentation Engineering

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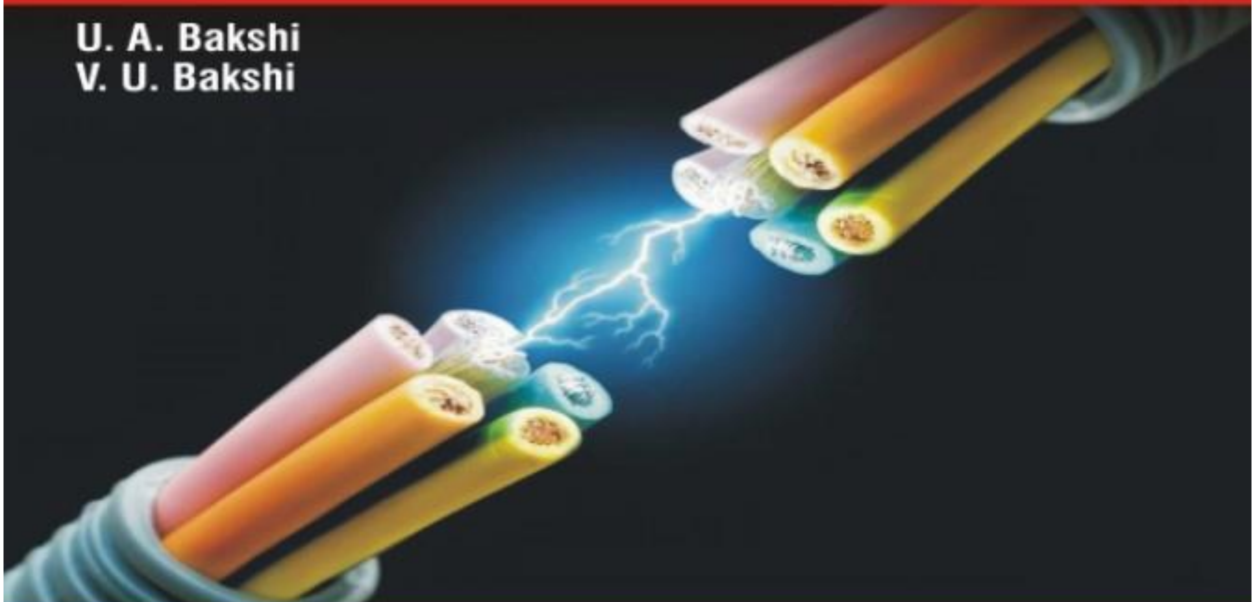

Technical Publications

UNIT - I

1
A.C. Circuits and Power Systems

Syllabus

Three phase power supply - Star connection - Delta connection - Balanced and Unbalanced Loads- Power equation - Star Delta Conversion - Three Phase Power Measurement - Transmission & Distribution of electrical energy - Over head Vs Underground system - Protection of power system - types of tariff - power factor improvement.

Contents

1.1 Introduction to Three Phase Power Supply

- There are certain loads which require polyphase supply. **Phase** means **branch**, **circuit** or **winding** while **poly** means **many**. So such applications need a supply having many a.c. voltages present in it simultaneously. Such a system is called **polyphase system**.
- To develop polyphase system, the armature winding in a generator is divided into number of phases required.
- In each section, a separate a.c. voltage gets induced. So there are many independent a.c. voltages present equal to number of phases of winding.
- The various phases of winding are arranged in such a manner that the magnitudes and frequencies of all these voltages is same but they have definite phase difference with respect to each other.
- The phase difference depends on number of phases in which winding is divided. For example, if winding is divided into 'n' phases then 'n' separate a.c. voltages will be available having same magnitude and frequency but they will have a phase difference of $(360°/n)$ with respect to each other.
- Thus in a three phase supply system, there are three voltages with a same magnitude and frequency but having a phase difference of $360°/3 = 120°$ between them. Such a supply system is called **three phase system**.

> In practice a three phase system is found to be more economical and it has certain advantages over other polyphase systems. Hence three phase system is very popularly used everywhere in practice.

1.2 Advantages of Three Phase System

AU : May-09,13

A three phase system has following advantages over single phase system :

1) The output of three phase machine is always greater than single phase machine of same size, approximately 1.5 times. So for a given size and voltage a three phase alternator occupies less space and has less cost too than single phase having same rating.
2) For a transmission and distribution, three phase system needs less copper or less conducting material than single phase system for given volt amperes and voltage rating so transmission becomes very much economical.
3) It is possible to produce rotating magnetic field with stationary coils by using three phase system. Hence three phase motors are self starting.
4) In single phase system, the instantaneous power is a function of time and hence fluctuates w.r.t. time. This fluctuating power causes considerable vibrations in single phase motors. Hence performance of single phase motors is poor. While instantaneous power in symmetrical three phase system is constant.
5) Three phase system give steady output.
6) Single phase supply can be obtained from three phase but three phase cannot be obtained from single phase.
7) Power factor of single phase motor is poor than three phase motors of same rating.
8) For converting machines like rectifiers, the d.c. output voltage becomes smoother if number of phases are increased.

- But it is found that optimum number of phases required to get all above said advantages is three. Hence three phase system is accepted as standard system throughout the world.

Review Question

1. *List the advantages of three phase system over single phase system.* **AU : May-09, 13, Marks 4**

1.3 Generation of Three Phase Voltage System

- It is already discussed that alternator consisting of one group of coils on armature produces one alternating voltage. But if armature coils are divided into three groups such that they are **displaced by**

the angle 120° from each other, three separate alternating voltages get developed.

- Consider armature of alternator divided into three groups as shown in the Fig. 1.3.1. The coils are named as R_1 - R_2, Y_1 - Y_2 and B_1 - B_2 and mounted on same shaft.
- The ends of each coil are brought out through the slip ring and brush arrangement to collect the induced e.m.f.

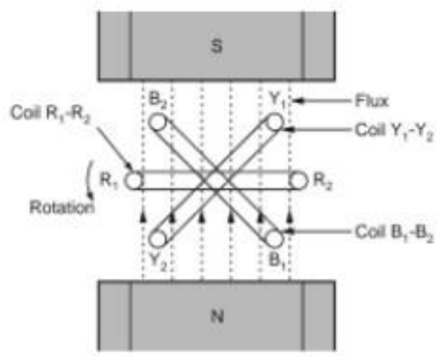

Fig. 1.3.1 Generation of 3 phase

- Let e_R, e_Y and e_B be the three independent voltages induced in coils R_1-R_2, Y_1-Y_2 and B_1 - B_2 respectively. All are alternating voltages having same magnitude and frequency as they are rotated at uniform speed.
- All of them will be displaced from one other by 120°.
- Suppose e_R is assumed to be the reference and is zero for the instant shown in the Fig. 1.3.2. At the same instant e_Y will be displaced by 120° from e_R and will follow e_R while e_B will be displaced by 120° from e_Y and will follow e_Y i.e. if e_R is reference then e_Y will attain its maximum and minimum position 120° later than e_R and e_B will attain its maximum and minimum position 120° later than e_Y i.e. 120°+120° = 240° later with respect to e_R. All coils together represent three phase supply system. The waveforms are shown in the Fig. 1.3.2.

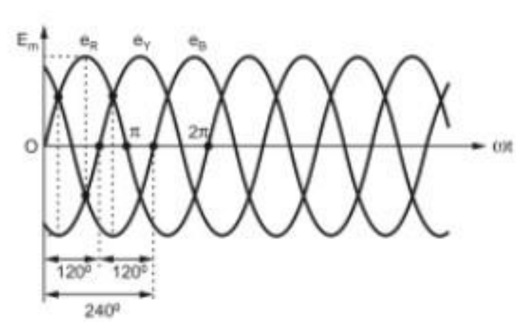

Fig. 1.3.2 Waveforms of 3 phase voltages

The equations for the induced voltages are :

$$
\begin{aligned}
e_R &= E_m \sin(\omega t) \\
e_Y &= E_m \sin(\omega t - 120°) \\
e_B &= E_m \sin(\omega t - 240°) \\
&= E_m \sin(\omega t + 120°)
\end{aligned}
$$

- The phasor diagram of these voltages can be shown as in the Fig. 1.3.3.

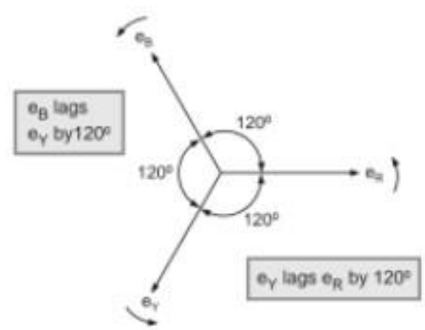

Fig. 1.3.3 Phasor diagram

- As phasors rotate in anticlockwise direction, we can say that e_Y lags e_R by 120° and e_B lags e_Y by 120°.
- If we add three voltages vectorially, it can be observed that the **sum of the three voltages at any instant is zero**.

Mathematically this can be shown as :

$$e_R + e_Y + e_B = E_m \sin\omega t + E_m \sin(\omega t - 120°) + E_m \sin(\omega t + 120°)$$

$$= E_m [\sin \omega t + \sin \omega t \cos 120° - \cos \omega t \sin 120° + \sin \omega t \cos 120° + \cos \omega t \sin 120°]$$

$$= E_m [\sin \omega t + 2 \sin \omega t \cos 120°] = E_m \left[\sin \omega t + 2 \sin \omega t \left(\frac{-1}{2}\right)\right] = 0$$

$\therefore$ $\boxed{\bar{e}_R + \bar{e}_Y + \bar{e}_B = 0}$

> The phasor addition of all the phase voltages at any instant in three phase system is always zero.

Review Questions

1. *State the principle of 3 phase e.m.f. generation and state the equations of all the three phase voltages. Represent them in graphical form.*
2. *Show that the sum of the instantaneous values of the voltages in a three phase system is always zero.*

1.4 Important Definitions Related to Three Phase System

1) Symmetrical system : It is possible in polyphase system that magnitudes of different alternating voltages are different. But a three phase system in which the three voltages are of same magnitude and frequency and displaced from each other by 120° phase angle is defined as **symmetrical system**.

2) Phase sequence : The sequence in which the voltages in three phases reach their maximum positive values is called **phase sequence**. Generally the phase sequence is R-Y-B.

> The phase sequence is important in determining direction of rotation of a.c. motors, parallel operation of alternators etc.

- There are two possible phase sequences which are RYB and RBY. The phase sequence of a three phase system can be changed by interchanging any two terminals out of R, Y and B. If three phase supply is given to a three phase motor with a phase sequence of RYB then by interchanging any two terminals of RYB the phase sequence can be reversed. Due to this the direction of motor gets reversed.

Review Questions

1. *Define symmetrical three phase system.*
2. *Define phase sequence and explain it's significance.*

1.5 Three Phase Supply Connections

- In single phase system, two wires are sufficient for transmitting voltage to the load i.e. phase and neutral. But in case of three phase system, two ends of each phase i.e. R_1-R_2, Y_1-Y_2, and B_1-B_2 are available to supply voltage to the load.
- If all the six terminals are used independently to supply voltage to load as shown in the Fig. 1.5.1, then total six wires will be required and it will be very much costly.

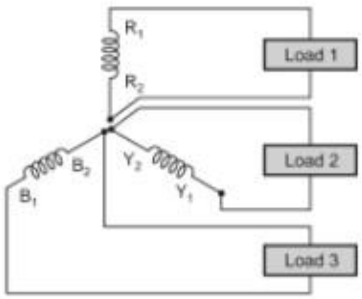

Fig. 1.5.1 Three phase connections

- To reduce the cost by reducing the number of windings, the three windings are interconnected in a particular fashion. This gives different three phase connections.

1.5.1 Star Connection

- The star connection is formed by connecting starting **or** terminating ends of all the three windings together. The ends R_1 - Y_1 - B_1 are connected or ends R_2 - Y_2 - B_2 are connected together. This common point is called **Neutral Point**. The remaining three ends are brought out for connection purpose. These ends are generally referred as R-Y-B, to which load is to be connected.
- The star connection is shown in the Fig. 1.5.2.

1.5.2 Delta Connection

- The delta is formed by connecting one end of winding to starting end of other and connections are continued to form a closed loop. The supply terminals are taken out from the three junction points. Delta connection always forms a closed loop.
- The delta connection is shown in the Fig. 1.5.3.

1.5.3 Concept of Line Voltages and Line Currents

- The potential difference between any two lines of supply is called **line voltage** and current passing through any line is called **line current**.
- Consider a star connected system as shown in the Fig. 1.5.4 see on next page.

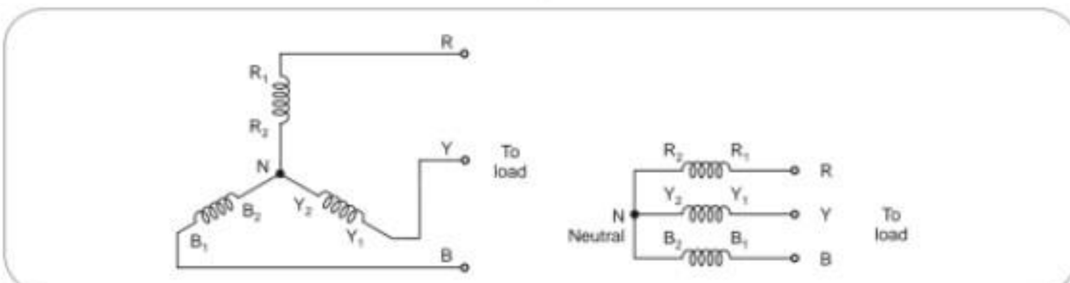

Fig. 1.5.2 Star connection

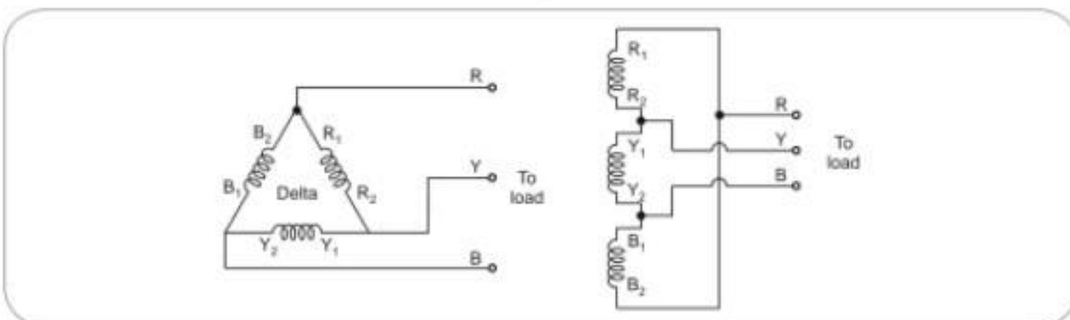

Fig. 1.5.3 Delta connection

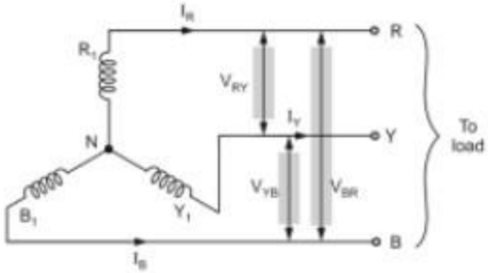

Fig. 1.5.4 Star connection

- Line voltages are denoted by V_L. These are V_{RY}, V_{YB} and V_{BR}.
- Line currents are denoted by I_L. These are I_R, I_Y and I_B.
- Similarly for delta connected system we can show the line voltages and line currents as in the Fig. 1.5.5.

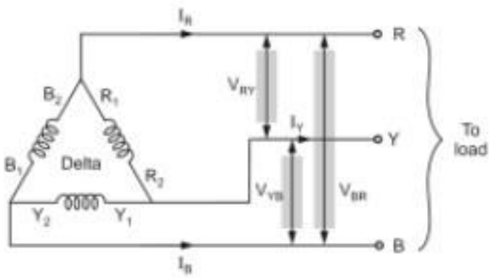

Fig. 1.5.5 Delta connection

Line voltages V_L are V_{RY}, V_{BR}, V_{YB}.

while Line currents I_L are I_R, I_Y and I_B.

1.5.4 Concept of Phase Voltages and Phase Currents

- To define the phase voltages and phase currents let us see the connections of the three phase load to the supply lines.
- The load can be connected in two ways,
  i) Star connection, ii) Delta connection
- The **three phase load** is nothing but three different impedances connected together in star or delta fashion.

i) Star connected load : There are three different impedances and are connected such that one end of each is connected together and other three are connected to supply terminals R-Y-B. This is shown in the Fig. 1.5.6.

> The voltage across any branch of the three phase load i.e. across Z_{ph1}, Z_{ph2} or Z_{ph3} is called **phase voltage** and current passing through any branch of the three phase load is called **phase current.**

- In the diagram shown in the Fig. 1.5.6 V_{RN}, V_{YN} and V_{BN} are phase voltages while I_R, I_Y and I_B as shown in the Fig. 1.5.6 are phase currents. The phase voltages are denoted as V_{ph} while the phase currents are denoted as I_{ph}. Generally suffix N is not indicated for phase voltages in star connected load. So $V_{ph} = V_R = V_Y = V_B$

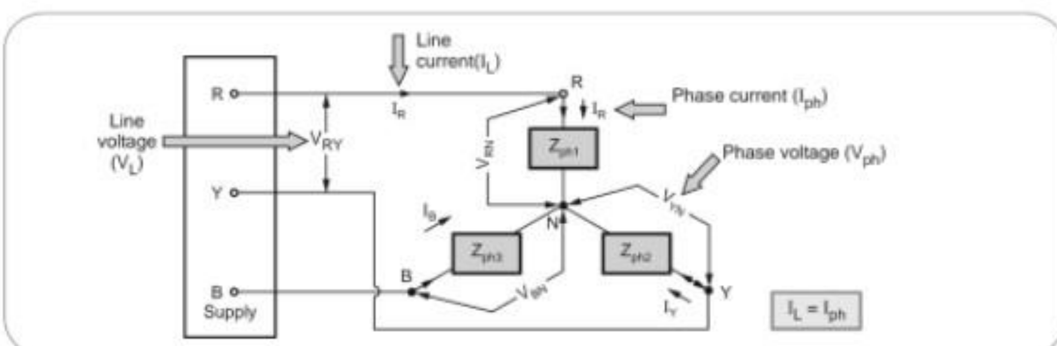

Fig. 1.5.6 Star connected load

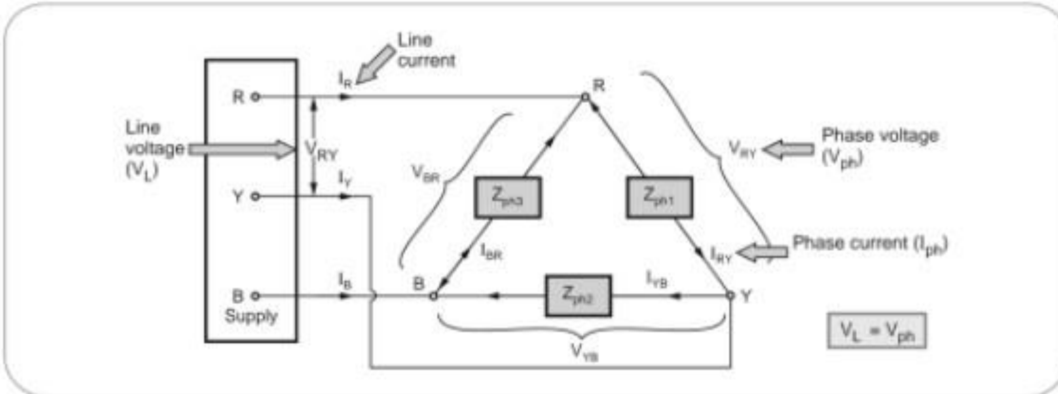

Fig. 1.5.7 Delta connected load

It can be seen from the Fig. 1.5.6 that,

$$I_{ph} = I_R = I_Y = I_B$$

- But same are the currents flowing through the three lines also and hence defined as line currents. Thus we can conclude that for star connection $I_L = I_{ph}$.

$$\mathbf{I_L = I_{ph}} \quad \textbf{(For star connection)}$$

ii) Delta connected load : If the three impedances Z_{ph1}, Z_{ph2} and Z_{ph3} are connected such that starting end of one is connected to terminating end of other, to form a closed loop it is called delta connection of load. The junction points are connected to supply terminals R-Y-B. This is shown in the Fig. 1.5.7.

- The current I_{RY}, I_{YB} and I_{BR} flowing through the various branches of the load are **phase currents**. The lines currents are I_R, I_Y, I_B flowing through supply lines. Thus in delta connection of load, line and phase currents are different.
- In the Fig. 1.5.7, the voltage across Z_{ph1} is V_{RY}, across Z_{ph2} is V_{YB} and across Z_{ph3} is V_{BR} and all are phase voltages.

$$V_{ph} = V_{RY} = V_{YB} = V_{BR}$$

- But as per definition of line voltages, same are the voltages across supply lines also. Thus it can be concluded that in delta connection $V_L = V_{ph}$.

$$\mathbf{V_L = V_{ph}} \quad \textbf{For delta connection}$$

1.5.5 Balanced and Unbalanced Loads

- The load is said to be balanced when **magnitudes** of all the impedances Z_{ph1}, Z_{ph2} and Z_{ph3} are **equal** and the **phase angles** of all of them are **equal** and of **same nature** either all inductive or all capacitive or all resistive.

In such case all phase voltages have equal magnitudes and are displaced from each other by 120° while all phase currents also have equal magnitudes and are displaced from each other by 120°.

The same is true for all the line voltages and line currents.

- The load is said to be unbalanced when **magnitudes** of all the impedances Z_{ph1}, Z_{ph2} and Z_{ph3} are **unequal** and the **phase angles** of all of them are **unequal**. In such a case the phase voltages are unequal and not displaced from each other by 120°. Same is true for phase currents.

Review Questions

1. *Explain the star connection of a three phase system.*
2. *Explain the delta connection of a three phase system.*
3. *Explain the concept of line voltages and line currents.*

4. *Explain the concept of phase voltages and phase currents.*
5. *Describe the meaning of three phase unbalanced load and balanced load ?*

1.6 Relations for Star Connected Load

AU : May-11,14,15,16, Dec.-10,12,15

- Consider the balanced star connected load as shown in the Fig. 1.6.1.

Line voltages,

$$V_L = V_{RY} = V_{YB} = V_{BR}$$

and Line currents,

$$I_L = I_R = I_Y = I_B$$

Phase voltages,

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

and Phase currents,

$$I_{ph} = I_R = I_Y = I_B$$

As seen earlier,

$I_L = I_{ph}$ for star connected load.

To derive relation between V_L and V_{ph}, consider line voltage V_{RY}. From the Fig. 1.6.1 we can write,

$$\overline{V}_{RY} = \overline{V}_{RN} + \overline{V}_{NY} \quad \text{But} \quad \overline{V}_{NY} = -\overline{V}_{YN},$$

Hence $\quad \overline{V}_{RY} = \overline{V}_R - \overline{V}_Y \quad \dots (1.6.1)$

Similarly, $\quad \overline{V}_{YB} = \overline{V}_{YN} + \overline{V}_{NB} = \overline{V}_{YN} - \overline{V}_{BN}$

$$= \overline{V}_Y - \overline{V}_B \quad \dots (1.6.2)$$

and $\quad \overline{V}_{BR} = \overline{V}_B - \overline{V}_R \quad \dots (1.6.3)$

- The three phase voltage are displaced by 120° from each other.
- The phasor diagram to get V_{RY} is shown in the Fig. 1.6.2. The V_Y is reversed to get $-V_Y$ and then it is added to V_R to get V_{RY}.

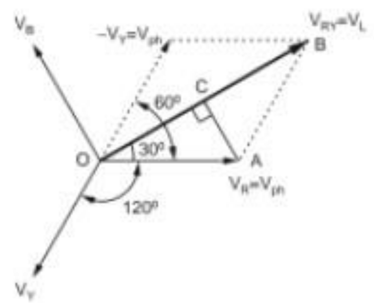

Fig. 1.6.2

- The perpendicular is drawn from point A on vector OB representing V_L.
- In triangle OAB, the sides OA and AB are same as phase voltages. Hence OB bisects angle between V_R and $-V_Y$.

$\therefore \quad \angle BOA = 30°$

- And perpendicular AC bisects the vector OB.

$\therefore \quad OC = CB = \frac{V_L}{2}$

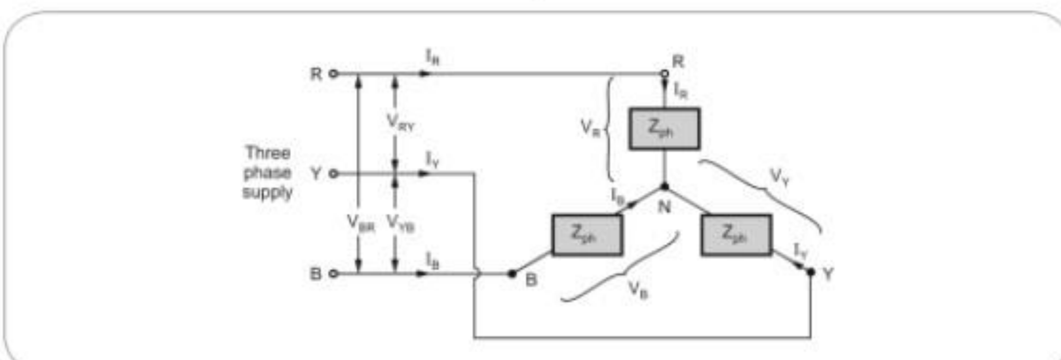

Fig. 1.6.1 Star connected load

From triangle OAB,

$$\cos 30^\circ = \frac{OC}{OA} = \frac{(V_{RY}/2)}{V_R}$$

i.e. $$\frac{\sqrt{3}}{2} = \frac{(V_L/2)}{V_{ph}}$$

$\therefore$ $\mathbf{V_L = \sqrt{3}\ V_{ph}}$ for star connection

and $\mathbf{I_L = I_{ph}}$

Thus line voltage is $\sqrt{3}$ times the phase voltage in star connection.

- The lagging or leading nature of current depends on per phase impedance. If Z_{ph} is inductive i.e. $R + j\ X_L$ then current I_{ph} lags V_{ph} by angle ϕ where ϕ is $\tan^{-1}(X_L/R)$. If Z_{ph} is capacitive i.e. $R - j\ X_C$ then I_{ph} leads V_{ph} by angle ϕ. If Z_{ph} is resistive i.e. $R + j\,0$ then I_{ph} is in phase with V_{ph}.

Remember that $\mathbf{Z_{ph}}$ relates $\mathbf{I_{ph}}$ and $\mathbf{V_{ph}}$ hence angle ϕ is always between $\mathbf{I_{ph}}$ and $\mathbf{V_{ph}}$ and not between the line values.

And $$|Z_{ph}| = \frac{|V_{ph}|}{|I_{ph}|}$$

Key Point : The line values do not decide the impedance angle or power factor angle.

- The complete phasor diagram for lagging power factor load is shown in the Fig. 1.6.3.

$$Z_{ph} = R_{ph} + j\ X_{Lph} = |Z_{ph}| \angle \phi\ \ \Omega$$

- Each I_{ph} lags corresponding V_{ph} by angle ϕ.
- All line voltages are also displaced by 120° from each other.

Every line voltage leads the respective phase voltage by 30°.

For star connection, to draw phasor diagram, use

$$\bar{V}_{RY} = \bar{V}_R - \bar{V}_Y,$$

$$\bar{V}_{YB} = \bar{V}_Y - \bar{V}_B \quad \text{and} \quad \bar{V}_{BR} = \bar{V}_B - \bar{V}_R$$

Power : The power consumed in each phase is single phase power given by,

$$P_{ph} = V_{ph}\ I_{ph}\ \cos\phi$$

For balanced load, all phase powers are equal. Hence total three phase power consumed is,

$$P = 3P_{ph} = 3\ V_{ph}\ I_{ph}\ \cos\phi$$

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

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

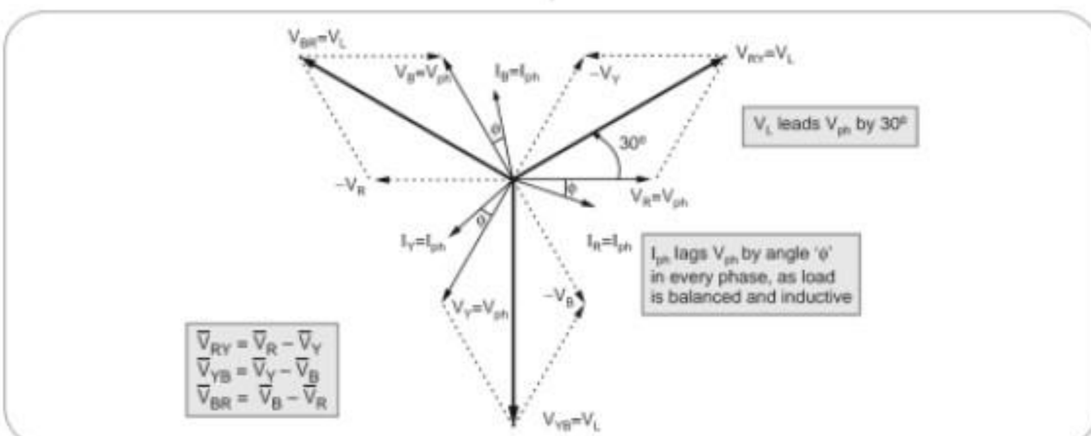

Fig. 1.6.3 Star and lagging p.f. load