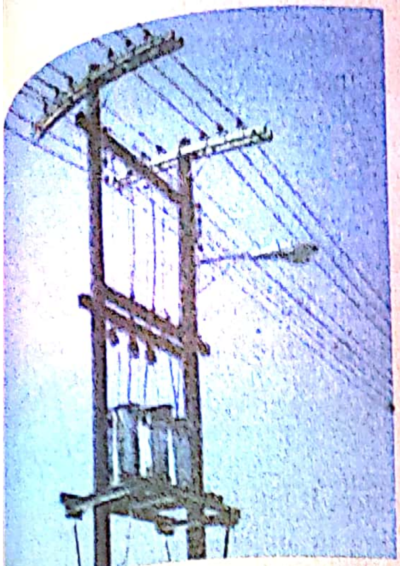




# 19

# Three-Phase Circuits

## INTRODUCTION

The a.c. circuits discussed so far in the book are termed as single phase circuits because they contain a single alternating current and voltage wave. The generator producing a single phase supply (called single-phase generator) has only one armature winding. But if the generator is arranged to have two or more separate windings displaced from each other by equal electrical angles, it is called a *polyphase generator and will produce as many independent voltages as the number of windings or phases. The electrical displacement between the windings depends upon the number of windings or phases. For example, a 2-phase generator has two separate but identical windings that are 90° electrical apart and rotate in a common magnetic field. Obviously, such a generator will produce two alternating voltages of the same magnitude and frequency having a phase difference of 90°. Similarly, a 3-phase generator has three separate but identical windings that are 120° electrical apart and

* The electrical displacement between the windings is determined by the number of phases or windings. For a 2-phase alternator, the two windings are displaced by 90 electrical degrees. For other polyphase systems (*e.g*,. 3-phase, 6-phase), the electrical displacement between different phases or windings is equal to 360/N where N is the number of phases. Thus, for a 3-phase alternator, the three windings are 120 electrical degrees apart.

rotate in a common magnetic field. A 3-phase generator will, therefore, produce three voltages of same magnitude and frequency but displaced 120° electrical from one another. Although other polyphase systems are possible, the 3-phase system is by far the most popular. In this chapter, we shall confine our attention to 3-phase system.

## 19.1. POLYPHASE SYSTEMS

Fig. 19.1 shows the generation of single-phase, two-phase and 3-phase voltages.

(i) Fig. 19.1 (i) shows an elementary single-phase alternator. It has one winding or coil rotating in anticlockwise direction with an angular velocity $\omega$ in the 2-pole field. The equation of the e.m.f. induced in the coil is given by;

$$e_{a_1a_2} = E_m \sin \omega t$$

(ii) Fig. 19.1 (ii) shows an elementary two-phase alternator. It has two identical coils A and B displaced 90° electrical from each other and rotating in anticlockwise direction with angular velocity $\omega$ in the 2-pole field. The wave diagram is shown in Fig. 19.1 (ii). Note that the e.m.f. in coil A leads that in coil B by 90°. The equations of the two e.m.f.s are:

$$e_{a_1a_2} = E_m \sin \omega t$$

$$e_{b_1b_2} = E_m \sin (\omega t - 90°)$$

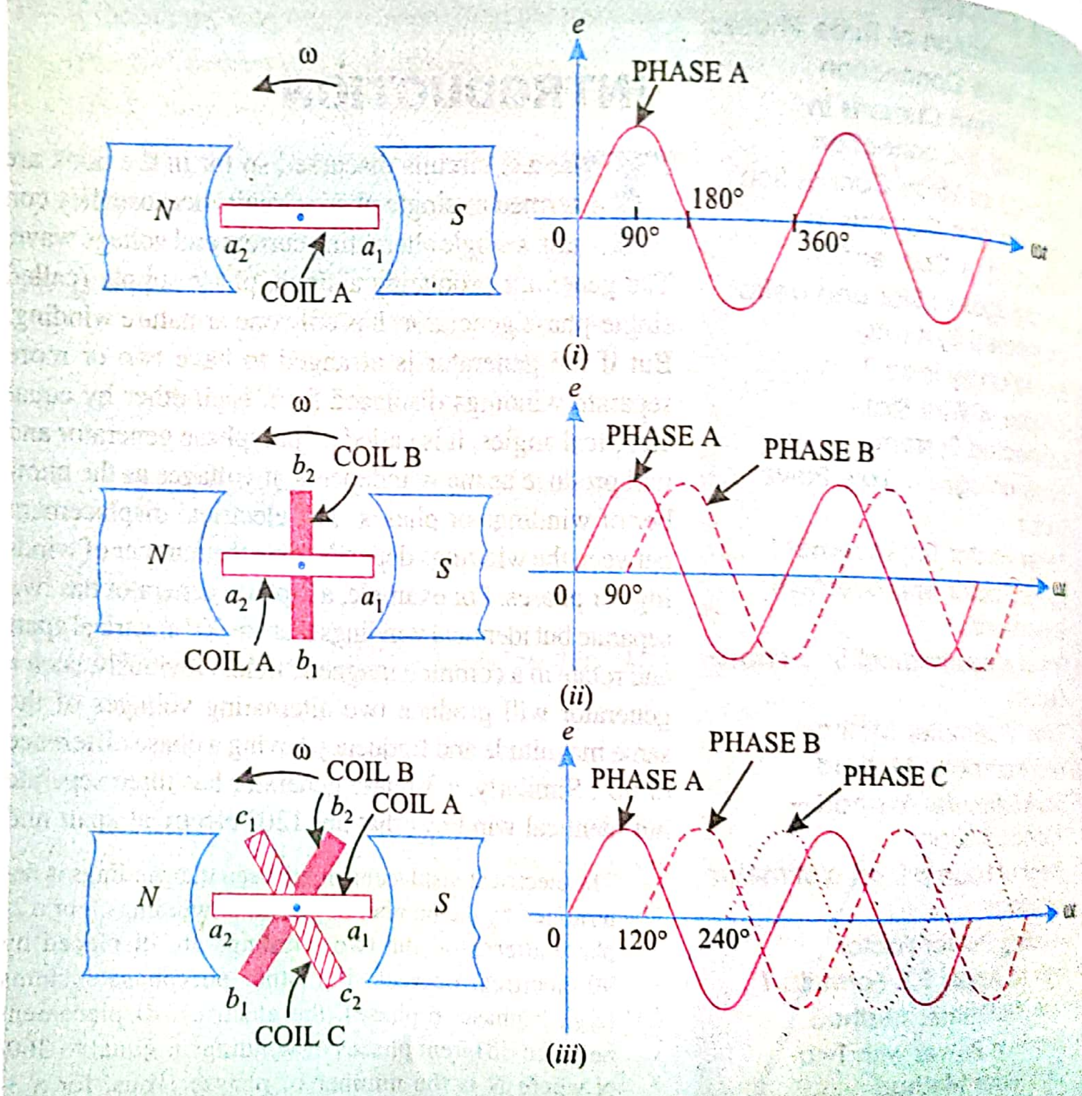



Fig. 19.1

(iii) Fig. 19.1 (*iii*) shows an elementary 3-phase alternator. It has three identical windings or coils *A*, *B* and *C* displaced *120 electrical degrees from each other and rotating in anticlockwise direction with angular velocity $\omega$ in the 2-pole field. Fig. 19.1 (*iii*) shows the wave diagram. Note that e.m.f. in coil *B* will be 120° behind that of coil *A* and e.m.f. in coil *C* will be 240° behind that of coil *A*. The equations of the three e.m.f.s can be represented as :

$$e_{a_1a_2} = E_m \sin \omega t$$
$$e_{b_1b_2} = E_m \sin (\omega t - 120°)$$
$$e_{c_1c_2} = E_m \sin (\omega t - 240°)$$

## 19.2. REASONS FOR THE USE OF 3-PHASE SYSTEM

Electric power is generated, transmitted and distributed in the form of 3-phase power. Homes and small establishments are wired for single phase power but this merely represents a tap-off from the basic 3-phase system. Three-phase power is preferred over single-phase power for the following reasons :

(*i*) 3-phase power has a constant magnitude whereas single-phase power pulsates from zero to peak value at twice the supply frequency.

(*ii*) A 3-phase system can set up a rotating magnetic field in stationary windings. This cannot be done with a single-phase current.

(*iii*) For the same rating, 3-phase machines (*e.g.*, generators, motors, transformers) are smaller, simpler in construction and have better operating characteristics than single phase machines.

(*iv*) To transmit the same amount of power over a fixed distance at a given voltage, the 3-phase system requires only three-fourth the weight of copper that is required by the single-phase system.

(*v*) The voltage regulation of a 3-phase transmission line is better than that of a single-phase line.

A knowledge of 3-phase power and 3-phase circuits is, therefore, essential to an understanding of power technology. Fortunately, the basic circuit techniques used to solve single-phase circuits can be directly applied to 3-phase circuits. It is because the three phases are identical and one phase (*i.e.*, single phase) represents the behaviour of all the three.

## 19.3. ELEMENTARY THREE-PHASE ALTERNATOR

In an actual 3-phase alternator, the three windings or coils are stationary and the field **rotates. Fig. 19.2 (*i*) shows an elementary 3-phase alternator. The three identical coils *A*, *B* and *C* are symmetrically placed in such a way that e.m.f.s induced in them are displaced 120 electrical degrees from one another. Since the coils are identical and are subjected to the same rotating field, the e.m.f.s induced in them will be of the same magnitude and frequency. Fig. 19.2 (*ii*) shows the wave diagram of the three e.m.f.s whereas Fig. 19.2 (*iii*) shows the phasor diagram. Note that r.m.s. values have been used in drawing the phasor diagram. The equations of the three e.m.f.s are :

$$e_A = E_m \sin \omega t$$
$$e_B = E_m \sin (\omega t - 120°)$$
$$e_C = E_m \sin (\omega t - 240°)$$

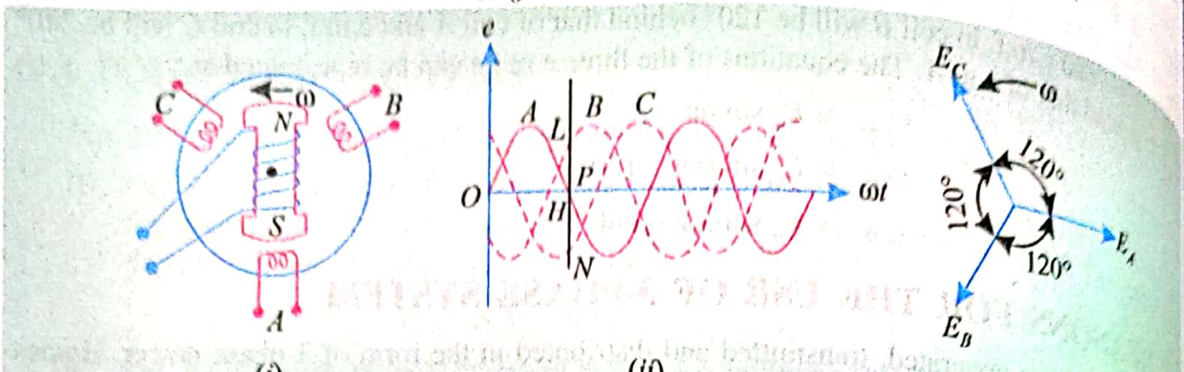
It can be proved in many ways that the sum of the three e.m.f.s at every instant is zero.

(*i*) $$\text{Resultant} = e_A + e_B + e_C$$
$$= E_m [\sin \omega t + \sin (\omega t - 120°) + \sin (\omega t - 240°)]$$

* This can be accomplished by placing their start ends (denoted by $a_1$, $b_1$ and $c_1$) 120 electrical degrees apart.

** This arrangement has many technical and economical advantages.

$$= E_m\,[\sin \omega t + 2 \sin (\omega t - 180°) \cos 60°]$$
$$= E_m\,[\sin \omega t - 2 \sin \omega t \cos 60°]$$
$$= 0$$




(i) (ii) (iii)

**Fig. 19.2**

*(ii)* Referring to the wave diagram in Fig. 19.2 (*ii*), the sum of the three e.m.f.s at any instant is zero. For example, at the instant *P*, ordinate *PL* is positive while the ordinates *PN* and *PH* are negative. If you make actual measurements, it will be seen that :

$$PL + (-PN) + (-PH) = 0$$

*(iii)* Since the three windings or coils are identical, $E_A = E_B = E_C = E$ (in magnitude). As shown in Fig. 19.3, the resultant of $E_A$ and $E_B$ is $E_r$ and its magnitude is $= 2E \cos 60° = E$. This resultant is equal and opposite to $E_C$. Hence the resultant of the three e.m.f.s is zero.

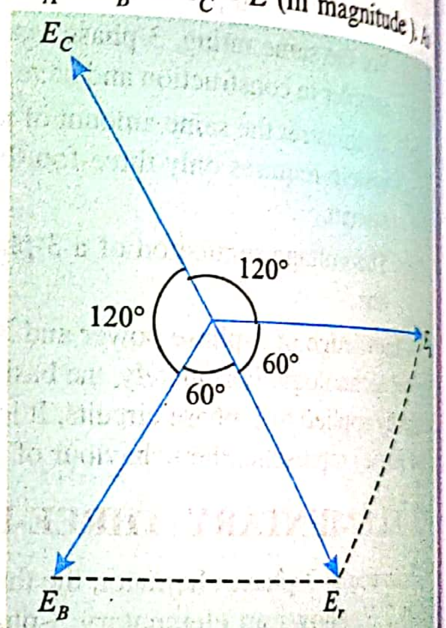



**Fig. 19.3**

*(iv)* Using complex algebra, we can again prove that the sum of the three e.m.f.s is zero. Thus, taking $E_A$ as the reference phasor, we have,

$$\mathbf{E}_A = E\angle 0° = E + j\,0$$
$$\mathbf{E}_B = E\angle -120°$$
$$= E\,(-0.5 - j\,0.866)$$
$$\mathbf{E}_C = E\angle -240°$$
$$= E\,(-0.5 - j\,0.866)$$
$$\therefore\ \mathbf{E}_A + \mathbf{E}_B + \mathbf{E}_C = (E + j\,0) + E\,(-0.5 - j\,0.866)$$
$$+ \mathrm{E}\,(-0.5 + j\,0.866) = 0$$

## 19.4. SOME CONCEPTS

In the analysis of 3-phase system, we often come across the following terms :

*(i)* **Phase sequence.** The order in which the voltages in the three phases (or coils) reach their *maximum positive values is called the *phase sequence* or *phase order*. This is determined by the direction of rotation of the alternator. Thus, in Fig. 19.2 (*i*), the three coils *A*, *B* and *C* are producing voltages that are displaced 120 electrical degrees from one another. Referring to the wave diagram in Fig. 19.2 (*ii*), it is easy to see that voltage in coil *A* attains maximum positive value first, next coil *B* and then coil *C*. Hence the phase sequence is *ABC*. If the direction of rotation of the alternator is reversed, then the order in which the three phases attain their maximum positive values would be *ACB*. Hence the phase sequence is now *ACB i.e.*, voltage in coil *A* attains maximum positive value first, next coil *C* and then coil *B*. Since the alternator can be rotated in either clockwise or anticlockwise direction, there can be only two possible phase sequences.

* Instead of the positive maximum value, any other instantaneous value can be used to determine the phase sequence.

(ii) **Naming the phases.** The three phases or windings may be numbered (1, 2, 3) or lettered (A, B, C). However, it is a usual practice to name the three phases or windings after the three natural colours viz. red (R), yellow (Y) and blue (B). In that case, the phase sequence is *RYB*, *i.e.* voltage in phase R attains maximum positive value first, next phase Y and then phase B. It may be noted that there are only two possible phase sequences viz *RYB* and *RBY*. By convention, sequence *RYB* is taken as positive and *RBY* as negative. Throughout this book, the phase sequence considered is *RYB* unless stated otherwise.

(iii) **Double-subscript notation.** The double-subscript notation is a very useful concept and may be found advantageous in the analysis of 3-phase system. In this notation, two letters are placed at the foot of the symbol for voltage or current. The two letters indicate the two points between which voltage (or current) exists and the order of the letters indicates the relative polarity of voltage (or current) during *positive half-cycle.

(a) Thus, $V_{RY}$ indicates a voltage $V$ between points $R$ and $Y$ with point $R$ being positive *w.r.t.* point $Y$ during its positive half-cycle. On the other hand, $V_{YR}$ means that point $Y$ is positive *w.r.t.* point $R$ during its positive half-cycle.

Obviously, $$V_{RY} = -V_{YR}$$

(b) Again $I_{RY}$ indicates a current $I$ between points $R$ and $Y$ and that its direction is from $R$ to $Y$ during its positive half-cycle. The advantage of double-subscript notation lies in the fact that a formal description of voltage or current under consideration is not necessary; the subscripts and the order of the subscripts describe the quantity completely.

## 19.5. INTERCONNECTION OF THREE PHASES

In a 3-phase alternator, there are three windings or phases. Each phase has two terminals viz. start and finish. If a separate load is connected across each winding as shown in Fig. 19.4, 6 conductors are required to transmit power. This will make the whole system complicated and expensive. In practice, the three windings are interconnected to give rise to two methods of connections *viz.*

(i) Star or Wye (Y) connection (ii) Mesh or Delta (Δ) connection

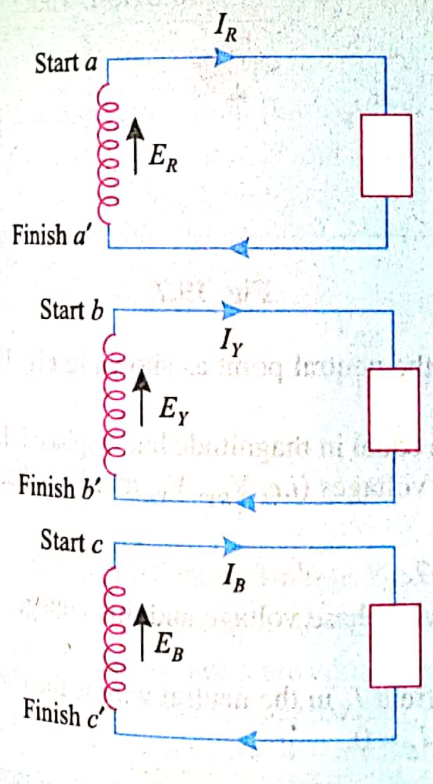
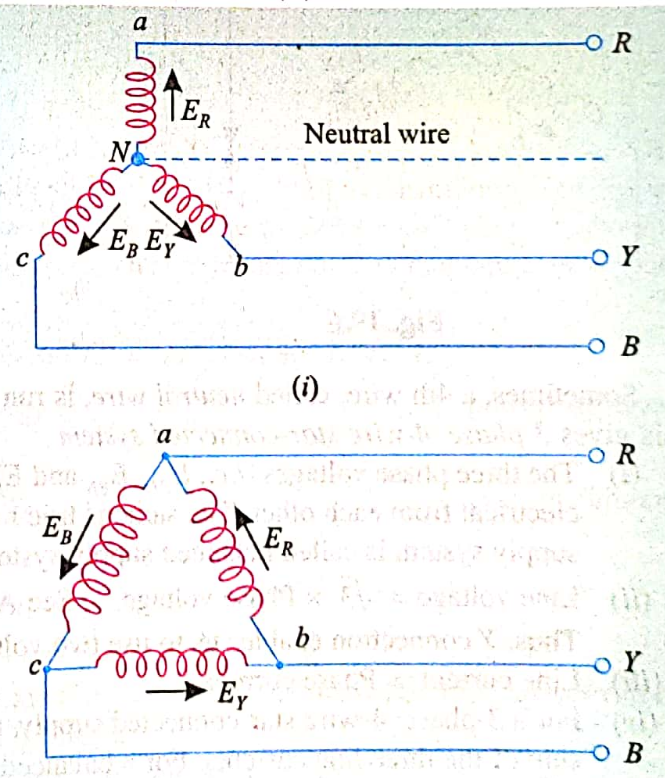



**Fig. 19.4**




(ii)

**Fig. 19.5**

* One may consider negative half-cycle. This criterion must be applied to all the three phases.

(i) In Y-connection, similar ends (start or finish) of the three phases are joined together within the alternator and three lines are run from the other free ends as shown in Fig. 19.5 (i). The common point N is called neutral point. In Y-connection, neutral conductor (shown dotted) may or may not be brought out. If a neutral conductor exists, the system is called 3-phase, *4-wire system*. If there is no neutral conductor, it is called *3-phase, 3-wire system*.

(ii) In Δ-connection, dissimilar ends (start to finish) of the phases are joined to form a closed mesh and the three lines are run from the junction points as shown in Fig. 19.5 (ii). In a Δ-connection, no neutral point exists and only *3-phase, 3-wire system* can be formed.

**Note.** The Y or delta connection serves substantially all the functions of three separate single phase circuits but with one important advantage that the number of conductors required is reduced. This results in the saving of conductor material and hence leads to economy.

## 19.6. STAR OR WYE CONNECTION

In this method, *similar ends* (start or finish) of the three phases are joined together to form a common junction N as shown in Fig. 19.6. The common junction N is called the *star point or neutral point*. The three line conductors are run from the three free ends (finish ends F in this case) and are designated as R, Y and B. This constitutes a *3-phase, 3-wire star-connected system*. The voltage between any line and the neutral point (*i.e.*, voltage across each winding) is called the *phase voltage* while the voltage between any two lines is called the *line voltage*. The currents flowing in the phases are called the *phase currents* while those flowing in the lines are called the *line currents*. Note that the phase sequence is *RYB*.

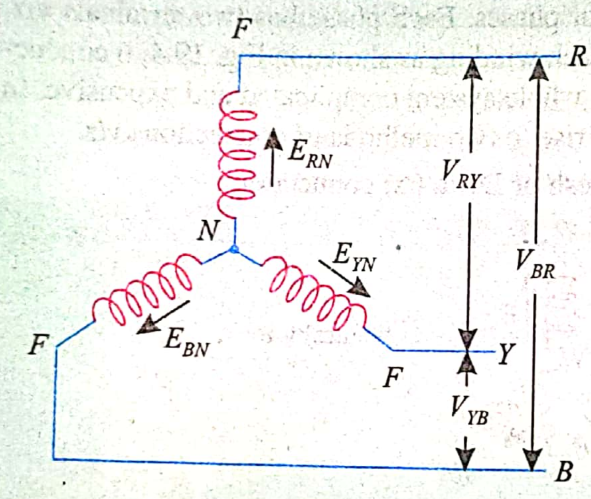



Fig. 19.6

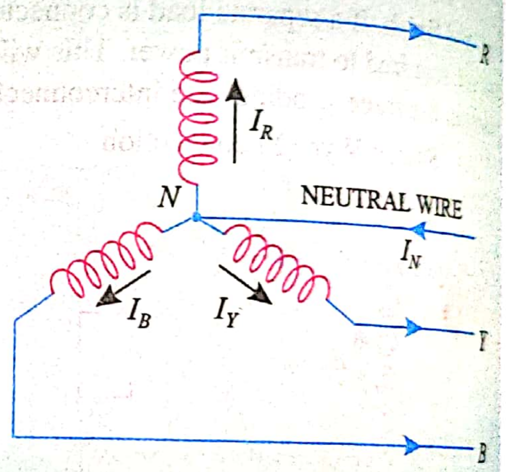



Fig. 19.7

Sometimes, a 4th wire, called *neutral wire*, is run from the neutral point as shown in Fig. 19.7. This gives *3-phase, 4-wire star-connected system*.

(i) The three phase voltages (*i.e.*, $E_{RN}$, $E_{YN}$ and $E_{BN}$) are equal in magnitude but displaced 120° electrical from each other. The same is true for line voltages (*i.e.* $V_{RY}$, $V_{YB}$ and $V_{BR}$). Such a supply system is called balanced supply system.

(ii) Line voltage = $\sqrt{3}$ × Phase voltage ... See Art. 19.7.

Thus, Y connection enables us to use two voltages viz. phase voltage and line voltage.

(iii) Line current = Phase current

(iv) For a 3-phase, 4-wire star-connected supply, the current $I_N$ in the neutral wire is the phasor sum of the three line currents. For a balanced load, $I_N = 0$.

* The reader may note that the figure looks like a star or inverted Y. Hence, the name. But it is a misnomer. It is because star-connected windings can be represented diagramatically in a manner which does not look like a star or inverted Y.

*Note.* The arrowheads alongside currents (or voltages) indicate their directions when they are assumed to be positive and not their actual directions at a particular instant. At no instant will *all the three line currents flow in the same direction either outwards or inwards.* This is expected because the three line currents are displaced 120° from one another. When one is positive, the other two might both be negative or one positive and one negative. Thus, at any one instant, current flows from the alternator through one of the lines to the load and returns through the other two lines. Or else current flows from the alternator through two of the lines and returns by means of the third.

## 19.7. VOLTAGES AND CURRENTS IN BALANCED Y-CONNECTION

Fig. 19.8 shows a balanced 3-phase $Y$-connected system in which the r.m.s. values of the *e.m.f.s* generated in the three phases are $E_{RN}$, $E_{YN}$ and $E_{BN}$. It is clear from the circuit diagram (See Fig. 19.8) that p.d. between any two line terminals (*i.e.*, line voltage) is the phasor difference between the potentials of these terminals *w.r.t.* neutral point *i.e.*,

P.D. between lines $R$ and $Y$, $\quad$ *$V_{RY} = E_{RN} - E_{YN}$ $\quad$ ... *phasor difference*

P.D. between lines $Y$ and $B$, $\quad$ $V_{YB} = E_{YN} - E_{BN}$ $\quad$ ... —do—

P.D. between lines $B$ and $R$, $\quad$ $V_{BR} = E_{BN} - E_{RN}$ $\quad$ ...—do—

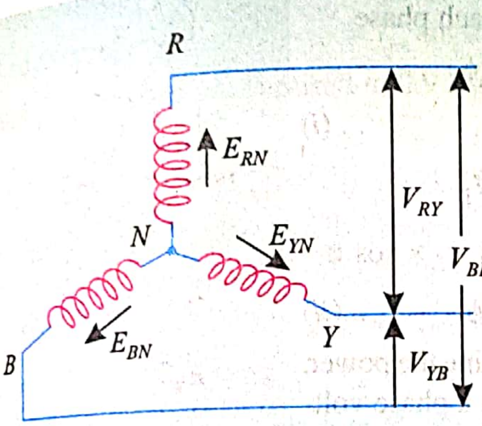



Fig. 19.8

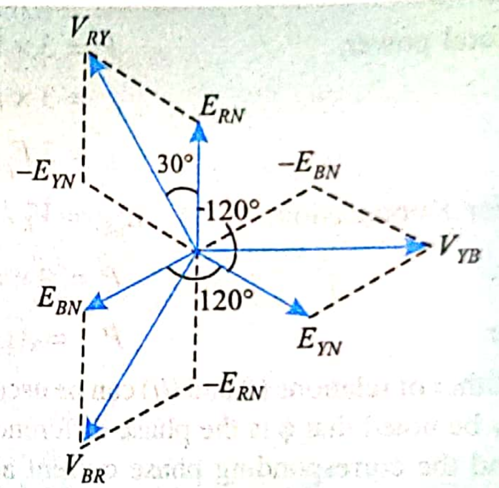



Fig. 19.9

### 1. Relation between line voltage and phase voltage

Considering the lines $R$ and $Y$, the line voltage $V_{RY}$ is equal to the phasor difference of $E_{RN}$ and $E_{YN}$. To subtract $E_{YN}$ from $E_{RN}$, reverse the phasor $E_{YN}$ and find its phasor sum with $E_{RN}$ as shown in the phasor diagram in Fig. 19.9. The two phasors $E_{RN}$ and $-E_{YN}$ are equal in magnitude ($= E_{ph}$) and are 60° apart.

$\therefore$ $\quad$ $V_{RY} = 2E_{ph}\cos(60°/2) = 2E_{ph}\cos 30° = \sqrt{3}\,E_{ph}$

Similarly, $\quad$ $V_{YB} = E_{YN} - E_{BN}$ $\quad$ ... *phasor difference*

$= \sqrt{3}\,E_{ph}$

and $\quad$ $V_{BR} = E_{BN} - E_{RN}$ $\quad$ ... *phasor difference*

$= \sqrt{3}\,E_{ph}$

Hence in a balanced 3-phase $Y$-connection,

(*i*) Line voltage, $V_L = \sqrt{3}\ E_{ph}$

(*ii*) All line voltages are equal in magnitude (*i.e.*, $= \sqrt{3}\,E_{ph}$) but displaced 120° apart from one another (See the phasor diagram in Fig. 19.9).

(*iii*) Line voltages are 30° ahead of their respective phase voltages.

---

* $V_{RY} = E_{RN} + E_{NY}$ ......... phasor sum

$= E_{RN} - E_{YN}$ ......... phasor difference

Between lines $R$ and $Y$, there is point $N$ (*i.e.*, neutral point). The voltage $V_{RY}$ is the phasor sum of voltages from $R$ to $N$ and $N$ to $Y$.

**2. Relation between line current and phase current**

In $Y$-connection, each line conductor is connected in series to a separate phase as shown in Fig. 19.10. Therefore, current in a line conductor is the same as that in the phase to which the line conductor is connected.

∴ Line current, $I_L = I_{ph}$

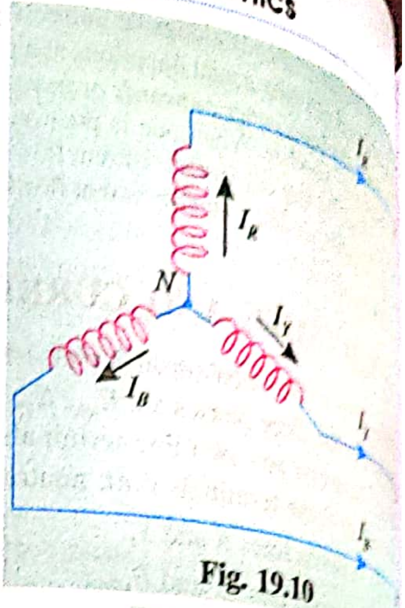


Fig. 19.10

Fig. 19.11 shows the phasor diagram for a balanced lagging load; the phase angle being $\phi$.

Hence in a balanced 3-phase Y-connection :

(*i*) Line current, $I_L = I_{ph}$

(*ii*) All the line currents are equal in magnitude (*i.e.*, $= I_{ph}$) but displaced 120° from one another.

(*iii*) The angle between the line currents and the corresponding line voltages is $30° \pm \phi$; + if p.f. is lagging and − if it is leading.

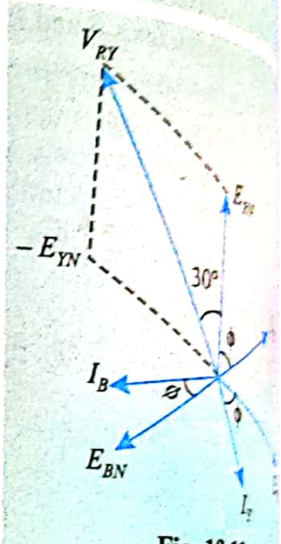


Fig. 19.11

**Power**

$$\text{Total power,} \quad P = 3 \times \text{Power in each phase}$$
$$= 3 \times E_{ph} I_{ph} \cos\phi$$
$$= 3\, E_{ph} I_{ph} \cos\phi \quad \text{... } (i)$$

For $Y$-connection, $E_{ph} = V_L/\sqrt{3};\ I_{ph} = I_L$

$$\therefore \quad P = 3 \times (V_L/\sqrt{3}) \times I_L \times \cos\phi$$

or
$$P = \sqrt{3}\, V_L I_L \cos\phi \quad \text{...}(ii)$$

Either of relations (*i*) and (*ii*) can be used to determine the power. It may be noted that $\phi$ is the phase difference between a phase voltage and the corresponding phase current and *not* between the line current and corresponding line voltage.

**Example 19.1.** *Three coils, each having a resistance of 20 Ω and an inductive reactance 15 Ω, are connected in star to a 400V, 3-phase, 50Hz supply. Calculate (i) the line current, (ii) power factor, and (iii) power supplied.*

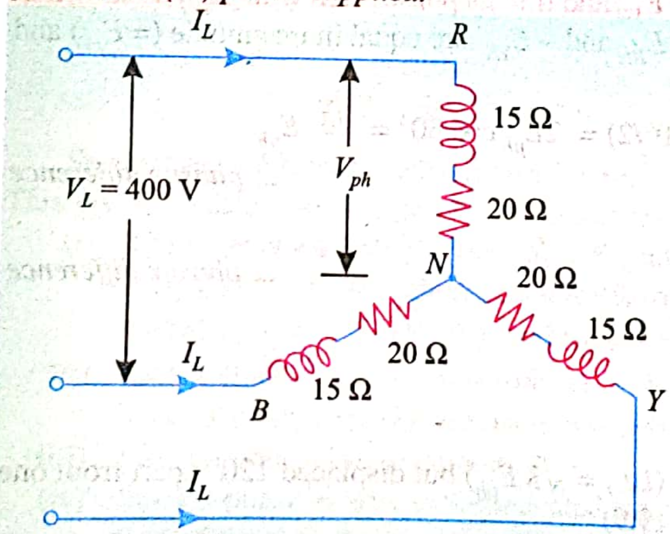


Fig. 19.12

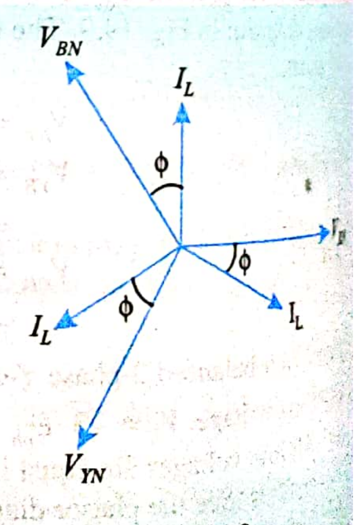


Fig. 19.13

**Solution.**

$$V_{ph} = V_L/\sqrt{3} = 400/\sqrt{3} = 231V$$
$$Z_{ph} = \sqrt{20^2 + 15^2} = 25\ \Omega$$

$$I_{ph} = V_{ph}/Z_{ph} = 231/25 = 9.24 \text{ A}$$

(i) $$I_L = I_{ph} = 9.24 \text{ A}$$

(ii) $$p.f. = \cos\phi = R_{ph}/Z_{ph} = 20/25 = 0.8 \text{ lag}$$

(iii) $$P = \sqrt{3} V_L I_L \cos\phi = \sqrt{3} \times 400 \times 9.24 \times 0.8 = 5121 \text{ W}$$

Alternatively, $$P = 3I_{ph}^2 R_{ph} = 3 \times (9.24)^2 \times 20 = 5121 \text{ W}$$

**Example 19.2.** *Calculate the active and reactive components of current in each phase of a star-connected 10,000 volts, 3-phase generator supplying 5,000 kW at a lagging p.f. 0.8. Find the new output if the current is maintained at the same value but the p.f. is raised to 0.9 lagging.*

**Solution.** $$P = \sqrt{3} V_L I_L \cos\phi$$

or $$I_L = \frac{P}{\sqrt{3} V_L \cos\phi} = \frac{5000 \times 10^3}{\sqrt{3} \times 10{,}000 \times 0.8} = 360.8 \text{ A}$$

$\therefore$ $$I_{ph} = I_L = 360.8 \text{ A}$$

Active component $$= I_{ph} \cos\phi = 360.8 \times 0.8 = 288.64 \text{ A}$$

Reactive component $$= I_{ph} \sin\phi = 360.8 \times 0.6 = 216.48 \text{ A}$$

Power output when p.f. is raised to 0.9 lagging

$$= \sqrt{3} \times 10{,}000 \times 360.8 \times 0.9 = 5624 \times 10^3 \text{ W}$$

**Example 19.3.** *A balanced star-connected load of impedance (6 + j8) ohms per phase is connected to a 3-phase, 230V, 50Hz supply. Find the line current and power absorbed by each phase.*

**Solution.**
$$Z_{ph} = \sqrt{6^2 + 8^2} = 10 \, \Omega$$
$$V_{ph} = V_L/\sqrt{3} = 230/\sqrt{3} = 133 \text{ V}$$
$$\cos\phi = R_{ph}/Z_{ph} = 6/10 = 0.6 \text{ lag}$$
$$I_{ph} = V_{ph}/Z_{ph} = 133/10 = 13.3 \text{ A}$$

$\therefore$ Line current, $$I_L = I_{ph} = 13.3 \text{ A}$$

Power absorbed/phase $$= V_{ph} I_{ph} \cos\phi = 133 \times 13.3 \times 0.6 = 1061 \text{ W}$$

**Example 19.4.** *Three 50-ohm resistors are connected in star across 400V, 3-phase supply.*
(i) *Find phase current, line current and power taken from the mains.*
(ii) *What would be the above values if one of the resistors were disconnected ?*

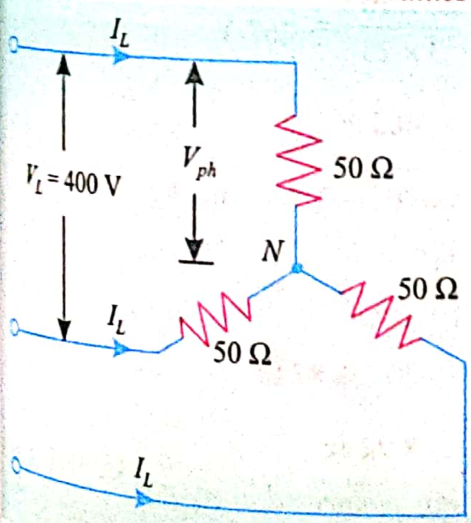



**Fig.19.14**

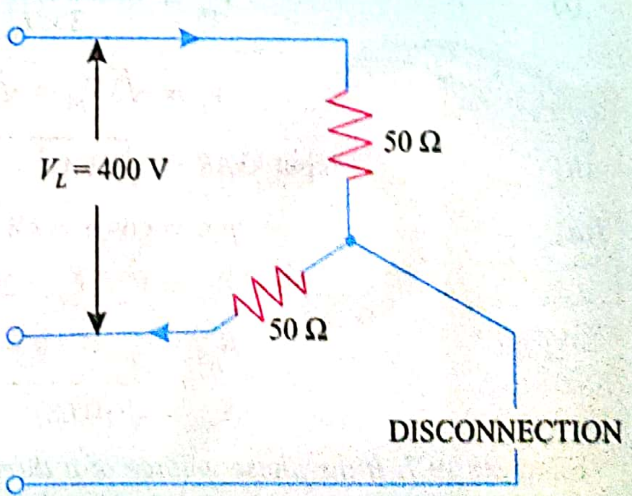



**Fig. 19.15**

**Solution.** $V_L = 400V;\ V_{ph} = 400/\sqrt{3} = 231V;\ R_{ph} = 50\Omega;\ \cos\phi = 1$

(*i*) **When the three resistors are star-connected** [See Fig. 19.14].

$$I_{ph} = V_{ph}/R_{ph} = 231/50 = \mathbf{4.62\ A}$$

$$\therefore \quad I_L = I_{ph} = \mathbf{4.62\ A}$$

Power taken, $P = \sqrt{3}\, V_L\, I_L \cos\phi = \sqrt{3} \times 400 \times 4.62 \times 1 = \mathbf{3200\ W}$

(*ii*) **When one of the resistors is disconnected.** When one of the resistors is disconnected [See Fig. 19.15], the remaining two resistors behave as if they were connected in series across the line voltage. In fact, the circuit behaves as a single phase circuit.

$$\therefore \quad I_{ph} = I_L = \frac{400}{50 + 50} = \mathbf{4\ A}$$

Power taken, $P = V_L I_L \cos\phi = 400 \times 4 \times 1 = \mathbf{1600\ W}$

Hence, by disconnecting one of the resistors, power consumption is reduced by half.

**Example 19.5.** *Three similar coils, connected in star, take a total power of 1.5 kW at a p.f. 0.2 lagging from a 3-phase, 400V, 50Hz supply. Calculate the resistance and inductance of each coil.*

**Solution.** $V_{ph} = V_L/\sqrt{3} = 400/\sqrt{3} = 231\ V$

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

$$\therefore \quad I_L = \frac{P}{\sqrt{3}\, V_L \cos\phi} = \frac{1500}{\sqrt{3} \times 400 \times 0.2} = 10.83\ A$$

$$I_{ph} = I_L = 10.83\ A$$

$$Z_{ph} = V_{ph}/I_{ph} = 231/10.83 = 21.33\ \Omega$$

$$R_{ph} = Z_{ph} \cos\phi = 21.33 \times 0.2 = \mathbf{4.27\ \Omega}$$

$$X_{ph} = \sqrt{(21.33)^2 - (4.27)^2} = 20.9\ \Omega$$

$$L_{ph} = X_{ph}/2\pi f = 20.9/2\pi \times 50 = \mathbf{0.0665\ H}$$

**Example 19.6.** *The load to a 3-phase supply comprises three similar coils connected in star. The line currents are 25A and the kVA and kW inputs are 20 and 11 respectively. Find (i) the phase and line voltages (ii) the kVAR input and (iii) resistance and reactance of each coil.*

**Solution.**

(*i*)
$$V_{ph} = \frac{\text{Apparent power}}{3 \times I_{ph}} = \frac{20 \times 10^3}{3 \times 25} = \mathbf{267\ V}$$

$$V_L = \sqrt{3} V_{ph} = \sqrt{3} \times 267 = \mathbf{462\ V}$$

(*ii*)
$$\text{Input } kVAR = \sqrt{(kVA)^2 - (kW)^2} = \sqrt{20^2 - 11^2} = \mathbf{16.7\ kVAR}$$

(*iii*)
$$p.f. = \cos\phi = kW/kVA = 11/20$$

$$Z_{ph} = V_{ph}/I_{ph} = 267/25 = 10.68\ \Omega$$

$$R_{ph} = Z_{ph} \cos\phi = 10.68 \times 11/20 = \mathbf{5.87\ \Omega}$$

$$X_{ph} = \sqrt{(10.68)^2 - (5.87)^2} = \mathbf{8.92\ \Omega}$$

**Example 19.7.** *If the phase voltage of a three-phase star connected alternator be 231V, what will be the line voltages (i) when the phases are correctly connected (ii) when the connections of one of the phases are reversed ?*