Module-IV

POLYPHASE CIRCUITS

Poly phase circuits are the circuits which has more than one circuit. A polyphase system is essentially a combination of several single phase voltages having same magnitude and frequency but displaced from one another by equal angle, the values of these angles being determined by the number of phases or windings. The number of phases can be determined from the following relation.

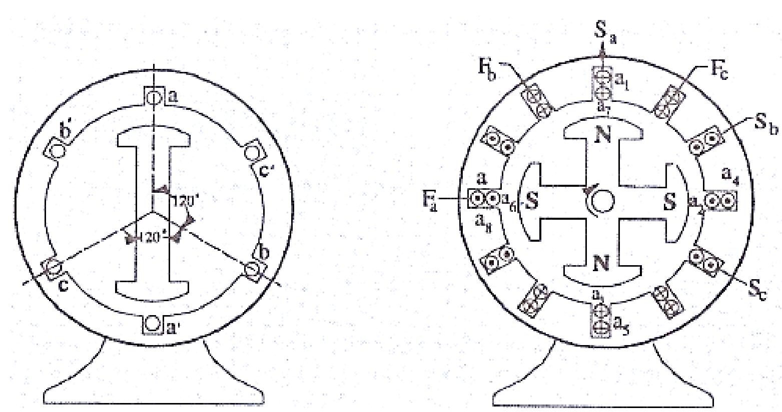
$$Electrical\ displacement = \frac{360\, electrical\ \deg rees}{Number\ of\ \ phases}$$

In a polyphase generator the number of armature winding will be greater than single phase generator. There are two-phase, three phase and greater number of phases used. For example, almost all mercury-arc rectifiers for power purposes are either six-phase or twelve-phase and most of the rotary converters in use are six-phase. All modern generators are practically three phase. For transmitting large amounts of power, three-phase is invariably used. The reasons for the immense popularity of three phase apparatus are

a) It is more efficient
b) It uses less material for a given capacity
c) It costs less than single-phase apparatus.

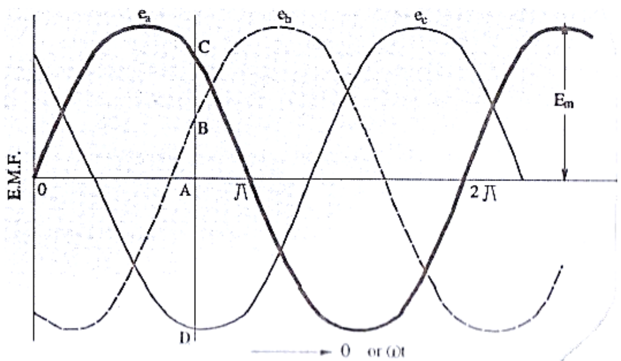
Generation of Three Phase

The generation of the three phase emf is carried out by using an alternator which has three distinct windings displaced 120^0 (electrical) apart from one another.



The figure shows a two pole stationary armature. In stationary armature, the field is rotated using a prime mover. Alternator has three armature winding, aa', bb', cc'. They are displaced 120^0 apart from one another. The emf induced in conductor **b** reaches maximum value 120^0 later than the maximum value in conductor **a.** similarly, the emf induced in conductor **c** is maximum 120^0 later than that in **b** or 240^0 later than in **a.** thus the e.m.f.s induced in all three conductors are equal in magnitude and of same frequency but have phase difference of 120^0 with one another.

Assuming these waves to be sinusoidal and counting the time from the instant when the emf in phase **a** is zero, the instantaneous values of the three e.m.f.s will be shown as the figure below.



The equations of the wave are as follows

$$e_a = E_m \sin \omega t$$

$$e_b = E_m \sin \omega t - 120^0$$

$$e_c = E_m \sin \omega t - 240^0$$

Phase Sequence

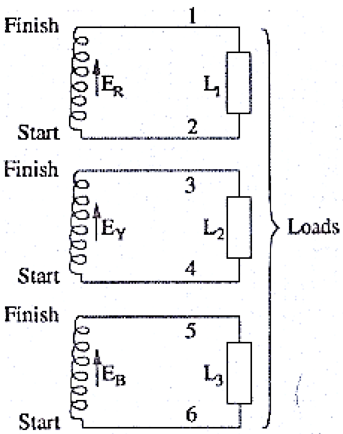
Phase sequence is the order or a sequence in which the currents or voltages in different their maximum values one after another. In the development of the three phase emf.s in figure, clockwise rotation of the field system was assumed. This assumption made the e.m.f.s of phase **b** lag behind that of **a** by 120^0 and in a similar way, made that of **c** lag behind that of b by 120^0(or that of a by 240^0). Hence the order in which the emf of phases **a,b,c** attain their maximum values is **abc**. It is called the phase order or phase sequences $a \to b \to c$ as shown in figure.

If, now, the rotation of the field structure is reversed ie, made anticlockwise, then the order in which the three phases would attain their corresponding maximum voltages would also be reversed. The phase sequence would become $a \to c \to b$. This means that emf of phase **c** would now lag behind that of phase **a** by 120^0 instead of 240^0 as in the previous case. Obviously, a three phase system has only two possible sequences **abc** and **cba**.

Advantages of Polyphase System Over Single Phase System

1. In a single phase circuit the power delivered is pulsating. While in a polyphase system the total power delivered is constant if loads are balanced
2. The output of the three phase motor is 1.5 times the output of single phase motor for a given size
3. Single phase induction motor are not self-starting, where 3 phase induction motors are self-starting
4. The efficiency of polyphase motors is greater than single phase motor
5. Power factor of polyphase motor is more than the single phase motor for same rating
6. Rotating magnetic field can be set up by polyphase supply
7. Three phase system requires $\frac{3}{4}th$ weight of copper to transmit same power at a given voltage
8. Polyphase system is more reliable
9. Parallel operation of polyphase alternators is simple

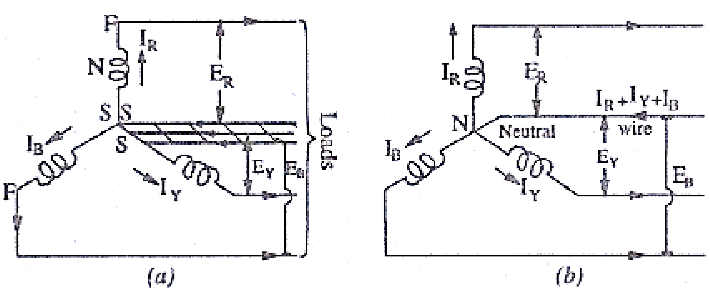
Inter Connection of Three phases



If three armature coils of three phase alternator are not inter connected, then each phase or circuit would need two conductors, total no of conductor in that case would be six. This means that each transmission cable will contain six conductors. This will make the entire system more complicated and expensive. In order to reduced complexity and expenses we go for interconnection of these three phases. The general methods used for interconnection are

1. Star or Wye (Y) connection
2. Delta or mesh connection

Star (Y) Connection



This type of connection is obtained by joining together similar ends (start or finish ends) at common point. This point is known as neutral point (N) or star point. The conductor at this point is known as neutral conductor. This type of system is known as 3-phase, 4 wire system.

If this system is applied across a balanced load, the neutral wire will be carrying three currents which are exactly equal in magnitude, but are 120^0 out of phase with each other. Hence their vector sum is zero. $I_a + I_b + I_c = 0$.The neutral wire in that case, may be omitted although its retention is useful for supplying lighting loads at low voltages. The p.d. between any terminal or line and neutral pint gives the phase or star voltage. But the p.d. between any two lines gives the line-to- line voltage or simply line voltage.

Values of Phase Currents

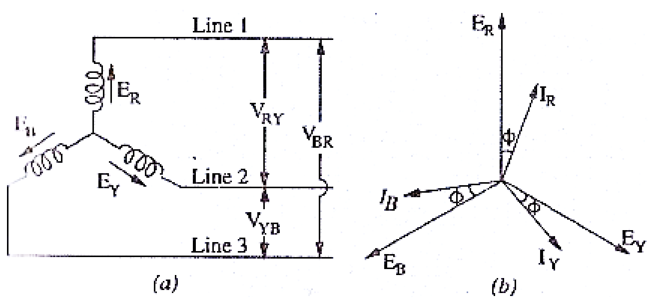
When considering the distribution of current in a 3-phase system, it is extremely important to bear in mind that

(i) The arrow placed alongside the currents I_R I_Y and I_B blowing in the three phases, indicate the direction of currents when they are assumed to be positive and not the directions at a particular instant. It should be clearly understood that at no instant will all the three currents flow in the same direction either outwards or inwards. The three arrows indicate that first the current flows outwards n phase R, then after a phase-time of 120^0, it will flow outwards from phase Y and after a further 120^0, outwards from phase B.

(ii) The current flowing outwards in one or two conductors is always equal to that flowing inwards in the remaining conductor or conductors. In other words, each conductor in turn, provides a return path for the currents of the other conductors.

(iii) It may be noted that although the distribution of currents between the three lined is continuously changing, yet at any instant the algebraic sum of the instantaneous values of the three currents is zero. ie, $I_R + I_Y + I_B = 0$.

Voltages and Currents in Y-Connection



The voltage induced in each winding is called the phase voltage and current in each winding is likewise known as phase current. However, the voltage available between any pair of terminals or outers I called line voltage (V_L) and the current flowing in each line is called line current (I_L).

In the Y connection, there are two phase winding between each pair of terminals but since their similar ends have been joined together they are in opposition obviously, the instantaneous value of p.d. between any two terminals is the arithmetic difference of the two phase e.m.f.s concerned. However, the rms value of this p.d. is given by the vector difference of the two phase e.m.f.s.

$$V_{RY} = V_R - V_Y$$

$$V_{YB} = V_Y - V_B$$

$$V_{BR} = V_B - V_R$$

In a balanced system, $V_R = V_Y = V_B = V_{Phase.}$

Line Voltages and Phase Voltages

The p.d. between lines 1 and 2 is $V_{RY} = V_R - V_Y$ (vector difference)

Hence, V_{RY} is found by compounding V_R and V_Y reversed and its value is given by the diagonal of the parallelogram of figure. Obviously, the angle between V_R and V_Y reversed is 60^0. Hence if $E_{RY} = E_R - E_Y = E_{ph}$ - the phase emf., then

$$V_{RY} = 2 \times E_{ph} \times \cos(60/2)$$

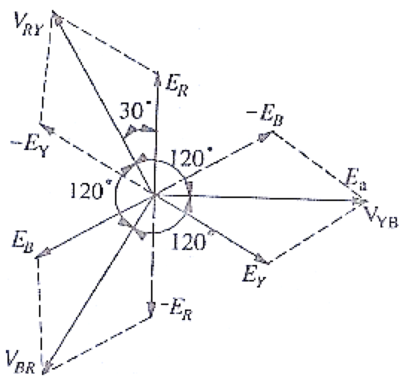
$$V_{RY} = 2 \times E_{ph} \times \cos 30 = V_{RY} = 2 \times E_{ph} \times \frac{\sqrt{3}}{2} = \sqrt{3}E_{ph}$$

Similarly, $V_{YB} = E_Y - E_B = \sqrt{3}E_{ph}$

$$V_{BR} = E_B - E_R = \sqrt{3}E_{ph}$$

Now, $V_{RY} = V_{YB} = V_{BR}$ = Line voltage, say, V_L. Hence, in star

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



connection .

It will be noted from the figure that

1. Line voltages are 120^0 apart.
2. Line voltages are 30^0 ahead of their respective phase voltages
3. The angle between the lined currents and the corresponding line voltages is with current lagging.

Line Currents and Phase Currents

It is seen from figure that each line is in series with its individual phase winding, hence the line current in each line is the same as the current in the phase winding to which the line is connected. Current in line 1 = I_R, Current in line 2= I_Y, Current in line 3=I_B

Since I_R= I_Y=I_B=say, I_{ph} -phase current, therefore line current I_L=I_{ph}

Power

The total active or true power in the circuit is the sum of the three phase powers. Hence, total active power = 3 $\times$ phase power or P=$3\times V_{ph} I_{ph} \cos\phi$

Now $V_{ph} = \frac{V_L}{\sqrt{3}}$ and I_{ph} = I_L, hence, in term of line values, the above expression becomes

$$P = 3 \times \frac{V_L}{\sqrt{3}} I_L \cos\phi \quad \text{or} \quad P = \sqrt{3} \times V_L I_L \cos\phi$$

It should be particularly noted that ϕ is the angle between phase voltage and phase current and **not** between the line voltage and line current.

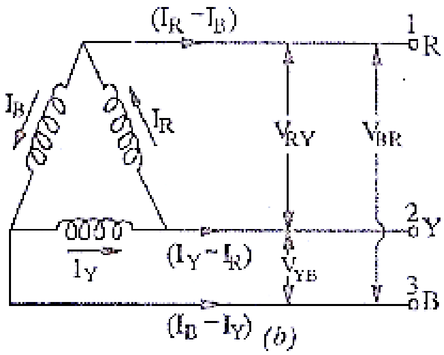
Similarly, total reactive power is given by $Q = \sqrt{3} \times V_L I_L \sin\phi$

By convention, reactive power of a coil is taken as positive and that of a capacitor as negative.

The total apparent power of the three phase is $S = \sqrt{3} \times V_L I_L$ obviously, $S = \sqrt{P^2 + Q^2}$

Delta(Δ) or Mesh Connection

In this form of interconnection the *dissimilar* ends of the three phase winding are joined together i.e. the starting end of one phase I joined to the finishing end of the other phase and so on as in figure. In other words, the three windings are joined in series to from a closed mesh as in figure. Three leads are taken out from the three junctions



as shown and outward directions are taken as positive. It might look as if this sort of interconnection results in short circuiting the three windings.

However, if the system is balanced then sum of the three voltages round the closed mesh is zero, hence no current fundamental frequency can flow are open. It should be clearly understood that at any instant, the emf in one phase is equal and opposite to the resultant of those in the other two phases. This type of connection is also referred to as 3-phase, 3 wire system.

Line voltages and Phase Voltages

It is seen from the figure that, there is only one phase winding completely included between any pair of terminals. Hence, in delta connection, the voltage between any pair of line is equal to the phase voltage of the phase winding connected between the two lines considered. Since phase sequence is RYB, the voltage having its positive direction from R to Y leads by 120^0 on that having its positive direction from Y to B. Calling the voltage between lines 1 and 2 as V_{RY} and that between lines 2 and 3 as V_{YB}, we find that V_{RY} leads V_{RB} by 120^0. Similarly, V_{YB} leads V_{BR} by 120^0 as in figure. Let V_{BY}=V_{BR}=V_{YR}= Line voltage V_L. Then it is seen that V_L=V_{ph}.

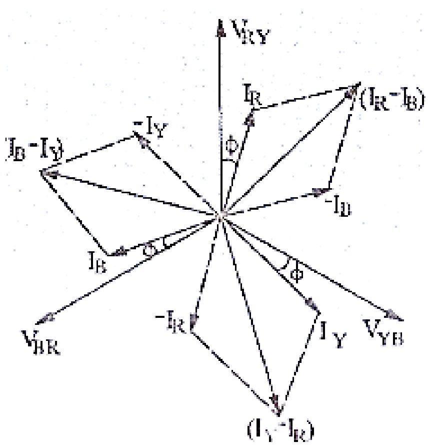
Line Currents and Phase Currents

It will be seen from the figure that current in each line is the vector difference of the two phase currents flowing through that line. For example

Current in line 1 is I_1= $I_R - I_B$

Current in line 2 is I_2= $I_Y - I_R$

Current in line 3 is I_3= $I_B - I_Y$



Current in line no 1 is found by compounding I_R and I_B reversed and its value is given by the diagonal of the parallelogram of figure. The angle between I_R and I_B reversed (ie, $-I_B$) is 60^0. If I_R=I_Y= phase current I_{ph}, then current in line No. is

$$I_1 = 2\times I_{ph} \times \cos(60/2) = 2\times I_{ph} \times \cos 30$$

$$= 2\times I_{ph} \times \frac{\sqrt{3}}{2} = \sqrt{3}\, I_{ph}$$

Current in line No 2 is

$I_2 = I_Y - I_R$ …vector difference is $= \sqrt{3}\, I_{ph}$

Current in line No. 3 is

$I_3 = I_B - I_Y$ ….vector difference is $= \sqrt{3}\, I_{ph}$

Since all the line currents are equal in magnitude, $I_1 = I_2 = I_3 = I_L$

$$\therefore\ I_L = \sqrt{3}\, I_{ph}$$

With reference to the vector diagram above, it should be noted that

1. Line currents are 120^0 apart
2. Line currents are 30^0 behind the respective phase currents
3. The angle between the line currents and the corresponding line voltages is $30+\phi$ with the current lagging.

Power

Power/phase $= V_{ph} I_{ph} \cos\phi$; Total power for 3 phases $= 3 \times V_{ph} I_{ph} \cos\phi$.

However, $V_{ph} = V_L$ and $I_{ph} = \dfrac{I_L}{\sqrt{3}}$

Hence, in terms of line values, the above expression for power becomes

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

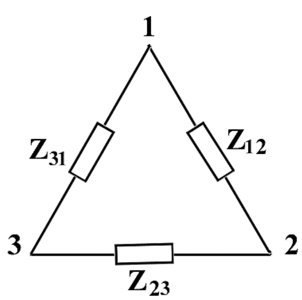
Hence, the total power in the three phase circuit is obtained from the expression,

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

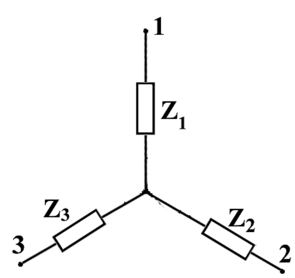
Balanced Star/ Delta and Delta / Star Conversion

In view of the above relationship between line and phase currents and voltages, any balanced Y-connected system may be completely replaced by an equivalent Delta connected system.

Let us consider a delta connected load and star connected load as in figure. If the two systems are to be equivalent, then the impedances between corresponding pairs of terminals must be the same.



Delta



Star

Delta/ Star Conversion

For Y- load, total impedance between terminals 1 and 2 is Z_1+Z_2 (it should be noted that double subscript notation of Z_{01} and Z_{02} has been avoided.

Considering terminals 1 and 2 of delta load, we find that there are two parallel paths having impedances of Z_{12} and $(Z_{31} + Z_{23})$. Hence, the equivalent impedance between terminals 1 and 2 is given by

$$\frac{1}{Z} = \frac{1}{Z_{12}} + \frac{1}{Z_{13}+Z_{23}} \; or \; Z = \frac{Z_{12}(Z_{13}+Z_{23})}{Z_{12}+Z_{13}+Z_{23}}.$$

Therefore, for equivalence between the two systems

$$Z_1 + Z_2 = \frac{Z_{12}(Z_{13}+Z_{23})}{Z_{12}+Z_{13}+Z_{23}} \qquad \text{.........1}$$

Similarly,

$$Z_2 + Z_3 = \frac{Z_{23}(Z_{13}+Z_{12})}{Z_{12}+Z_{13}+Z_{23}}, \qquad \text{......2}$$

$$Z_3 + Z_1 = \frac{Z_{31}(Z_{23}+Z_{12})}{Z_{12}+Z_{13}+Z_{23}} \qquad \text{.......3}$$

Adding equation 3 to 1 and subtracting equation 2, we get

$$2Z_1 = \frac{Z_{12}(Z_{13}+Z_{23}) + Z_{31}(Z_{12}+Z_{23}) - Z_{23}(Z_{12}+Z_{13})}{Z_{12}+Z_{13}+Z_{23}}$$

$$= \frac{2Z_{12}Z_{13}}{Z_{12}+Z_{13}+Z_{23}}$$

$$\therefore Z_1 = \frac{Z_{12}Z_{13}}{Z_{12}+Z_{13}+Z_{23}} \qquad \text{........4}$$

$$\therefore Z_2 = \frac{Z_{12}Z_{23}}{Z_{12}+Z_{13}+Z_{23}} \qquad \text{..........5}$$

$$\therefore Z_3 = \frac{Z_{13}Z_{23}}{Z_{12}+Z_{13}+Z_{23}} \qquad \text{...........6}$$

The above expression can be easily obtained by remembering that

$$star\, Z = \frac{\Pr oduct\, of\, \Delta Z's\, connected\, to\, the\, same\, ter\min als}{Sum\, of\, \Delta Z's}$$

Star and Delta Conversion

The equations for this conversion can be obtained by rearranging the equations 4, 5 and 6 Rewriting these equations, we get

Equation (4) $$Z_1 = \frac{Z_{12}Z_{13}}{Z_{12}+Z_{13}+Z_{23}}$$

$$Z_1(Z_{12}+Z_{13}+Z_{23}) = Z_{12}Z_{13} \qquad \text{................7}$$

Equation (5), $$Z_2 = \frac{Z_{12}Z_{23}}{Z_{12}+Z_{13}+Z_{23}}$$

$$Z_2(Z_{12}+Z_{13}+Z_{23}) = Z_{12}Z_{23} \qquad \text{..................8}$$

$$Z_3 = \frac{Z_{13}Z_{23}}{Z_{12}+Z_{13}+Z_{23}}$$

$$Z_3(Z_{12}+Z_{13}+Z_{23}) = Z_{13}Z_{23} \qquad \text{...........9}$$

Dividing the equation 7 by 9 we get, $\frac{Z_1}{Z_3} = \frac{Z_{12}}{Z_{23}}$ 10

$$Z_{23} = Z_{12}\frac{Z_3}{Z_1} \qquad \text{.........11}$$

Dividing the equation 8 by 9 we get , $\frac{Z_2}{Z_3} = \frac{Z_{12}}{Z_{13}}$ 12

$$Z_{13} = Z_{12}\frac{Z_3}{Z_2} \qquad \text{.........13}$$

Substituting equations 11 and 13 in equation7, we have $Z_1(Z_{12}+Z_{13}+Z_{23}) = Z_{12}Z_{13}$

$$Z_1(Z_{12}+Z_{13}+Z_{12}\frac{Z_3}{Z_1}) = Z_{12}.Z_{12}\frac{Z_3}{Z_2} \qquad \text{.........14}$$

Take out Z_{12} from the LHS of the equation 14

$$Z_1Z_{12}\left(1+\frac{Z_{13}}{Z_{12}}+\frac{Z_3}{Z_1}\right) = Z_{12}.Z_{12}\frac{Z_3}{Z_2} \qquad \text{.........15}$$

Consider the equation 12 and rearrange $\left(\frac{Z_2}{Z_3} = \frac{Z_{12}}{Z_{13}}\right)$, $\frac{Z_{13}}{Z_{12}} = \frac{Z_3}{Z_2}$ 16

Substitute the equation 16 in 15, we get $Z_1Z_{12}\left(1+\frac{Z_3}{Z_2}+\frac{Z_3}{Z_1}\right) = Z_{12}.Z_{12}\frac{Z_3}{Z_2}$ 18

Take LCM on LHS of equation 18

$$Z_1Z_{12}\left(\frac{Z_1Z_2+Z_1Z_3+Z_2Z_3}{Z_1Z_2}\right) = Z_{12}.Z_{12}\frac{Z_3}{Z_2} \qquad \text{.............19}$$

$$Z_1Z_2+Z_1Z_3+Z_2Z_3 = Z_{12}Z_3 \qquad \text{.................20}$$

$$Z_{12} = \frac{Z_1Z_2+Z_1Z_3+Z_2Z_3}{Z_3} \quad \text{or} \quad Z_{12} = Z_1+Z_2+\frac{Z_1Z_2}{Z_3}$$

Similarly,

$$Z_{23} = \frac{Z_1Z_2+Z_1Z_3+Z_2Z_3}{Z_1} \quad \text{or} \quad Z_{23} = Z_2+Z_3+\frac{Z_3Z_2}{Z_1}$$

$$Z_{31} = \frac{Z_1Z_2+Z_1Z_3+Z_2Z_3}{Z_2} \quad \text{or} \quad Z_{31} = Z_1+Z_3+\frac{Z_3Z_1}{Z_2}$$

Comparison of Star and Delta Systems

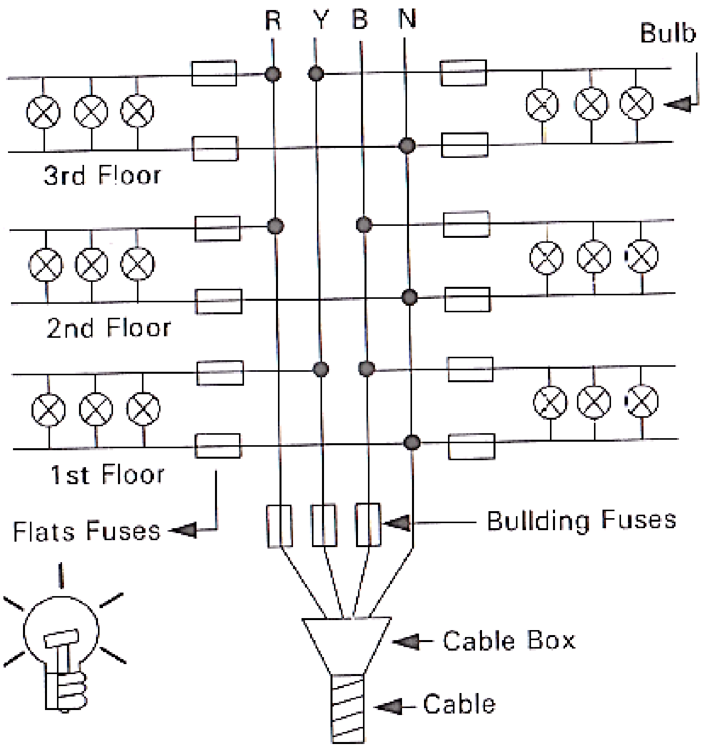
Star	Delta
Favorable for 3-phase distribution system	Favorable for 3-phase transmission system
Neutral point is available	No Neutral point
$V_L = \sqrt{3}E_{ph}$	$V_L=V_{ph}$
$I_L=I_{ph}$	$I_L = \sqrt{3}\, I_{ph}$
I_L are 30^0 behind the respective I_{ph}	V_L are 30^0 ahead of respective V_{ph}
Line currents (phase current also) 120^0 apart	Line Voltages (phase voltages also) 120^0 apart
The angle between IL and VL is $30 \pm \phi$	The angle between IL and VL is $30 \pm \phi$
$P = \sqrt{3} \times V_L I_L \cos\phi$	$P = \sqrt{3} \times V_L I_L \cos\phi$

Star and Delta Connected Lighting Load

Star Connected Lighting Load- Electrical Wiring

A star connected (3 phase 4 wire) lighting system in a multi-storey (3 storey) building is shown in figure. Four uniform load distribution among three phases. The lamp voltage rating must be equal to the phase voltage (230-V) for a 440 V, 3 phase system.

We may obtain single phase ad three phase supply system from star connection because there is a Neutral point. There are fuses on single phase supply at the flat entering cables to protect the others flats supply and two mains from short circuits in the same

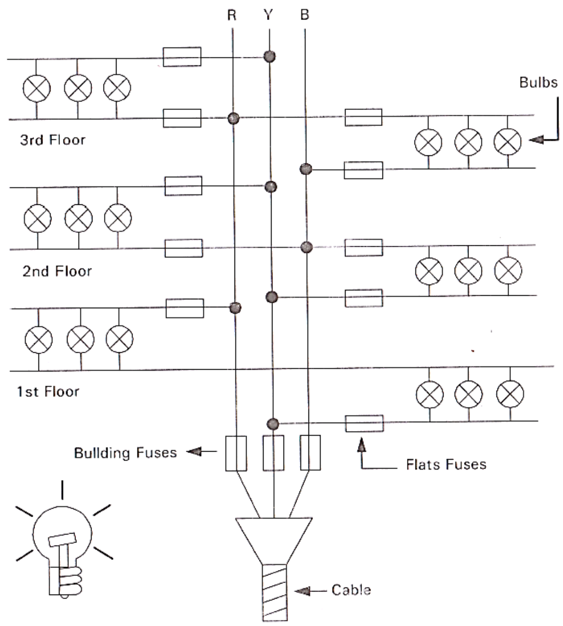


building. Note that there is no fuse on the neutral wire.

There is no fuse on the neutral of the mains supply because blowing such a fuse due to short circuit would mean a break in the neutral wire which disconnect the single phase supply as well as system would be unbalanced i.e. there would be unequal voltage across different lighting networks e.g. lamps in case they have different power raring. As result, lamps in one group of lighting system would glow too bright whereas the lamps in other groups would glow dim which cause to reduce the life of the bulbs.

Delta (Δ) Connected Lighting Load- Electrical Wiring

The home lighting wiring circuit diagram for delta connected lamps is shown in figure. Delta connected lighting system electrical wiring in a three story building. The voltage rating of the lamps must be line values only as V_L=$V_{ph.}$



Difference between Single Phase and Three Phase

Single Phase Power	Three Phase Power
Used for domestic purposes	Used for Industrial/business purposes
Able to supply ample power for most smaller customers, including offices and small workshops…etc.	Increasingly popular in high-density data centers
Used for motors upto 5 HP	Used for motors more than 5HP
Needs only two wires for supply	Minimum 3 wires
Handling voltage is 230 V	Handling voltage is High 400V and above
When wave passes through zero, the power supplied is zero	The power never becomes zero
Low efficiency for same rating/capacity	High efficiency than single phase for same rating/capacity
Only one wave cycle	3 distinct wave cycle that overlap and reaches its peak 120^0 apart from one another