MODULE 5A: SYNCHRONOUS GENERATOR

The electric supply used for industrial and domestic application is of alternating type. This is so because a highly efficient device called transformer is available. It is capable of transferring electrical energy from one circuit to another at different voltage level. The transformer is used for economically transmitting and distributing electrical power over long distance. This has permitted us to locate the generation of electric power remotely from the point of demand.

Generally, electric power is generated at about 11kV, then stepped up to higher voltages of 132kV, 220kV and 400kV for transmission lines. At distribution point, it is again stepped down to 400V or 220V for use in industry, offices and homes.

Many applications require the frequency of ac supply to be constant. Constant frequency of generated power can be obtained only if the generator runs at constant speed, called its synchronous speed. Hence, the name **synchronous generator**. Large size generators are also called **alternators.**

DIFFERENCE BETWEEN ALTERNATOR AND D.C. GENERATOR

1. The armature winding of a synchronous generator is an a.c. winding, i.e. it is connected to produce a.c. supply, and the field is connected to d.c. supply. Therefore no commutator is required in an alternator, which makes its construction simpler than that of d.c. generator.
2. In the d.c. generator, the armature winding rotates and the field system is stationary, whereas in the case of synchronous generator, the armature winding is mounted on a stationary element called the stator and the field winding on a rotating element called the rotor.

ADVANTAGES OF STATIONARY ARMATURE

1. As everywhere a.c. is used, the generation level of a.c. voltage may be higher as 11kV to 33kV. This gets induced in the armature. For stationary armature large space can be provided to accommodate large number of conductors and the insulation.
2. It is always better to protect high voltage winding from centrifugal forces caused due to rotation. So high voltage armature is generally kept stationary. This avoids the interaction of mechanical and electrical stresses.

3. It is easier to collect larger currents at high voltages from a stationary member than from the slip ring and brush assembly. The voltage required to be supplied to the field is very low and hence can be easily supplied with the help of slip ring and brush assembly by keeping it rotating.
4. The problem of sparking at the slip ring can be avoided by keeping field rotating which is low voltage circuit and high voltage armature as stationary.
5. Due to low voltage level of the field side, the insulation required is less and hence field system has very low inertia. It is always better to rotate low inertia system than high inertia, as efforts required to rotate low inertia system are always less.
6. Rotating field makes the overall construction very simple. With simple robust mechanical construction and low inertia of rotor, it can be driven at high speeds. So greater output can be obtained from an alternator of given size.
7. If field is rotating, to excite it by an external D.C. Supply two slip rings are enough. One each for positive and negative terminals. As against this, in three phase rotating armature, the minimum numbers of slip rings required are three and cannot be easily insulated due to high voltage levels.
8. The ventilation arrangements for high voltage sides can be improved if it is kept stationary.

CONSTRUCTION

Most of the alternators prefer rotating field type of construction. In alternators the stationary winding is called **Stator** while the rotating winding is called **Rotor.**

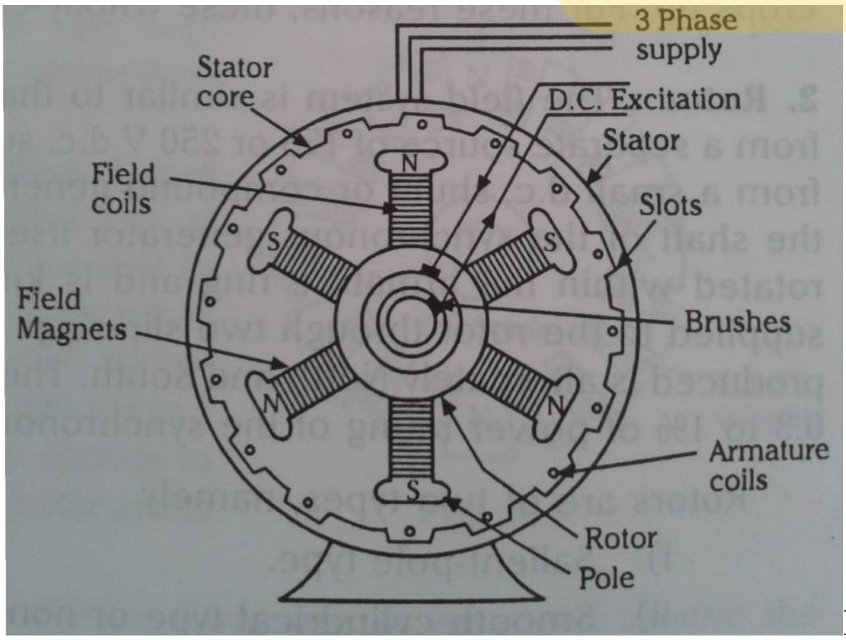


Fig 1

STATOR

- The stator is stationary armature.
- This consist of a core and the slots to hold the armature winding.
- The stator core uses a laminated construction.
- It is built up of special steel stampings insulated from each other with varnish or paper.
- The laminated construction is basically to keep down the eddy current losses.
- Generally the choice of material is steel to keep down hysteresis losses.
- The entire core is fabricated in a frame made of steel plates.
- The core has slots on its periphery for housing armature conductors.
- Frames do not carry any flux and serves as a support to the core.
- Ventilation is maintained with the help of holes cast in the frame.

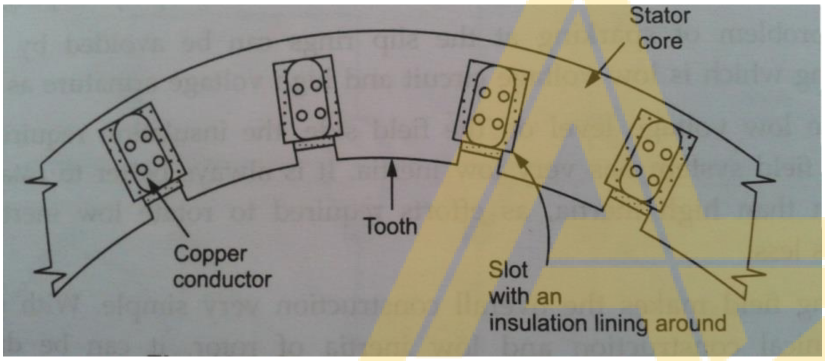


Fig. 2 Section of alternator stator

ROTOR

There are two types of rotor used in alternators

1. Salient pole type
2. Smooth cylindrical type

SALIENT POLE TYPE ROTOR

- This is also called projected pole type as all the poles are projected out from the surface of the rotor.
- The poles are built up of thick steel lamination.
- The poles face has been given a specific shape.
- The field winding is provided on the pole shoe.
- These rotors have large diameter and small axial lengths.
- The limiting factor for the size of the rotor is the centrifugal force acting on the rotating member of the machine.

- As mechanical strength of the salient pole rotor is less, this preferred for low speed alternators ranging from 125rpm to 500rpm.

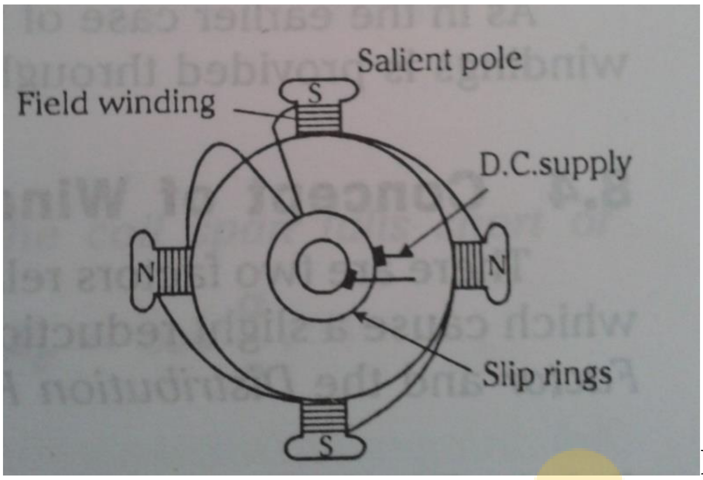


Fig 3. Salient pole type rotor

SMOOTH CYLINDRICAL TYPE ROTOR

- This is also called non salient type or non-projected pole type rotor.
- The rotor consists of smooth solid steel cylinder, having number of slots to accommodate the field coils.
- The slots are covered at the top with the help of steel or manganese wedges.
- The unslotted portion of the cylinder itself acts as the poles.
- The poles are not projected out and surface of the rotor is smooth which maintains uniform air gap between stator and rotor.
- These rotors have small diameters and large axial length. This is to keep peripheral speed within limits.
- The main advantage of this type is that these are mechanically very strong and thus preferred for high speed alternators ranging from 1500 to 3000rpm.
- Such high speed alternators are called turbo alternators.
- The prime movers used to drive such type of rotors are generally steam turbines and electric motors.

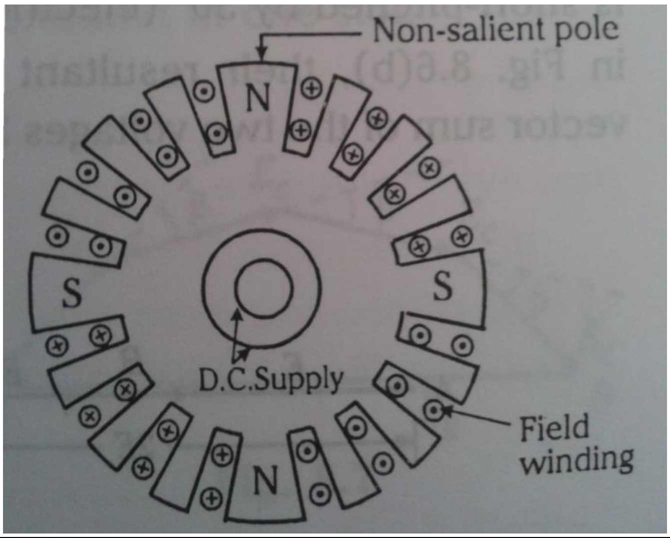
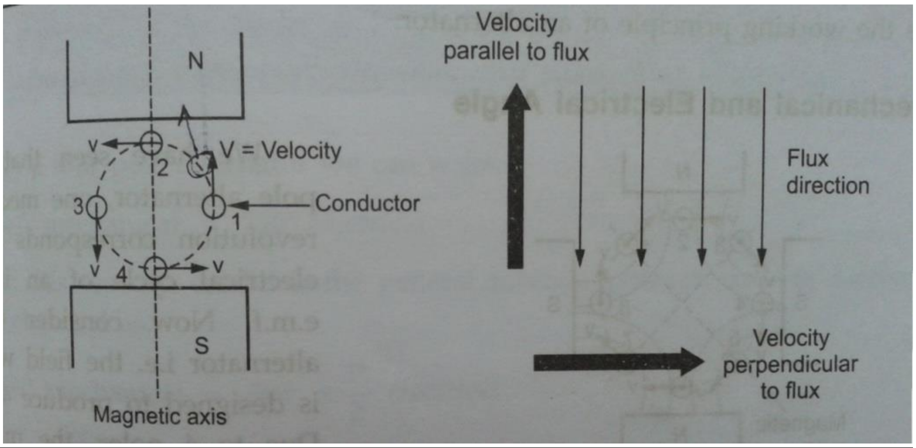


Fig. Smooth cylindrical rotor

Difference between salient pole and cylindrical type rotor

Sr.No	Salient pole type	Smooth cylindrical type
1.	Poles are projecting out from the surface	Unslotted portion of the cylinder acts as poles hence poles are non projecting
2.	Air gap is uniform	Air gap is uniform due to smooth cylindrical periphery
3.	Diameter is high and axial length is small	Small diameter and large axial length
4.	Mechanically weak	Mechanically robust
5.	Preferred for low speed alternator	Preferred for high speed alternator
6.	Prime movers used are water turbines and I.C. engine	Prime movers used are steam turbine and electric motors
7.	For same size, the rating is smaller than cylindrical type	For same size, the rating is higher than salient type

Working principle



The alternators work on the principle of electromagnetic induction. When there is a relative motion between the conductors and the flux, emf gets induced in the conductors. The DC generator also works on the same principle. The only difference is that in an alternator the conductors are stationary and field is rotating.

Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles. The magnetic axis of the two poles produced by field is vertical.

Let the conductor start rotating from position 1. At this instant, the entire velocity component is parallel to the flux lines. Hence there is no cutting of flux lines by the conductor. So dØ/dt at this instant is zero and hence induced emf in the conductor is zero.

As the conductor moves from position 1 towards position 2, the part of the velocity component becomes perpendicular to the flux lines and proportional to that emf gets induced in the conductor. The magnitude of such an induced emf increases as the conductor moves from position 1 towards 2.

At position 2, the entire velocity component is perpendicular to the flux lines. Hence there exist maximum cutting of flux lines. And at this instant, the induced emf in the conductor is at its maximum.

As the position of conductor changes from 2 towards 3, the velocity component perpendicular to the flux starts decreasing and hence induced emf magnitude also starts decreasing. At position 3, again the entire velocity component is parallel to the flux lines and hence at this instant induced emf in the conductor is zero.

As the conductor moves from position 3 towards 4, the velocity component perpendicular to the flux lines again starts increasing. But the direction of velocity component now is opposite to the direction of velocity component existing during the movement of the conductor from position 1 to 2. Hence an emf induced the conductor increases but in the opposite direction.

At position 4, it achieves maxima in the opposite direction, as the entire velocity component becomes perpendicular to the flux lines.

Again from position 4 to 1, induced emf decreases and finally at position 1 again becomes zero. This cycle continues as conductor rotates at a certain speed.

So if we plot the magnitudes of the induced emf against the time, we get an alternating nature of the induced emf .

FREQUENCY OF INDUCED E.M.F.

P= Number of poles

N= speed of motor in rpm

f = frequency of induced e.m.f.

Consider a single conductor placed in the slot of the stator. Let the rotor with alternate north and south poles N and S, rotate with an angular velocity ω in the clockwise direction.

Positive half cycle of emf is induced in the conductor, when the North Pole N sweeps across the conductor. Negative half cycle of emf is induced in the conductor when the South Pole S sweeps across it and hence one cycle of emf is induced in the conductor; when one pair of poles N an S sweep across it.

One mechanical revolution of rotor = $\frac{P}{2}$ cycles of e.m.f. electrically

Thus there are $P/_2$ cycles per revolution

As speed is N rpm, in one second, rotor will complete $(\frac{N}{60})$ revolutions.

But cycles/sec = frequency= f

Therefore frequency f = (No. of cycles per revolution)*(No. of revolution per second)

$$f=\frac{P}{2}*\frac{N}{60}$$

$$\mathbf{f=\frac{PN}{120}\ Hz}$$

SYNCHRONOUS SPEED(N_S)

From the above expression, it is clear that for fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated e.m.f constant at the required value. Such a speed is called synchronous speed of the alternator denoted as N_S.

So $\mathbf{N_S=\frac{120f}{P}}$ where f =Required frequency

Following table gives the value of the synchronous speeds for the alternators having different number of poles (f=50Hz)

Number of poles P	2	4	6	8	10	12	24
Synchronous speed N_S in rpm	3000	1500	1000	720	600	500	250

ARMATURE WINDING

- The armature winding of an alternator differs from that of a dc generator.
- In a three phase alternator, three sets of windings are arranged in the slots made around the inner periphery of the stator.
- The placing of these windings is done in such a way that there exists a phase difference of 120° between the induced emfs in them.
- These windings are open ended.
- Two ends of each set are brought out.
- For three phases, six terminals are brought out which may then be connected either in star or delta.
- Thus, finally only three terminals are brought out from the alternators.
- Each set of winding is called winding per phase and the induced emf in each winding is called emf per phase denoted as E_{ph}.
- The coil in one phase is connected in such a way that their emfs end up.

Winding terminology

1. Conductor :

- ➢ The conductors are placed in the armature slots.
- ➢ The active length of the conductor is that part which is under the influence of magnetic field and is responsible for induced emf.
- ➢ The conductor, when connected to other conductor, forms turns, coils and windings.

2. Turn:

- ➢ A conductor in one slot when connected to a conductor in another slot forms a turn.
- ➢ Thus, two conductors with their one end connected together form a turn.
- ➢ Thus, if there are Z_{ph} conductors per phase, the number of turns per phase will be $T_{ph}= Z_{ph}/2$.

3. **Coil :**
   - As there are many conductors per slot, a number of turns are grouped together a form a multiturn coil.

4. **Coil side:**
   - A coil is accommodated in two distant slots with many slots in between.
   - Part of the coil in each slot is called coil side.
   - Thus, the two coil sides are many slots away.

5. **Pole pitch:**
   - The distance between the centres of two adjacent poles is called pole pitch.
   - Pole pitch is expressed in terms of the number of slots per pole, denoted as n.

$$\textbf{Pole pitch n= slots per pole=}\ \frac{\textbf{number of slots}}{\textbf{P}}$$

6. **Slot angle (α)**
   - The electrical angle between two consecutive slots is known as slot angle.
   - The emf induced in two conductors placed in adjacent slots will have a phase difference of α.

$$\text{Slot angle } \alpha = \frac{180°}{n}$$

Types of armature windings

1. **Single layer and double layer windings:**
   - If a slot contains only one coil side, the type of winding is called **single layer winding.**
   - To save space, two coil sides are accommodated in each slot. It is then known as **double layer winding**.

2. **Full pitch and short pitch windings:**
   - When a coil side in one slot is connected to a coil side in another slot on pole pitch away, the coil is called **full pitch coil** and the winding is called **full pitch winding.**
   - When a coil side in one slot is connected to a coil side in another slot slightly less than one pole pitch away, the coil is called **short pitch coil** and the winding is called **short pitch winding**.

3. **Concentrated and distributed winding**
   - When all conductors of coil belonging to a phase are placed in one slot under every pole, the winding is called concentrated winding.
   - In practice, the coils comprising a phase of the winding are distributed in two or more slots per pole.
   - Compared to concentrated winding, the distributed winding is preferred as it results in an induced emf of waveform nearer to sinusoidal and better heat dissipation.

Concepts of winding factor

Due to some advantages, the coils of the windings are usually wound a little short pitched. Also, the conductors of the coils are distributed over 2-3 slots per pole. Because of these two factors, the induced emf per phase E_{ph} gets reduced compared to the full pitched concentrated winding.

1. **Pitch factor (K_p)**

The pitch factor is defined as the factor by which the emf per coil is reduced because of the pitch being less than full pitch.

In a full pitch coil AB as shown in fig, the emfs induced in the two coil sides E_a and E_b (each equal to E) are in phase and the resultant emf of the coil is simply

$$E_r = E_a + E_b = E + E = 2E$$

However, due to some advantages, the coils are usually wound a little short pitched as shown in fig c. In such a short pitched coil, the emf induced in the two coil sides E_a and E_b(each equal to E) are out of phase by an angle β. The two emfs must then be added vectorially to get the resultant emf E_r of the coil.

$$E_r = OQ = 2*OS = 2*OP*\cos(\beta/2) = 2E\cos(\beta/2)$$

Thus the pitch factor is given as

$$\mathbf{K_p = \frac{\text{phase sum of the coil side emf}}{\text{arithmatic sum of the coil side emf}} = \frac{2E\cos(\frac{\beta}{2})}{2E} = \cos(\beta/2)}$$

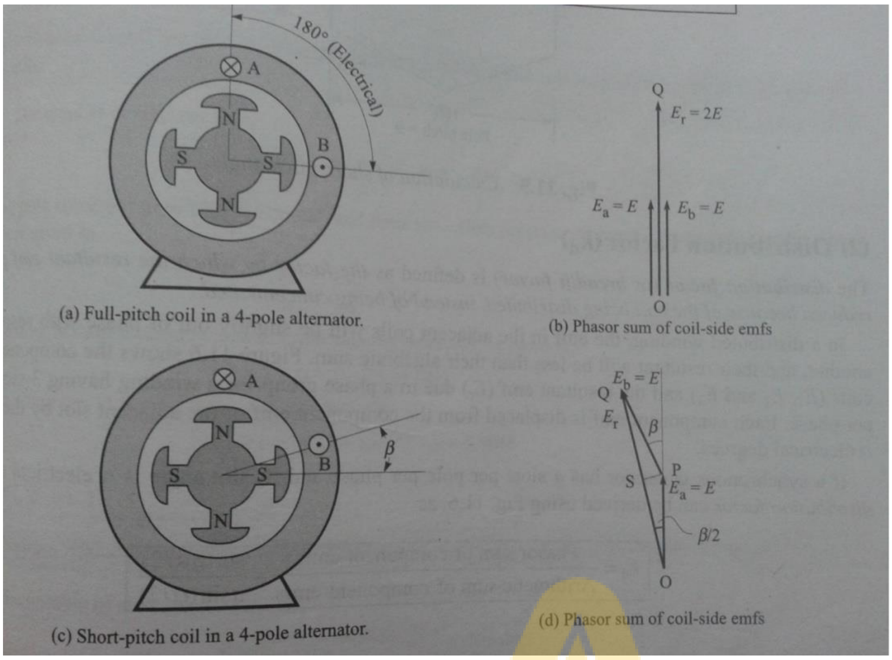


Fig 5 Definition of pitch factor

Distribution factor (K_d)

The distribution factor is defined as the factor by which the resultant emf per coil is reduced because of the coil being distributed, instead of being concentrated.

In a distributed winding, the emf in the adjacent coils will be slightly out of phase with respect to one another, and their resultant will be less than their algebraic sum. Each component emf is displaced from the component emf of the adjacent slot by the slot angle α electrical degrees.

If a synchronous generator has q slots per pole per phase and its slot angle is α electrical degree, its distribution factor may be derived as

$$K_d = \frac{\text{phasor sum of component emf}}{\text{arithmetic sum of component emf}} = \frac{\sin\left(\frac{q\alpha}{2}\right)}{q\sin\left(\frac{\alpha}{2}\right)}$$

E.M.F. Equation of an alternator

Let
$\varnothing$ = flux per pole in Wb
P = number of poles
N_S= synchronous speed in rpm
f= frequency of induced emf in Hz
Z= total number of conductors
Z_{ph} = conductors per phase connected in series
$Z_{ph} = \frac{Z_{ph}}{3}$ as number of phase=3

Consider a single conductor placed in a slot

The average value of emf induced in a conductor = $\frac{d\text{Ø}}{dt}$

For one revolution of a conductor,

$$e_{avg} \text{ per conductor} = \frac{\text{flux cut in one revolution}}{\text{time taken for one revolution}}$$

Total flux cut in one revolution is Ø*P.

Time taken for one revolution is $\frac{60}{N_S}$ seconds, as speed is $N_S$rpm

Therefore, e_{avg} per conductor = $\frac{\text{Ø}P}{\frac{60}{N_S}}$

$$= \text{Ø}\,\frac{PN_S}{60} \quad \text{----------------(1)}$$

But f= $\frac{PN_S}{120}$

Therefore $\frac{PN_S}{60}$ =2f

Substituting in equation (1)

e_{avg} per conductor = 2 f Ø

Assume full pitch winding for simplicity i.e. this conductor is connected to a conductor which is 180° electrical apart. So these two emf will try to set up a current in the same direction i.e. the two emfs are helping each other and hence the resultant emf per turn will be twice the emf induced in a conductor

Therefore emf per turn = 2 * (emf per conductor)

= 2 * (2 f Ø)

= 4 f Ø

Let T_{ph} be the total number of turns per phase connected in series. Assuming concentrated winding, we can say that all are placed in single slot per pole per phase. So the induced emf in all the turns will be in phase as placed in single slot. Hence net emf per phase will be algebraic sum of the emfs per turn

Therefore average $E_{ph} = T_{ph}$ * (average emf per turn)

Average $E_{ph} = T_{ph}$ * 4 f Ø

But in ac circuits RMS value of an alternating quantity is used for analysis. The form factor is 1.11 for purely sinusoidal emf

$K_f = \frac{\text{RMS}}{\text{Average}}$ =1.11 for sinusoidal

Therefore RMS value of $E_{ph} = K_f$ * Average value

$$E_{ph} = 1.11 * 4\, f\, Ø\, T_{ph}$$

$\mathbf{E_{ph} = 4.44\, f\, Ø\, T_{ph}}$ where T_{ph} number of turns per phase = $Z_{ph}/2$.

But due to short pitch, distribution winding in practice, this E_{ph} will reduce by factors K_d and K_p. So the generalized expression for emf equation can be written as

$$\boxed{\mathbf{E_{ph} = 4.44\, K_d\, K_p f\, Ø\, T_{ph}}}$$

For full pitched coil K_p =1
For concentrated winding K_d=1

MODULE 5B: THREE PHASE INDUCTION MOTOR

INTRODUCTION

The three phase induction motor is the most widely used a.c. motor. It differs from other type of motors in that there is no connection from the rotor winding to any source of supply. The necessary voltage and current in the rotor circuit are produced by induction from the stator winding which is why it is called induction motor.

Advantages

1. It is very simple, very robust and rugged, practically unbreakable construction.
2. Its cost is low.
3. It is very reliable.
4. It is highly efficient
5. It has a fairly good power factor.
6. Its maintenance requires minimum of attention.
7. It does not need to be synchronized. It has a simple starting arrangement.

Disadvantage

1. It is essentially a constant speed motor and the speed cannot be varied easily.
2. Its speed reduces to some extent with increase in load as in case of D.C. shunt motor.
3. It has somewhat lesser starting torque as compared to D.C. shunt motor.

CONSTRUCTION

Three phase induction motor consists of two parts

1. Stator
2. Rotor

Stator

- It is the stationary part of the motor supporting the entire motor assembly.
- This outer frame is made up of a single piece of cast iron in case of small machines.
- In case of larger machines they are fabricated in sections of steel and bolted together.

- The core is made of thin laminations of silicon steel and flash enamelled to reduce eddy current and hysteresis losses.
- Slots are evenly spaced on the inner periphery of the laminations.
- Conductors insulated from each other are placed in these slots and are connected to form a balanced 3 - phase star or delta connected stator circuit.
- Depending on the desired speed the stator winding is wound for the required number of poles. Greater the speed lesser is the number of poles.

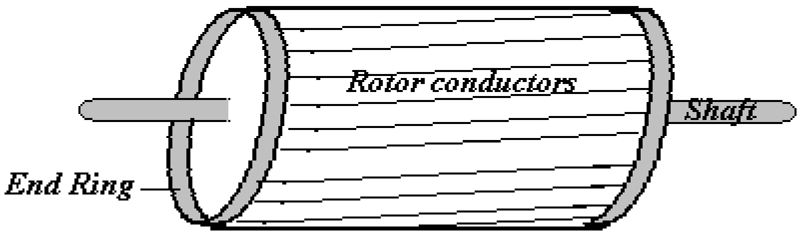
Rotor

They are basically classified into two types based on the rotor construction

1. Squirrel cage motor
2. Slip ring motor or phase wound motor

Squirrel cage rotor

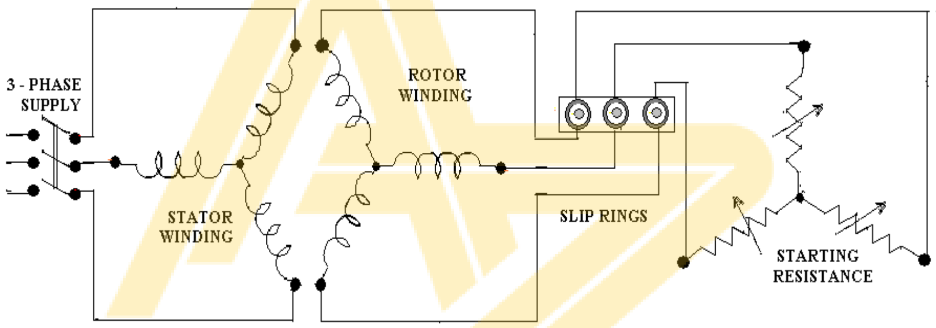
- Squirrel cage rotors are widely used because of their ruggedness.
- The rotor consists of hollow laminated core with parallel slots provided on the outer periphery.
- The rotor conductors are solid bars of copper, aluminium or their alloys.
- The bars are inserted from the ends into the semi-enclosed slots and are brazed to the thick short circuited end rings.
- This sort of construction resembles a squirrel cage hence the name “squirrel cage induction motor”.
- The rotor conductors being permanently short circuited prevent the addition of any external resistance to the rotor circuit to improve the inherent low starting torque.
- The rotor bars are not placed parallel to each other but are slightly skewed which reduces the magnetic hum and prevents cogging of the rotor and the stator teeth.



Squirrel cage induction rotor

Phase wound/slip ring rotor

- The rotor in case of a phase wound/ slip ring motor has a 3-phase double layer distributed winding made up of coils, similar to that of an alternator.
- The rotor winding is usually star connected and is wound to the number of stator poles.
- The terminals are brought out and connected to three slip rings mounted on the rotor shaft with the brushes resting on the slip rings.
- The brushes are externally connected to the star connected rheostat in case a higher starting torque and modification in the speed torque characteristics are required.
- Under normal running conditions all the slip rings are automatically short circuited by a metal collar provided on the shaft and the condition is similar to that of a cage rotor.
- Provision is made to lift the brushes to reduce the frictional losses.
- The slip ring and the enclosures are made of phosphor bronze.



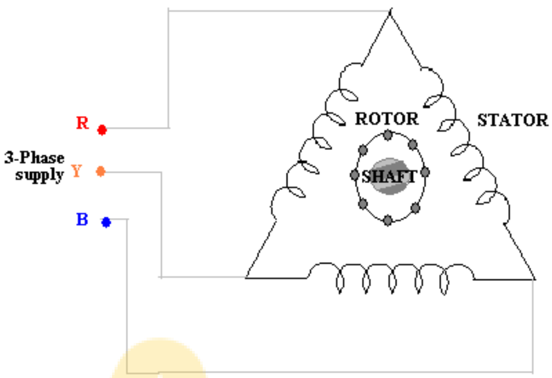
SLIP RING INDUCTION MOTOR

Comparison of the squirrel cage and slip ring rotors

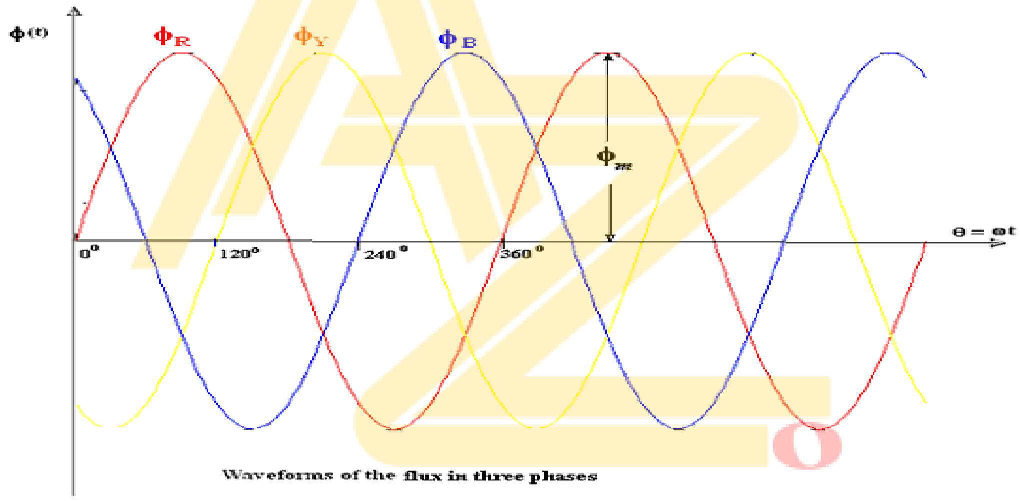
S.No	Slip ring rotor	Squirrel cage rotor
1.	Rotor consist of a 3-phase winding similar to stator winding	Rotor consist of bars which are shorted at the ends with the help of end rings
2.	Construction is complicated	Construction is very simple
3.	Resistance can be added externally	As permanently shorted external resistance cannot be added
4.	Slip rings and brushes are present	Slip rings and brushes are absent
5.	Rotors are very costly	Due to simple constructions rotors are cheap
6.	High starting torque can be obtained	Moderate starting torque which cannot be controlled
7.	Rotor resistance starter can be used	Rotor resistance starter cannot be used
8.	Rotor must be wound for same number of poles as stator	The rotor automatically adjusts itself for the same number of poles as that of stator
9.	Rotor copper loss is high hence efficiency is less	Rotor copper loss is less and hence efficiency is more

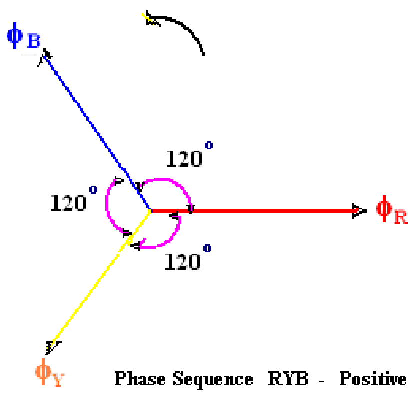
Production of rotating magnetic field

Consider a 3- phase induction motor whose stator windings mutually displaced from each other by 120° are connected in delta and energized by a 3- phase supply.



The currents flowing in each phase will set up a flux in the respective phases as shown





The corresponding phase fluxes can be represented by the following equations

$$\Phi_R = \Phi_m \sin\omega t = \Phi_m \sin\theta$$
$$\Phi_Y = \Phi_m \sin(\omega t - 120°)$$
$$\Phi_Y = \Phi_m \sin(\theta - 120°)$$

$$\Phi_B = \Phi_m \sin(\omega t - 240°)$$
$$\Phi_B = \Phi_m \sin(\theta - 240°)$$

The resultant flux at any instant is given by the vector sum of the flux in each of the phases.

(i) When $\theta = 0^\circ$, from the flux waveform diagram ,we have

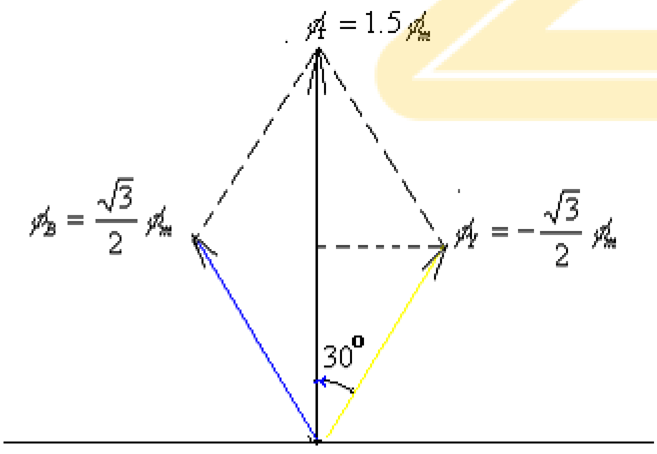
$$\phi_R = 0$$

$$\phi_Y = \phi_{km} \sin(-120^\circ) = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(-240^\circ) = \frac{\sqrt{3}}{2}\phi_m$$

The resultant flux ϕ_r is given by,

$$\phi_r = 2 * \frac{\sqrt{3}}{2}\phi_m \cos(30^\circ) = 1..5\phi_m$$



Resultant flux at $\theta = 0^0$

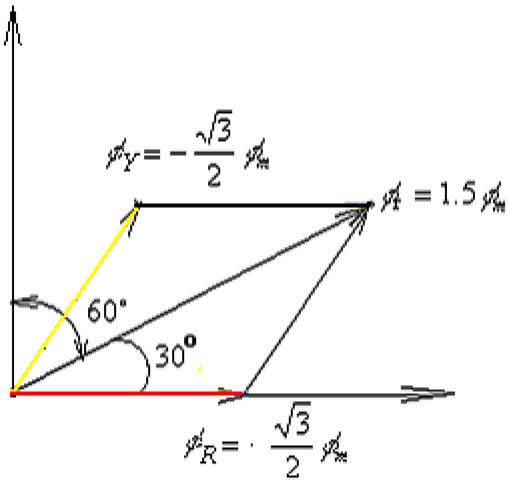
So the magnitude of φ_T is 1.5φ_m and its position is vertically upward at θ=0°

(ii) When θ=60°

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = 0$$



Resultant flux at θ = 60°

Doing the same construction, we get the same result as $\boldsymbol{\varphi_T = 1.5\varphi_m}$

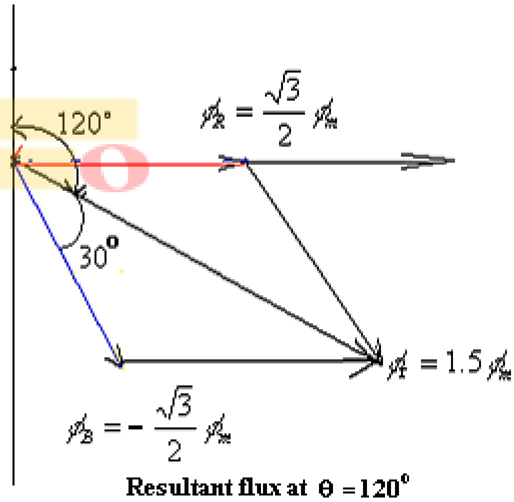
So the magnitude of φ_T is 1.5φ_m , but it has rotated through 60° in space, in clockwise direction from its previous position.

(iii) When θ= 120°

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = 0$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi_m$$



Resultant flux at θ =120°

Doing the same construction, we get the same result as $\boldsymbol{\varphi_T = 1.5\varphi_m}$

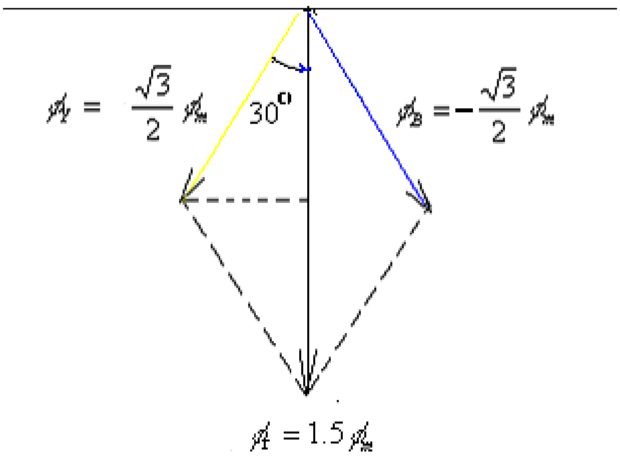
So the magnitude of φ_T is 1.5φ_m , but it has rotated through 120° in space, in clockwise direction from its position θ=0°.

(iv) When θ=180°

$$\phi_R = 0;$$

$$\phi_Y = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi$$



Resultant flux at θ = 180°

Doing the same construction, we get the same result as $\boldsymbol{\varphi_T = 1.5\varphi_m}$

So the magnitude of $\boldsymbol{\varphi_T}$ is 1.5$\boldsymbol{\varphi_m}$, but it has rotated through 180° in space, in clockwise direction from its position θ=0°.

From the above discussion we have the following conclusion

1. The resultant of the three alternating fluxes, separated from each other by 120° has constant amplitude of **1.5$\boldsymbol{\varphi_m}$** where $\boldsymbol{\varphi_m}$ is the maximum amplitude of an individual flux due to any flux.

2. The resultant always keeps on rotating with a certain speed in space.

Speed of the RMF

There exist a fixed relation between frequency f of AC supply to the winding, the number of poles for which the winding is wound and speed N rpm of rotating magnetic field. For a standard frequency whatever speed of RMF results is called Synchronous Speed. In case of induction motor it is denoted as N_S

$$N_S = \frac{120f}{P}$$

Working principle

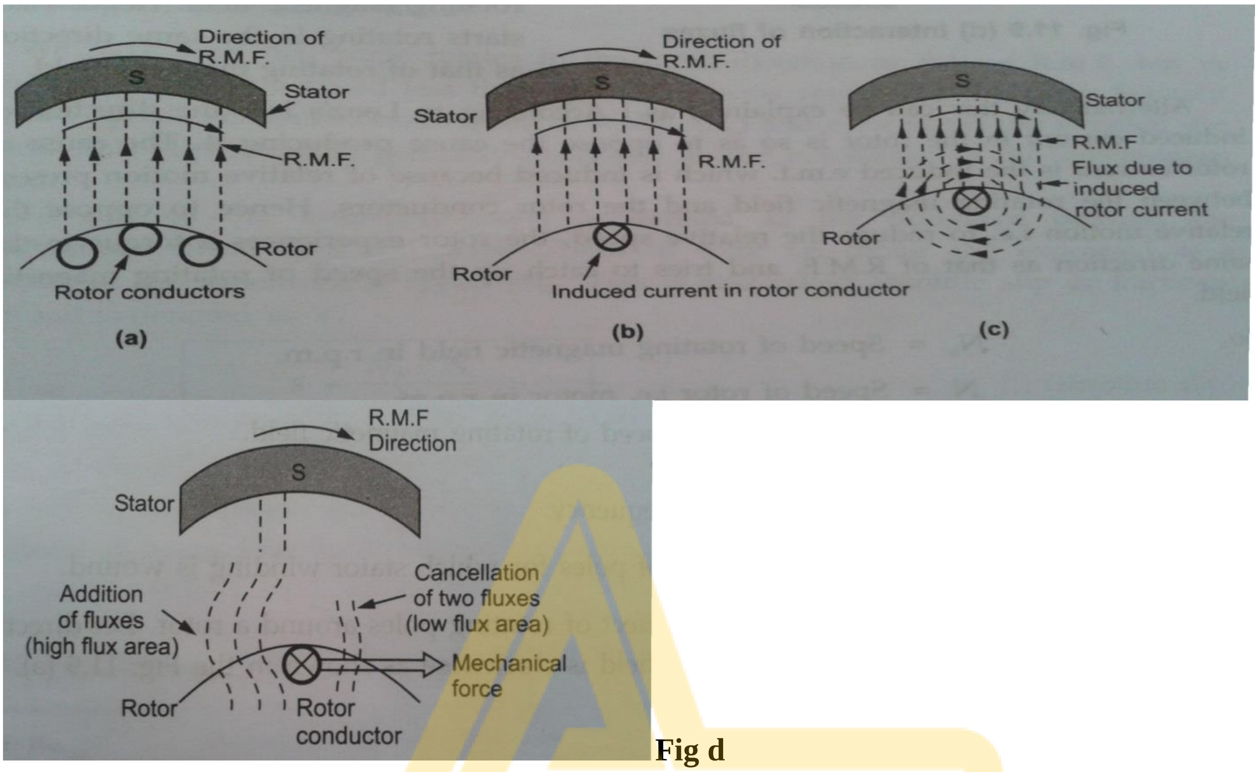


Fig d

Induction motor works on the principle of electromagnetic induction.
When a 3 phase is given to the 3 phase stator winding, a rotating magnetic field of constant magnitude is produced. The speed of this rotating magnetic field is synchronous speed N_S rpm.

$$N_S = \frac{120f}{P}$$

This rotating field produces an effect of rotating poles around a rotor. Let the direction of this rotating magnetic field be clockwise as shown in fig above.

Now at this instant rotor is stationary and stator flux RMF is rotating. So it's obvious that there exist a relative motion between the RMF and rotor conductors. Now the RMF gets cut by the rotor conductors as RMF sweeps over the rotor conductors. Whenever conductor cuts the flux, emf gets induced in the rotor. The emf that gets induced in the rotor conductor is called rotor induced emf. This is electromagnetic induction. As rotor forms closed circuit, induced emf circulates current through the rotor called rotor current as shown in fig b above. Let the direction of the current be going into the paper denoted by cross.

Any current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. For assumed direction of rotor current, the direction of rotor flux is shown in fig c. this direction can be easily determined using right hand thumb rule. Now there are two fluxes, one RMF and other rotor flux. Both fluxes interact with each other as shown in fig d. On left of the rotor conductor, two fluxes are in same direction hence added up to get high flux area. On the right side, the two fluxes cancel each other to produce low flux area. As the flux acts as stretched rubber bands, high density area exerts a push on rotor conductors towards low flux density area. So the rotor conductors experiences a force from left to right in the case as shown in fig d due to interaction of two fluxes.

As all the rotor conductors experience a force the overall rotor experiences a torque and starts rotating. So the interaction of the two fluxes is very important for a motoring action. As seen from fig d the direction of force experienced is same as that of RMF. Hence rotor starts rotating in the same direction as RMF.

Alternatively this can be explained as:

According to Lenz`s law the direction of the induced current in the rotor is so as to oppose the cause producing it. The cause of the rotor current is the induced emf which is induced because of the relative motion present between the RMF and rotor conductors. Hence to oppose the relative motion i.e. to reduce the relative speed, the rotor experiences a torque in the same direction as that of RMF and tries to catch up the speed of the RMF.

So

N_S = speed of RMF

N = speed of motor

$N_S - N$ = relative speed between RMF and rotor conductor

Can $N=N_S$?

When rotor starts rotating, it tries to catch up the speed of RMF. If it catches the speed of the RMF, the relative motion between the rotor and the RMF will vanish ($N_S - N=0$). In fact the relative motion is the main cause for the induced emf in the rotor. So induced emf will vanish and hence there cannot be rotor current and the rotor flux which is essential to produce torque on the rotor. Eventually the motor will stop. But immediately there will exist a relative motion between the rotor and RMF and it will start. But due to inertia of rotor, this does not happen in practice and rotor continues to rotate with a speed slightly less than the synchronous speed of the RMF in a steady state. The induction motor never rotates at synchronous speed. The speed at which it rotates is hence called subsynchronous speed and motor sometimes called asynchronous motor.

$$N < N_S$$

So it can be said that rotor slips behind the RMF produced by stator. The difference between the two is called slip speed.

$N_S - N$ = slip speed of the motor in rpm

This speed decides the magnitude of the induced emf and the rotor current, which in turn decides the torque produced.

Slip of the induction motor

The rotor rotates in the same direction as that of RMF but in steady state attains a speed less than the synchronous speed. The difference between the two speeds is called the slip speed. This slip speed is generally expressed as % of synchronous speed.

So the slip speed of the induction motor is defined as the difference between the synchronous speed and the actual speed of the rotor expressed as a fraction of synchronous speed.

$$S = \frac{N_S - N}{N_S}$$

% slip is expressed as

$$S = \frac{N_S - N}{N_S} * 100$$

In terms of slip actual speed of motor can be expressed as

$$N = N_S(1-S)$$

At start, motor is at rest and hence its speed N=0

Therefore S=1 at start

Frequency of rotor current

When the rotor is at standstill, the frequency of the rotor current is the same as the supply frequency. However, when there is relative speed between the rotor and stator field, the frequency of the induced voltage and hence the current in the rotor varies with the rotor speed i.e. slip. Let at any speed N of the rotor, the frequency of the rotor current be f`.

Then,
$$N_S - N = \frac{120f`}{P} \text{------------- (1)}$$

As,
$$N_S = \frac{120f}{P} \text{--------------------- (2)}$$

Dividing (1) by (2)

$$\frac{N_S - N}{N_S} = \frac{f`}{f}$$

$$S = \frac{f`}{f}$$

Note: In an induction motor the slip value ranges from 2% to 4%

Application of squirrel cage and slip ring induction motor

1. Squirrel cage type of motor having moderate starting torque and constant speed characteristic are preferred for driving fans, blowers, water pumps, grinders, lathe machines, printing ,machines, drilling machines.

2. Slip ring induction motor can have high starting torque. Hence they are preferred for lifts, hoists, elevators, cranes.

Need for starters

When a 3- phase motor of higher rating is switched on directly from the mains it draws a starting current of about 4 -7 times the full load (depending upon on the design) current. This will cause a drop in the voltage affecting the performance of other loads connected to the mains. Hence starters are used to limit the initial current drawn by the 3 phase induction motors.

The starting current is limited by applying reduced voltage in case of squirrel cage type induction motor and by increasing the impedance of the motor circuit in case of slip ring type induction motor. This can be achieved by the following methods.

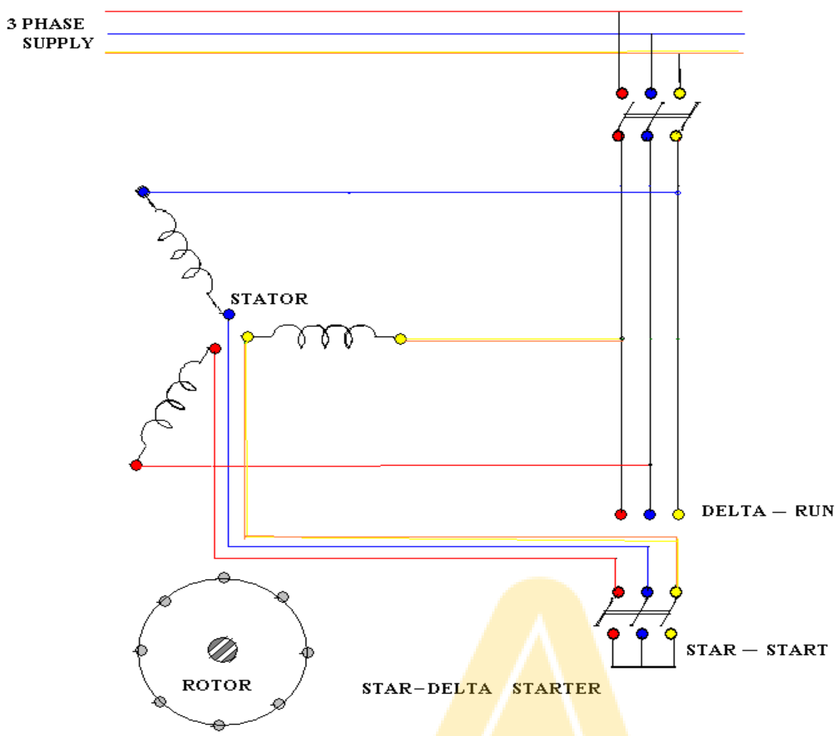
1. Star –delta starter

2. Auto transformer starter

3. Soft starter

Star delta starter

The star delta starter is used for squirrel cage induction motor whose stator winding is delta connected during normal running conditions. The two ends of each phase of the stator winding are drawn out and connected to the starter terminals as shown in the following figure



When the switch is closed on the star-start side

(1) **The winding is to be shown connected in star**
(2) **The current I = 1/3 * (I $_{direct\ switching}$)**
(3) **Reduction in voltage by1/√3**

$$V = V_{supply} * 1/\sqrt{3}$$

When the switch is closed on to delta –run side

(1) the winding to be shown connected in delta
(2) application of normal voltage V_{supply}
(3) normal current I

During staring the starter switch is thrown on to the **STAR - START**. In this position the stator winding is connected in star fashion and the voltage per phase is **1/√3** of the supply voltage. This will limit the current at starting to **1/3** of the value drawn during direct switching. When the motor accelerates the starter switch is thrown on to the **DELTA - RUN** side. In this position the stator winding gets connected in the **Δ** fashion and the motor draws the normal rated current.