Chapter 14

Three-Phase Induction Motors

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14.1 INTRODUCTION

The polyphase induction motor is, by a very considerable margin, the most widely used ac motor (almost more than 90 per cent of the mechanical power used in industry is provided by 3-phase induction motors). The reasons are its low cost, simple and rugged construction, absence of commutator, good operating characteristic (reasonably good power factor, sufficiently high efficiency and good speed regulation). An induction motor of a medium size may have an efficiency as high as 90 per cent and a power factor of 0.89. It is substantially a constant speed motor with a shunt characteristic; a few per cent speed drop from no load to full load. The physical size of such a motor for a given output rating is relatively small as compared with other types of motors.

The distinguishing feature of such a motor is that it is a singly-excited machine, although such machines are equipped with both field and armature windings. In such a machine the field* (or stator) winding is connected to an ac supply and there is no electrical connection from the armature* (or rotor) to any source of supply. Currents are made to flow in the armature (or rotor) conductors by induction which interact with the field produced by the field (or stator) winding and thereby produce a net unidirectional torque. Such motors are also called *asynchronous motors* as they run at a speed other than the synchronous speed of the rotating field developed by the stator currents.

Like other electrical machines, the asynchronous machine is reversible, *i.e.*, it can operate as both a motor and a generator. The mode of operation of the machine is determined by the speed of the rotating field in relation to the rotor.

An asynchronous machine may be considered to be a transformer in the sense that the power is transferred from the stator (primary) to the rotor (secondary) winding only by mutual induction. For this reason such a machine is often called the *induction* machine.

There is no simple and cheaper method of controlling the speed of the induction motor as is possible in case of a dc shunt motor and the torque developed by a polyphase induction motor is also not so strong as that developed by a dc shunt motor. It still finds stiff competition from the dc shunt motor in industrial applications.

* The terminology of the field and armature windings is seldom used for polyphase induction motors.

14.2 CONSTRUCTION

The 3-phase induction motor is very simple in construction compared to a dc motor or a synchronous motor. The essential features of a polyphase induction motor are: a laminated stator core carrying a polyphase winding; a laminated *rotor* core carrying either a cage or polyphase winding, the latter with shaft-mounted slip rings; a stiff *shaft* to preserve the very short air gap; a *frame* to form the stator housing and carry the end covers, bearings, and terminal box. It is not possible, as in the dc machines, to use the frame as part of the magnetic circuit. The end covers receive the ball- or roller-bearings with their clamping plates. Non-salient pole construction is used for all polyphase induction motors.

1. Frame. It is the outer body of the motor. Its functions are to support the stator core and winding, to protect the inner parts of the machine and serve as a ventilating housing or means of guiding the coolant into effective channels. The frame may be die cast or fabricated. Machines up to about 50 kW rating may have frame die cast in a strong silicon-aluminium alloy, sometimes with the stator core cast in. The frames for medium and large machines are almost exclusively fabricated.

2. Stator Core. The stator of an induction motor is quite similar in construction to that of a 3-phase synchronous alternator or motor. The stator core is to carry the alternating flux which produces hysteresis and eddy current losses. In order to reduce eddy currents and hysteresis loss in the stator core it is assembled of high grade, low electrical loss, silicon steel punchings. The thickness of punchings varies from 0.35 mm to 0.65 mm. In small motors, or if low core loss is not so important, slightly thicker laminations may be used. In the smaller sizes, the stator plates form complete annular rings, as shown in Fig. 14.1, but for larger machines they are prepared of segmental laminations to avoid wastage of steel. The punchings are insulated from one another by coating of varnish or oxide produced by heat treatment. The stampings are assembled under hydraulic pressure and are keyed to the frame. Careful alignment is required to prevent the rotor from rubbing against the stator, the air gap between the stator and rotor being very small. The radial ventilating ducts are provided along the length of the stator core, spaced every 5 or 7 cm. These are provided by the use of spacers placed between the laminations. The air gap between the stator and rotor is made as small as practicable (0.3 to 0.35 mm in small machines and 1.0 to 1.5 mm in high power machines) so as to make air-gap reluctance minimum. The slots are punched out on the inner periphery of the stator laminations, as shown in Fig. 14.1, to accommodate the stator winding, also sometimes known as *primary winding.* Some motors, especially of large ratings, have open type slots so that form-wound coils can be used but usually the motors are provided with semi-closed type slots to make the air-gap reluctance minimum and to prevent excessive tooth loss. In large, high-speed motors it is not essential to employ semi-closed slots to reduce the reluctance. The reason of it is that in large, high-speed motors, pole pitch is large, therefore, the number of conductors per pole is large, so the desired flux density in the air gap can be attained without an excessive magnetizing current, even if open type slots are employed.

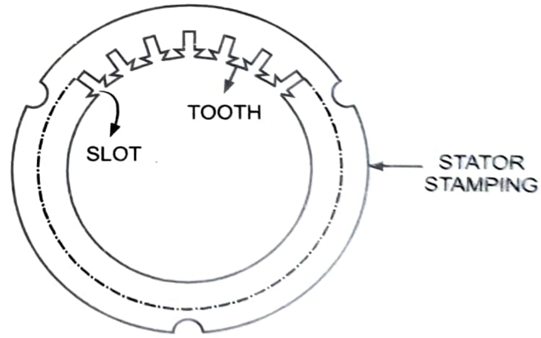


Fig. 14.1

3. Stator or Primary or Field Winding. Motors up to 250 kW operate usually at voltages in the range 380-440 V. For 3.3 kV the minimum economical rating is 250-300 kW, and for 11 kV about 750 kW.

In a polyphase induction motor the stator winding is usually 3-phase winding which is usually supplied from a 3-phase supply mains. The three phases of the winding can be connected in either star or delta depending upon the methods of starting used. The squirrel cage motors are usually started by star-delta starters and, therefore, their stators are designed for delta connections and six terminals (two from each phase) are brought out to be connected to the starter. The wound rotor motors are started by inserting resistance in the rotor circuit and, therefore, the stator winding can be connected in either star or delta as desired. It is wound for a definite number of poles as per requirement of speed. Greater the number of poles, lesser the speed or vice versa for a supply of given frequency.

In general, the same windings can be used on the stator of induction motor as were suitable for synchronous generators or motors. The double layer winding is mostly used in medium size motors because of its greater ease of manufacture, assembly, and repair. Moreover, stator windings are almost always short-pitched because of reduced copper weight and winding resistance as well as reduced leakage reactance and harmonic torque disturbances that result. Small motors, operating at ordinary supply voltages, with a small number of slots having a large number of turns per phase may use single layer mush winding. For large motors, or high-voltage motors the stator windings may be formed by single layer concentric coils. Double layer coils are placed in open slots so that form-wound coils can be used while mush winding is housed in semi-closed slots.

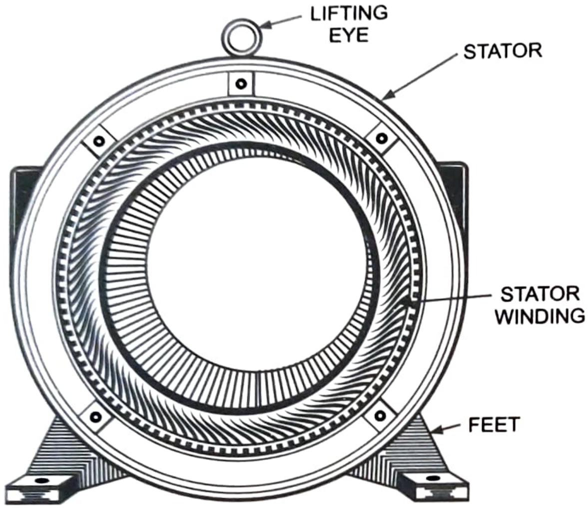


Fig. 14.2 *Stator of a 3-Phase Induction Motor*

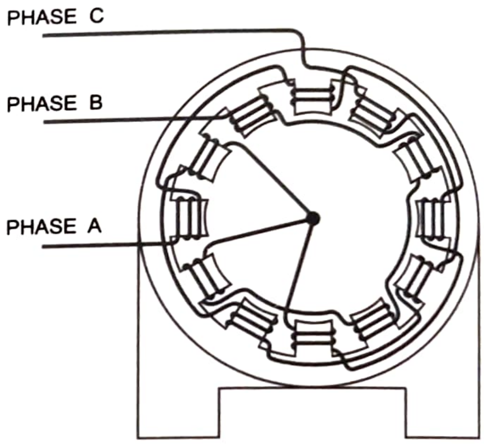


Fig. 14.3 *3-Phase, 4-Pole, Star-Connected Stator Winding*

Stator of a 3-phase induction motor and 3-phase, 4-pole, star-connected stator winding are illustrated in Figs. 14.2 and 14.3 respectively.

4. Rotor. The rotor comprises a cylindrical laminated iron core, much the same as that of a dc machine, with slots, around the core, carrying the rotor conductors. In general the same sheet steel laminations are employed for the rotor core as for the stator, but owing to the lower frequencies of the rotor flux, thicker laminations can be employed without excessive iron loss. The rotor stamping is shown in Fig. 14.4. Like stator, the rotor laminations are punched in one piece for small machines; in larger machines the laminations are segmented and dovetailed to a fabricated spider. If there are ventilating ducts on the stator core, an equal number of such ducts is provided on the rotor core also. Fan blades are usually employed on the ends of the rotor core to force circulating air through the motor for cooling.

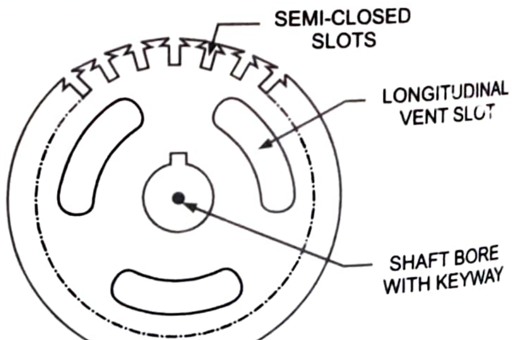


Fig. 14.4 *Rotor Stamping*

The rotor has a smaller number of slots than the stator and must be a non-integral multiple of stator slots so as to prevent magnetic locking of rotor and stator teeth at the starting instant.

The rotors employed in 3-phase induction motors, according to the type of windings used, are of two types, viz; squirrel cage rotor and the wound rotor.

1. *Squirrel Cage Rotor. Almost* 90 per cent of induction motors are provided with squirrel cage rotor because of its very simple, robust and almost instructible construction. In cage construction, copper, brass, or aluminium bars are placed, as the rotor conductors, parallel or approximately parallel to the shaft (one bar in each slot) and close to the rotor surface. The

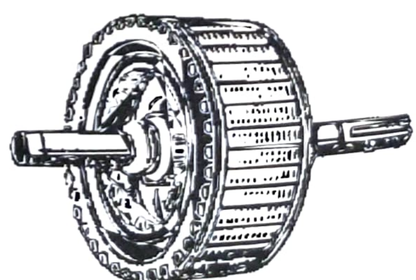


Fig. 14.5 *General View of Squirrel Cage Rotor*

conductors are not insulated from the core, since the rotor currents naturally follow the path of least resistance, *i.e.*, the rotor conductors. At both ends of the rotor, the rotor conductors are all short circuited by the continuous end rings of similar material to that of the rotor conductors. The rotor conductors and their end rings form a complete closed circuit in itself, resembling a squirrel cage, thus explaining the name. In motors with ratings up to 100 kW, the squirrel cage structure is formed by aluminium cast (under pressure) into the slots of the rotor (Fig. 14.6). In large motors the rotor bars, instead of being cast, are wedged into the rotor slots and are then welded securely to the end rings. The slots on the rotor are always not parallel to the motor shaft but are usually skewed in order to obtain a uniform torque, reduce the magnetic locking of the stator and rotor and reduce the magnetic humming noise while running.

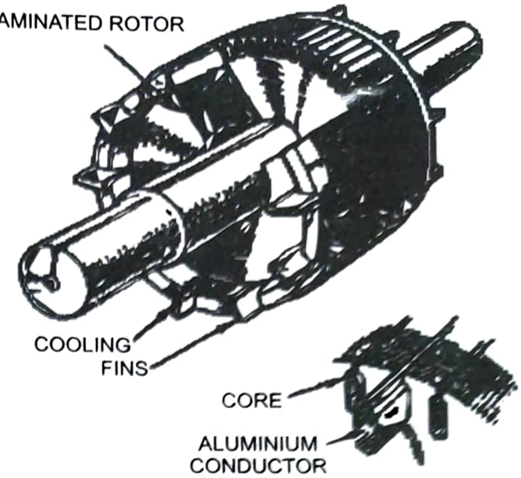


Fig. 14.6 *Cutaway View of Squirrel Cage Rotor*

The slots on rotor are either of semi-closed type or of totally closed type, because there is little difficulty in inserting the rotor bars in such slots. The advantage of semi–closed and totally closed slots is that the effective cross-sectional area of the air gap is increased, therefore, magnetizing current is reduced. Such slots also reduce the pulsations of flux in the individual teeth, therefore, tooth loss is reduced. The disadvantage of such slots is that these give higher slot inductance than the open slots, which lowers the power factor and reduces the starting and breakdown torques of the motor.

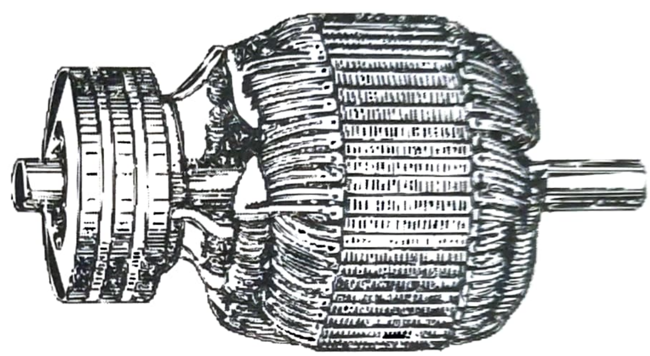


Fig. 14.7 *Rotor With Slip Rings*

The squirrel cage rotor windings are perfectly symmetrical and have the advantage of being adaptable to any number of pole pairs. The distribution of current due to electromagnetic induction in the rotor bars varies from bar to bar sinusoidally and depends upon the position and time, assuming sinusoidal distribution of radial flux density in space and also the applied voltage to be varying sinusoidally with time.

Since the rotor winding is permanently short circuited in cage construction, there is no possibility of adding any external resistance in the rotor circuit.

2. *Wound Rotor. As* the name implies, such a rotor is wound with an insulated winding similar to that of the stator except that the number of slots is smaller and fewer turns per phase of a heavier conductor are used. Bar, strap, or wire is used for rotor windings, the last being used where many turns are desired. A large number of rotor turns increases the secondary voltage and reduces the current that flows through the slip rings. The secondary voltage determines the insulation that must be provided; furthermore, the voltage and current influence the value of the resistance to be employed across the slip rings. The motor operation is not influenced by the number of rotor turns, but the ratio of transformation is determined by consideration of secondary current, danger of high secondary emf at starting, and distance to secondary resistors. The standstill open-circuit slip-ring voltage is usually 100 to 400 V for small machines using hand-operated gear and maximum up to 1 kV for large machines.

The rotor is wound for the same number of poles as that of the stator. The rotor winding is always 3-phase* winding even when the stator is wound for two phases. The rotor winding may be star or delta connected but star connection is usually preferred. The three finish terminals are connected together to form

*The flux set up by the stator windings is a rotating flux with a definite number of poles; operation is only slightly influenced by a change in the number of phases provided on the rotor winding so long as it is greater than one, but the number of poles must be the same on both (stator and rotor). Three-phase rotors are standard for both three-and two-phase motors and are sometimes employed in single-phase motors even.

star point and the three start terminals are connected to three phosphor-bronze (or brass) slip rings mounted on but insulated from the rotor shaft. The brushes, which carry the current from and to the rotor windings, are held in box type holders mounted on insulated steel rods and securely bolted to the end shield. Each brush is fed forward by a lever held in tension by an adjustable spring. These brushes are further externally connected to a 3-phase star-connected rheostat for the purpose of starting and speed control (Fig. 14.8). At the time of starting, the entire resistance is included in the rotor circuit and this resistance is gradually cut out as the rotor picks up the speed. For the normal running condition the entire external resistance is cut out and the rotor windings are short circuited automatically through the slip rings by means of a metal collar which is pushed along the shaft and connects all the rings together. Some machines are provided with brush lifting and slip ring short-circuiting arrangement for running condition. However, brush lifting and short-circuiting gear is usually not used in modern machines. The rotor is skewed in this case also. Since the connection of the wound secondary to the external terminals is made through slip rings and brushes, wound secondary motors often are called *slip-ring induction* motors. A sectional diagram of a slip-ring induction motor is shown in Fig. 14.9.

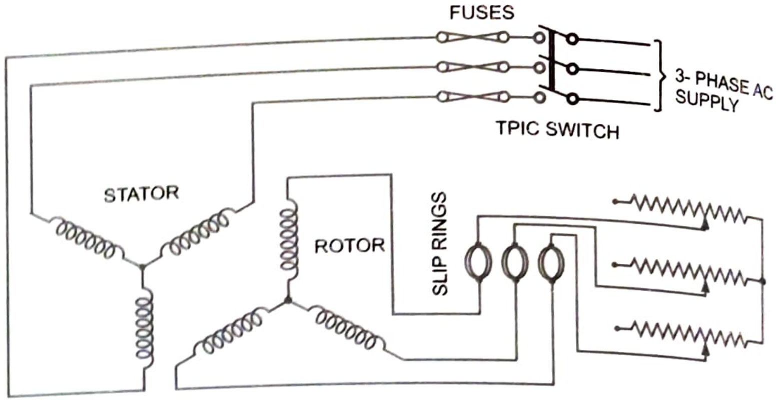


Fig. 14.8 *Slip-Ring Induction Motor With Starting Rheostat*

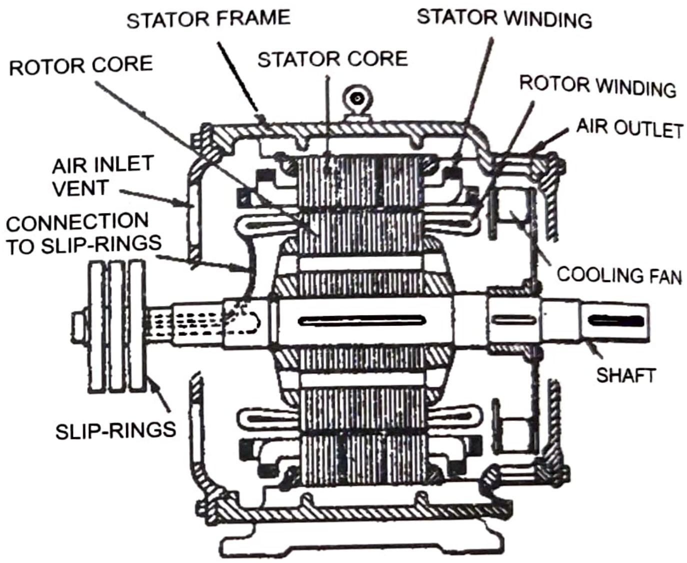


Fig. 14.9 *Section of a Slip-Ring Induction Motor*

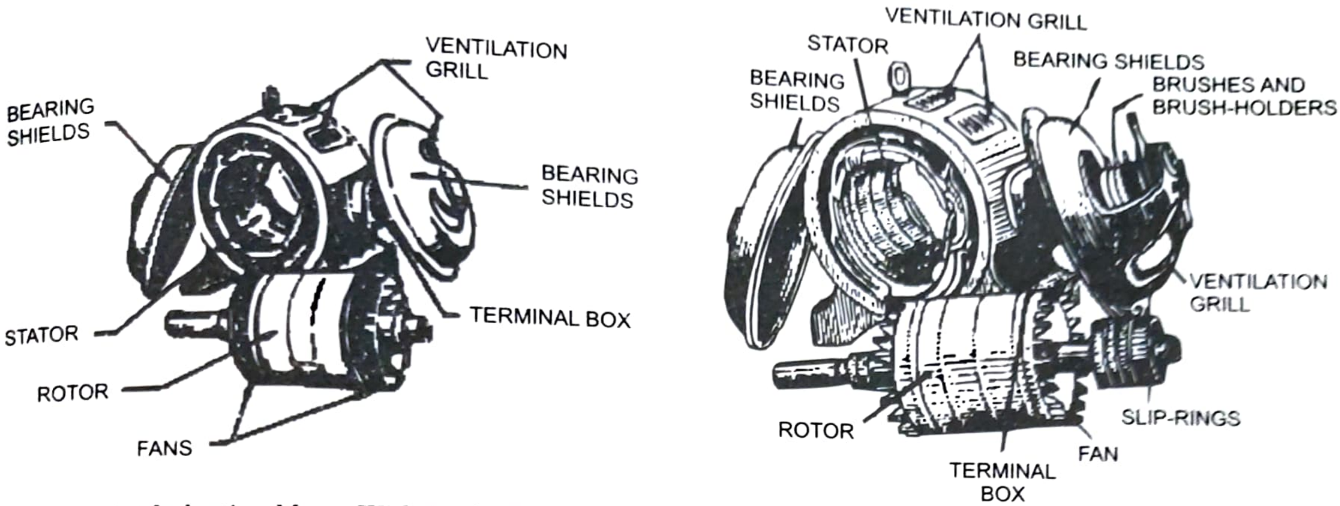
5. Shafts and Bearings. The rotor shaft is supported by bearings housed in the end shield. The air gap of an induction motor is kept necessarily small, therefore, the rotor shaft must be made short and stiff so that the rotor may not have any significant deflection. Even a minor deflection in the shaft would develop large irregularities in the air gap which would lead to production of an *unbalanced magnetic pull.* There is also a possibility of rotor and stator fouling with each other.

Ball- and roller-bearings are generally employed as their use makes accurate centring much simpler than with journal bearings. Also the overall length of the machine is reduced. In small motors, a roller-bearing may be employed at the driving end and a ball-bearing at the other end. For large and heavy rotors journal bearings of self aligning spherical seated type are useful.

14.3 TYPES OF 3-PHASE INDUCTION MOTORS

The 3-phase induction motors are of two types namely (*i*) squirrel cage and (*ii*) wound rotor or slip-ring induction motors. Both motors operate on the same principle and have the same stator construction but differ in rotor construction. The rotor of the squirrel cage induction motor is of squirrel cage type while slip-ring induction motor employs wound rotor. The slip-ring induction motors are less extensively used than squirrel cage type because of their higher first cost and greater maintenance cost. The slip-ring induction motors are employed only when speed control or high starting torque is required.

Induction motor with squirrel cage rotor and that with wound rotor, in disassembled form are shown in Fig. 14.10 (*a*) and 14.10 (*b*) respectively.



(*a*) *Induction Motor With Squirrel Cage Rotor (Disassembled)*

(*b*) *Induction Motor With Wound Rotor (Disassembled)*

Fig. 14.10

14.4 PRINCIPLE OF OPERATION

In a direct current motor, current is drawn from the supply and conducted into the armature conductors through the brushes and commutator. When the armature conductors carry current in the magnetic field established by the field, a force is exerted on the conductors which tends to move them at right angles to the field.

Though in an induction motor, there is no electrical connection to the rotor, but currents are induced in the rotor circuit, and therefore, the same condition exists as in the dc motors *i.e.* the rotor conductors carry current in the stator magnetic field and thereby have a force exerted upon them tending to move them at right angles to the field.

When the stator or primary winding of a 3-phase induction motor is connected to a 3-phase ac supply, a rotating magnetic field is established which rotates at synchronous speed. The direction of rotation of this field will depend upon the phase sequence of the primary currents and, therefore, will depend upon the order of connection of the primary terminals to the supply. The direction of rotation of the field can be reversed by interchanging the connection to the supply of any two leads of a 3-phase induction motor. The number of magnetic poles of the revolving field will be the same as the number of poles for which each phase of the primary or stator winding is wound. The speed at which the field produced by the primary currents will revolve is called the *synchronous speed* of the motor and is given by an expression, $N_s = 120 f/P$ where f is supply frequency and P is the number of poles on stator.

As the rotating magnetic field produced by the primary currents sweeps across the rotor conductors, an emf is induced in these conductors just as an emf is induced in the secondary winding of a transformer by the flux set up by the primary current. Since the rotor winding is either directly shorted or closed through some external resistance, the emf induced in the secondary by the revolving field causes a current to flow in the rotor conductors.

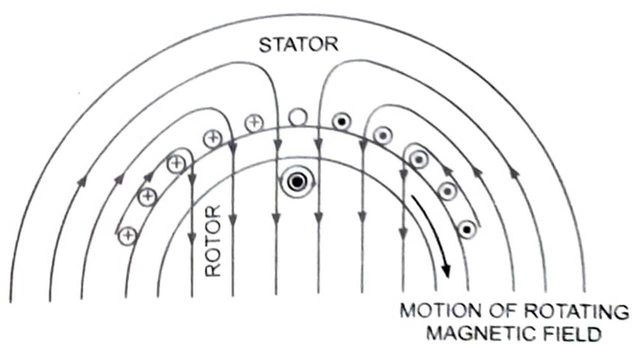
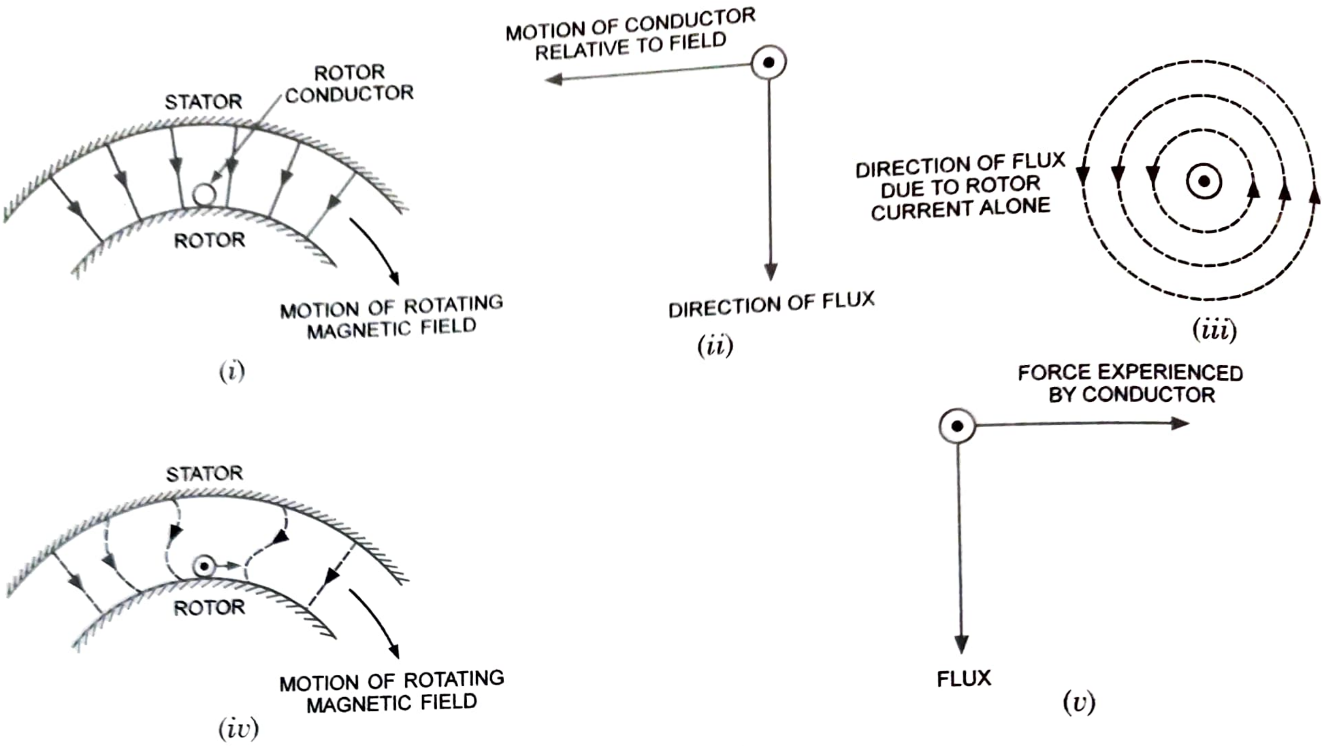


Fig. 14.11 (*a*)

The setting up of the torque for causing the rotor to rotate is explained below:



(*b*) *Production of Torque*

Fig. 14.11

A section of an induction motor stator and rotor, with the magnetic field assumed to be rotating in a clockwise direction and with the rotor stationary, as at starting, is shown in Fig. 14.11 (*a*). The relative motion of the rotor with respect to the stator field is anticlockwise. By applying right hand rule, the direction of induced emf or current in the rotor conductor shown is found outward. Hence the direction of the flux due to rotor current alone is anticlockwise, as shown in the Fig. Now, by applying the left hand rule, or by the effect of combined field, it is clear that the rotor conductor shown experiences a force tending to move the conductor to the right. For simplicity, only one rotor conductor is shown. However, other adjacent rotor conductors in the stator field likewise carry current in the same direction as the conductor shown and also have a force exerted upon them tending to move them towards the right. One half cycle later, the stator field direction will have reversed, but the rotor currents will have also reversed, so that the force on the rotor is still the same. Likewise rotor conductors under other stator field poles will have a force exerted upon them all tending to turn the rotor in the clockwise direction. If the developed torque is great enough to overcome the resisting torque of the load, the rotor will accelerate in the clockwise direction or in the same direction as the rotation of the stator field.

The above facts have been illustrated diagrammatically in Fig. 14.11 (*b*).

This may also be explained in terms of Lenz's law. According to Lenz's law we know that the direction of induced emf would be in such a direction that it would try to oppose the very cause for which it is due. Because the cause producing the induced currents is the relative speed between the rotating magnetic field and stationary rotor conductors, therefore, they circulate in such a way that a torque is produced in the rotor tending to cause it to follow the rotating magnetic field and thus reducing the relative speed.

When the rotor is stationary and about to start, the frequency of induced emf in the rotor is equal to that of the supply fed to the stator, because the relative motion is at synchronous speed. As the motor picks up the speed, the relative motion between the rotor and the synchronously rotating magnetic field becomes less and the frequency of emf induced in the rotor decreases. The magnitude of rotor induced emf, induced rotor current and so that of torque developed depends upon the relative motion. In case the relative motion is zero, *i.e.*, the rotor runs at synchronous speed, there would be no induced emf and no current in the rotor conductors, no rotor field and hence no torque. Thus we see that an *induction motor cannot run at synchronous speed.*

An induction motor running at no load will have a speed very close to the synchronous speed and, therefore, emfs in the rotor winding will be very small. This small emf gives a small current producing a torque just sufficient to overcome the losses such as due to friction and maintain the rotor in motion. As the mechanical load is applied on the motor shaft, it must slow down because the torque developed at no load will not be sufficient to keep the rotor revolving at the no-load speed against the additional opposing torque of load. As the motor slows down, the relative motion between the magnetic field and the rotor is increased. This results in greater rotor currents and greater developed torque. Thus, as the load is increased, the motor slows down until the relative motion between the rotor and the rotating magnetic field is just sufficient to result in the development of the torque necessary for that particular load. The decrease in speed from no load to full load is usually 4 to 5 per cent in case of small and medium size induction motors and in case of large size motors it varies from 2 to 2.25 per cent. In respect of speed- load characteristics, a 3-phase induction motor is quite similar to a dc shunt motor.

14.4.1. Reversal of Direction of Rotation of a 3-Phase Induction Motor. The direction of rotation of a 3-phase induction motor depends upon the direction of rotation of the field developed by the 3-phase supply applied to the stator. The direction of rotation of the field depends upon the order in which line terminals are connected to the stator. So the direction of rotation of the motor can be reversed by interchanging the connections to the supply of any two leads.

14.5 SLIP

In Art. 14.4, it has been determined that the speed of a polyphase induction motor must always be less than the synchronous speed and that, as the load is increased, the speed of the motor will decrease. The difference between the speed of the stator field, known as *synchronous speed* (N_s), and the actual speed of the rotor (N) is known as the *slip* and is denoted by *s*. Though the slip can be expressed in rpm or in radians per second, but usually it is expressed as a fraction or percentage of synchronous speed.

$$\text{Fraction slip, } s = \frac{\text{Synchronous speed} - \text{rotor speed}}{\text{Synchronous speed}} = \frac{N_s - N}{N_s} \quad \text{...(14.1)}$$

$$\text{and percentage slip} = \frac{N_s - N}{N_s} \times 100 \quad \text{...(14.2)}$$

At normal load the slip of an induction motor is usually between 2 and 5 per cent. At no load the slip is as small as 0.5 per cent and for many purposes the machine may then be considered to be running at synchronous speed. As the load is applied, the natural effect of the load torque is to cause the machine to slow down. As it does so, slip increases, and with it current and torque until the driving torque of the machine balances the retarding torque of the load. This determines the speed at which the machine runs on load.

The induction motor is thus a motor with substantially constant speed and plays the same role as a dc shunt motor.

Example 14.1. Find the probable number of poles of an induction motor having no-load speed of 1,400 rpm, when supplied from a 3-phase 50 Hz, ac supply. [*B.P. Univ. of Technology Basic Electrical Engineering, 2010*]

Solution:

No-load speed, $N_0 = 1{,}400$ rpm

Supply frequency, $f = 50$ Hz

The number of poles, even in number and to provide a synchronous speed nearest higher than no-load speed of motor (*i.e.* 1,400 rpm), that the induction motor must have is 4. **Ans.**

$$\because \quad P_m = \frac{120 f}{N_0} = \frac{120 \times 50}{1{,}400} \approx 4 \ \textbf{Ans.}$$

Example 14.2. Calculate the synchronous speed and slip of a 3-phase, 50 Hz, 4-pole induction motor running at 1,400 rpm. [*J.N. Technological Univ. Basic Electrical Engineering*]

From Eq. (14.17) it is obvious that

(i) Maximum torque is independent of rotor circuit resistance.

(ii) The slip at which maximum torque occurs is governed by the rotor resistance. As seen from above, the torque becomes maximum when rotor reactance equals the rotor resistance. So by varying the rotor circuit resistance, which is possible with wound rotors, maximum torque can be made to occur at any desired slip or motor speed.

(iii) Maximum torque varies inversely as standstill reactance of the rotor, hence to have maximum torque, standstill reactance *i.e.* inductance of the rotor should be kept as small as possible. This is achieved by placing the rotor conductors very close to the surface of the rotor and reducing the air gap between stator and rotor to the smallest possible value.

(iv) Maximum torque varies directly as the square of supply voltage.

14.9.4. Condition For Maximum Starting Torque

Starting torque T_{st} will be maximum when $\frac{R_2}{X_2} = s = 1$ or $R_2 = X_2$

Since the rotor resistance is not more than 1 or 2 per cent of leakage reactance otherwise efficiency will be low, so to increase the starting torque, extra resistance is required to be inserted in the rotor circuit at start and cut out gradually as the motor picks up speed. This is possible in case of wound rotor motors. This is the reason that wound rotor motors are used where heavy loads are to be accelerated at start such as cranes, lifts, elevators etc.

Example 14.15. A 0.6 kV, 20 poles, 50 Hz, 3-phase star-connected induction motor has rotor resistance of 0.12 Ω and a standstill reactance of 1.12 Ω. The motor has a speed of 292.5 rpm at full load. Calculate the slip at maximum torque. [*U.P. Technical Univ. Electrical Engineering First Semester, 2014-15*]

Solution: Rotor resistance per phase, $R_2 = 0.12\ \Omega$

Rotor standstill reactance per phase, $X_2 = 1.12\ \Omega$

Slip corresponding to maximum torque, $s_{\max T} = \frac{R_2}{X_2} = \frac{0.12}{1.12} = 0.107$ **Ans.**

Example 14.16. A 4-pole, 50 Hz, 3-phase induction motor has a rotor resistance of 0.02 Ω per phase and standstill reactance of 0.5 Ω per phase. Determine the speed at which the maximum torque is developed. [*M.D. Univ. Electrical Machine-II, December-2010*]

Solution: Rotor resistance per phase, $R_2 = 0.02\ \Omega$

Rotor standstill reactance per phase, $X_2 = 0.5\ \Omega$

Since the torque under running is maximum at that value of slip, which makes rotor reactance per phase equal to the rotor resistance per phase

$\therefore$ Slip corresponding to maximum torque, $s_{\max T} = \frac{R_2}{X_2} = \frac{0.02}{5} = 0.04$

Speed corresponding to maximum torque, $N_{\max T} = \frac{120f}{P}(1 - s_{\max T}) = \frac{120 \times 50}{4}(1 - 0.04) = 1{,}440$ rpm **Ans.**

14.10 TORQUE-SLIP AND TORQUE-SPEED CURVES

Torque developed by an induction motor rotor is given by the equation $T = \frac{K s R_2 E_2^2}{R_2^2 + s^2 X_2^2}$.

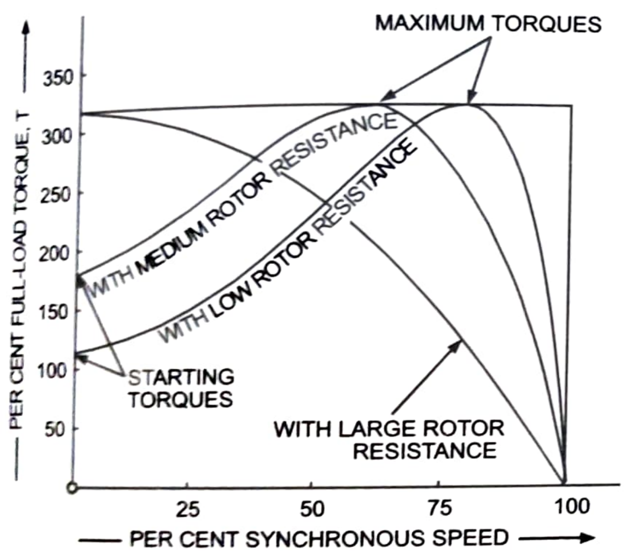
From the above equation it is revealed that

(i) When speed is synchronous *i.e.* when slip s is zero, the torque T is zero so the torque-slip curve starts from origin O.

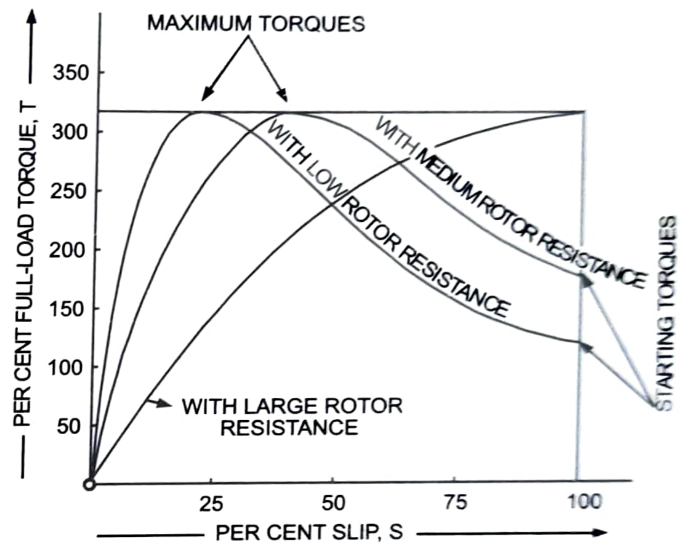
(ii) When the speed is very near to synchronous speed N_s *i.e.* when slip s is very low the value of term sX_2 is very small and is negligible in comparison with rotor resistance R_2, therefore, torque T is approximately proportional to slip s, if rotor resistance R_2 is constant *i.e.* at speeds near synchronous speed the torque-speed and torque-slip curves are approximately straight lines, as shown in Fig. 14.15 (*a*) and 14.15 (*b*) respectively.

(*iii*) As the slip increases, *i.e.* as the speed drops with the increase in load, torque increases, reaches its maximum value when slip $s = \frac{R_2}{X_2}$. The maximum torque is also known as *breakdown or pull-out torque*. The slip corrresponding to breakdown torque is called the breakdown slip s_b.

(*iv*) With the further increase in slip or drop in speed due to increase in load beyond the point of maximum torque the torque begins to decrease. The result is that the motor slows down and eventually stops. The motor operates for the value of slip between zero and that corresponding to breakdown or pull-out torque.



(*a*) *Torque-Speed Curves*



(*b*) *Torque-Slip Curves*

Fig. 14.15

With higher values of slip, R_2 becomes negligible as compared to $s\,X_2$ and the torque varies according to the relation $T \propto \frac{s}{s^2 X_2^2} \propto \frac{1}{s}$ if standstill reactance X_2 is constant. It means that torque-speed curves are rectangular hyperbola with the speed or slip beyond that corresponding to breakdown or pull-out torque.

Torque-speed and torque-slip curves are shown in Figs. 14.15 (*a*) and 14.15 (*b*) respectively for different values of rotor resistance R_2.

It is seen that although maximum torque is independent of rotor resistance R_2, yet the exact location of T_{max} is dependent on it. Greater the R_2, greater is the value of slip at which the maximum torque occurs.

14.10.1. Effect of Rotor Resistance Upon Torque-Slip or Torque-Speed Relationship. From the torque equation it is obvious that, for a constant supply voltage., when rotor resistance R_2 is very small compared with $s\,X_2$, the torque for a given slip is directly proportional to R_2; but when rotor resistance R_2 is large compared with $s\,X_2$, the torque for a given slip is inversely proportional to R_2.

From the Fig. 14.15 (*b*) it is seen that variation of rotor resistance does not change the magnitude of maximum torque T_{max}; merely changes the value of slip at which it occurs. Larger the rotor resistance the greater is the slip at which the maximum torque occurs.

For a given value of torque T, slip s is proportional to rotor resistance R_2, so addition of external resistance in the rotor circuit does not lower the torque curve but merely stretches it so that the same torque values occur at lower speeds (or higher slips) as shown in Fig. 14.15 (*a*) and 14.15 (*b*).

14.11 EFFECT OF CHANGE IN SUPPLY VOLTAGE ON TORQUE AND SLIP (OR SPEED)

When the motor is running with slip s, then torque acting on the rotor is given by

$$T = \frac{K\,s\,R_2 E_2^2}{R_2^2 + s^2 X_2^2} \quad \text{... Refer to Eq. (14.14)}$$

Since emf induced in the rotor at standstill, $E_2 \propto V$,

$$\text{torque developed, } T = \frac{K' s R_2 V^2}{R_2^2 + s^2 X_2^2} \quad \text{where } K' \text{ is another constant}$$

Since at full load, slip s is very low, $s^2 X_2^2$ can be neglected in comparison with R_2^2 and equation for torque may be written as

$$T = \frac{K' s R_2 V^2}{R_2^2} = \frac{K' s V^2}{R_2} \quad \text{or } T \propto sV^2$$

If the supply voltage is changed, it changes the torque under running conditions also. With the decrease in supply voltage, torque under running condition decreases. As the motor now develops a reduced torque, the motor slows down (*i.e.* slip increases) so as to cause increase in torque to meet the load torque and the motor may come to a standstill (if the load torque exceeds the pull-out torque of the motor corresponding to reduced supply voltage) unless the load is removed. Fig. 14.16 shows the variation of torque with slip for three different values of line voltage.

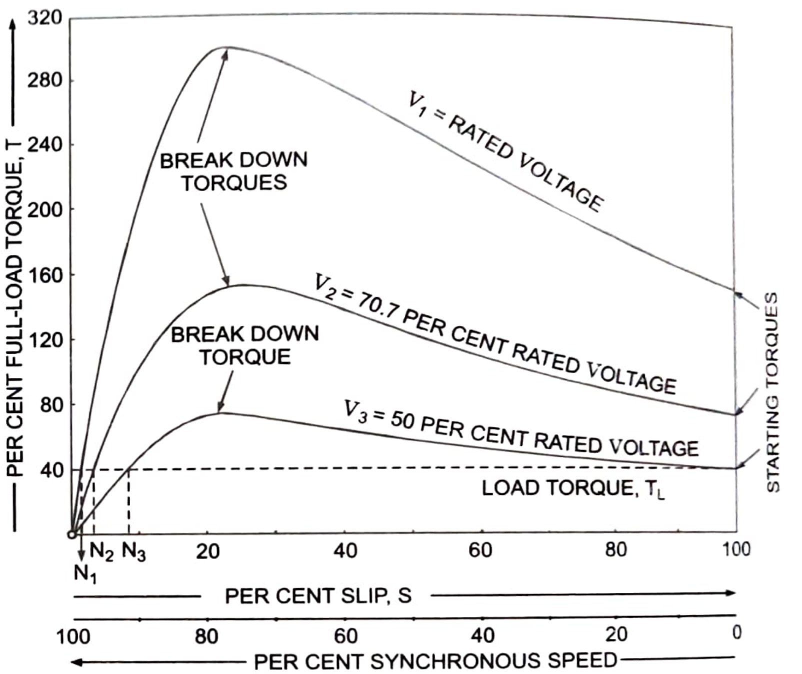


Fig. 14.16

14.12 TORQUE-SPEED CURVE AND OPERATING REGION

The torque-speed curve for an induction motor is given in Fig. 14.17. From Fig. 14.17 it is evident that for any load torque, there are two operating points (say B and D). But at position B, the operation is unstable because if there is tendency of speed rise, the developed torque also increases than the load torque causing further rise in speed. Thus at position B the operation is unstable. At position D operation is stable because a tendency to rise in speed will be opposed by the decrease in developed torque. Similarly when there is a tendency to fall in speed, there will be increase in developed torque to bring the motor to operating position D. Thus the region AC of the torque-speed characteristic is *unstable region* of operation while the region CF is stable region of operation.

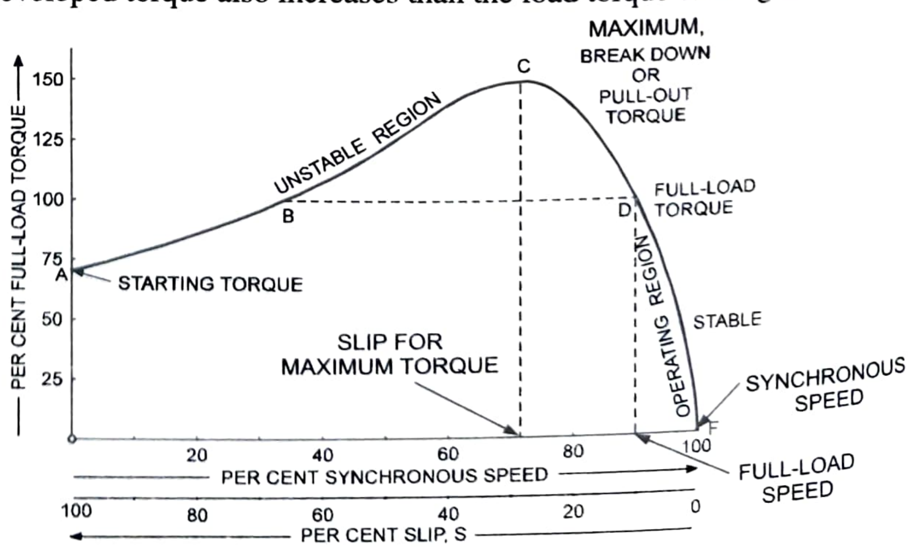


Fig. 14.17

At full load, the motor runs at a speed of N rpm. If the mechanical

$$(i)\ \text{Slip, } s = \frac{N_s - N}{N_s} = \frac{1{,}000 - 950}{1{,}000} = 0.05 \text{ or } 5\% \textbf{ Ans.}$$

$$\text{Motor output, } P_{out} = 20 \text{ kW}$$

$$\text{Rotor output, } P_{mech} = P_{out} + \text{mechanical losses} = 20 + 1 = 21 \text{ kW}$$

$$\text{Power input to rotor, } P_2 = \frac{P_{mech}}{1-s} = \frac{21}{1-0.05} = 22.1 \text{ kW}$$

$$(ii)\ \text{Rotor copper loss} = P_2 - P_{mech} = 22.1 - 21 = 1.1 \text{ kW } \textbf{Ans.}$$

$$\text{Stator losses} = 1{,}500 \text{ W} = 1.5 \text{ kW}$$

$$(iii)\ \text{Power input to stator, } P_1 = P_2 + \text{stator losses} = 22.1 + 1.5 = 23.6 \text{ kW } \textbf{Ans.}$$

$$(iv)\ \text{Line current, } I_L = \frac{P_1}{\sqrt{3}\, V_L \cos\phi} = \frac{23.6 \times 1{,}000}{\sqrt{3} \times 500 \times 0.8} = 34 \text{ A } \textbf{Ans.}$$

14.18 SPEED CONTROL OF INDUCTION MOTORS

The problem of speed control of electrical motors in general and of induction motors in particular is of great practical importance.

In a number of industries motors must satisfy very strict speed characteristic requirements, both with respect to the range and smoothness of control and also with respect to economical operation. From the view point of speed control characteristics, induction motors are inferior to dc motors. The speed of a dc shunt motor can be adjusted between wide range with good efficiency and speed regulation, but in induction motors speed cannot be varied without loosing efficiency and good speed regulation.

The speed of an induction motor is given by the expression $N = \frac{120\,f}{P}(1-s)$. Thus there are three factors viz, supply frequency f, number of poles P and slip s on which the speed of an induction motor depends. Hence to change the speed of an induction motor it is essential to change at least one of the above three factors.

Methods of speed control are distinguished according to the main action on the motor : (*i*) from the stator side, and (*ii*) from the rotor side.

Various methods of speed control from stator side are (*a*) variation of supply frequency (*b*) variation of applied voltage and (c) by changing the number of poles. From the rotor side the speed may be controlled (*a*) by changing the resistance in the rotor circuit and (*b*) by introducing into the rotor circuit an additional emf of the same frequency as the fundamental emf of the rotor.

For the latter method of speed control of induction motors, an additional electrical machine or several such machines are required. A set consisting of a regulated induction motor and one or more additional electrical machines connected to it electrically or mechanically is called *cascade*. Commutator machines are commonly used as the additional machines.

14.18.1. Speed Control By Variation of Supply Frequency. This method of speed control provides wide speed-control range with gradual variation of the speed throughout this range. The major difficulty with this method is how to get the variable frequency supply. The auxiliary equipment required for this purpose results in a high first cost, increased maintenance and lowering of the overall efficiency. That is why, this method is not employed for general purpose speed control applications. Inspite of the fact that this scheme is complicated, there are certain applications in which its wide, continuously variable, speed range and good speed regulation makes its use highly desirable.

This kind of variation can occur for example, if the supply generator is subjected to the speed variations, either due to momentary overloads or because of a noticeable speed regulation. Both output voltage and frequency vary as the speed if no automatic correction is provided. On some large marine drives, the propellor motors are induction type and are speed controlled from such a local supply which is provided by synchronous generators coupled to variable speed turbines. Even in such cases the range of speed variation is limited, because the efficiency of the prime movers falls rapidly with the change in speed from that for what they are designed.

14.18.2. Speed Control By Variation of Supply Voltage. This is a slip-control method with constant frequency variable supply voltage. In this method of speed control of induction motors, the voltage applied to the stator is varied for varying the speed.

This method of speed control is simple, low in first cost and has low maintenance cost but it has limited use because (*i*) the operation at voltages exceeding rated voltage is restricted by magnetic saturation, (*ii*) a large change in voltage is required for a relatively small change in speed (*iii*) the developed torque reduces greatly with the reduction in supply voltage and the motor will come to standstill if the load torque exceeds the pull-out torque of the motor corresponding to reduced supply voltage and (*iv*) the range of speed control is very limited in the downward direction *i.e.*, from rated speed to lower speeds.

14.18.3. Speed Control By Changing The Number of Poles. This method is easily applicable to squirrel cage motors because a cage winding automatically reacts to create the same number of poles as the stator. This method of speed control is generally not practicable with wound rotor motors as in such machines this method would involve considerable complications of design and switching, since the interconnections of both primary and secondary would have to be changed simultaneously in a manner to produce the same number of poles in both windings. Otherwise, negative torque will be developed by some of the rotor conductor belts.

The number of pole pairs in the stator can be changed as follows:

(*a*) by using multiple stator windings—by placing two or more independent windings on the stator, each producing a different number of poles;

(*b*) by using consequent pole technique — by placing one or two independent windings on the stator and changing the number of poles by changing the interconnections of primary coils;

(c) by using pole amplitude modulation technique — a suppressed– carrier modulation technique.

We will restrict our discussion to speed control by using multiple stator windings.

By Using Multiple Stator Windings. In this method of speed control two or more completely independent windings, each wound for different number of poles, are placed in the same stator slots. The number of stator winding poles are in this case in no way interrelated and can be arbitrarily chosen depending on the operating conditions of this motor. For example a two speed motor may have two stator windings, one wound for 4 poles and another for 6 poles which will give synchronous speeds of 1,500 rpm and 1,000 rpm with a supply frequency of 50 Hz. Motors with four independent stator windings are also used sometimes and they give four different synchronous (and hence running) speeds. Of course, one winding is used at a time, the others being entirely inoperative. Change over from one speed to the other may be done by a mechanical switch or by contactors. With such an arrangement, the winding or windings which is/are not being used must be kept open circuited by the switch, or at least left in star. Otherwise, because of transformer action, the winding which is connected to the supply would induce voltages in the idle winding(s) and cause overheating due to the subsequent circulating currents.

The regulation itself amounts to changing the motor speed in steps as one or another stator winding is connected to the supply mains. At each change, the motor finds itself under conditions essentially analogous to the starting conditions *i.e.* a large current and reduced torque. Because of inactive conductors, this method of pole changing requires a large stator than a single-speed motor of the same rating. This method has been used for elevator motors, traction motors and also for small motors driving machine tools.

14.18.4. Speed Control By Variation of Rotor Resistance (or Rotor Resistance Control). As the name implies, this type of control is only possible with wound rotor induction motors *i.e.* this method cannot be applied to squirrel cage motor.

Wound rotor motors are usually started by connecting starting resistances in the secondary circuit (refer to Art 14.20), which are shorted out as the motor speeds up. If the ohmic values of these resistors are properly chosen and if these resistors are designed for continuous operation, they can serve dual purpose — starting and speed control. This method of speed control has characteristics similar to those of dc shunt motor speed control by means of resistance in series with the armature.

From Eq. (14.14) torque developed by an induction motor is given as $T = \dfrac{K s R_2 E_2^2}{R_2^2 + s^2 X_2^2}$

When the speed is very near to synchronous speed N_s *i.e.* when slip s is very low the value of the term sX_2 is very small and can be neglected as compared to R_2 and torque developed becomes proportional to $\dfrac{s}{R_2}$ $\left(i.e.\ T \alpha \dfrac{s}{R_2}\right)$. So it is obvious that for a given torque, slip s can be increased (or speed can be reduced) by increasing the rotor resistance. It is also obvious that by this method speeds only below rated speed can be had. This method of speed control is stepped one. However, the larger the number of steps of the external resistances, the smoother is the speed control.

Secondary resistance control is simple and low in initial as well as in maintenance cost and it is possible to have a large starting torque with low starting current and large pull-out torques at small values of slip, as obvious from Fig. 14.15(b). The circuit arrangement is the same as shown in Fig. 14.8.

This method of speed control of polyphase induction motor has the following disadvantages.

(*i*) Reduction in speed is accompanied by reduction in efficiency.

(*ii*) Double dependence of speed not only on rotor resistance R_2 but on load as well— with a large resistance in the rotor circuit, the speed varies considerably with variation in torque [Fig. 14.15(*a*)].

(*iii*) The external rotor resistors are comparatively bulky and expensive as they have to dissipate a good deal of power without getting overheated.

This method of speed control as such is, therefore, not suitable for controlling speed at constant torque. But this method is widely used for loads where the torque required drops off considerably as the speed is reduced such as fan loads for which the power input drops noticeably as the speed is reduced which in turn reduces the rotor copper losses. Moreover, this method is not adopted for continuous speed control but is preferred for intermittent (short-time) operation. Such a method of speed control is widely used in practice, for low-power motors and in overhead cranes. It is sometimes used, however, for speed regulation of rolling mills especially where they are provided with flywheels for reducing the load peaks in the circuit. Here the rheostat, called the *speed regulator,* is automatically switched on when the load increases, and as a result speed decreases and part of the load is compensated at the expense of kinetic energy of the flywheel. Conversely, when the load decreases, the rotor circuit resistance is reduced; the speed increases and the flywheel begins to store kinetic energy.

14.19 STARTING OF 3-PHASE SQUIRREL CAGE INDUCTION MOTORS

Small induction motors up to 2 kW capacity can be directly put on the supply mains without any disturbance to the supply system. Since at the instant of starting, 3-phase induction motor acts as a polyphase transformer with a short-circuited rotating secondary, if motor of higher capacity is connected directly to the mains, then it will draw heavy current from the supply mains, which will cause large voltage drop in the distribution network and thus affect the operation of other electrical equipment connected to the same distribution network.

Therefore, to control the starting current, some starting device known as *starter* must be used. The principle of all types of starters is to impress the lower voltage across stator winding at the starting instant.

There are several methods of starting squirrel cage induction motors. The most common methods are described below.

1. Direct-on -Line Starting Method (or DOL Starter). Although there is no limitation on the size of the motor that may be started by this method, it should be understood that objectionable line voltage drops will usually occur, especially if large motors are started frequently. Whether or not normal voltage is employed will, therefore, depend upon the following factors :

(*i*) the size and design of the motor
(*ii*) the kind of application
(*iii*) the location of the motor in the distribution system and
(*iv*) the capacity of the power system and the rules governing such installations as established by power supply companies.

Squirrel cage motors of capacity up to 1.5 kW, double cage motors and squirrel cage motors of large capacity having a large rotor resistance are started by this method.

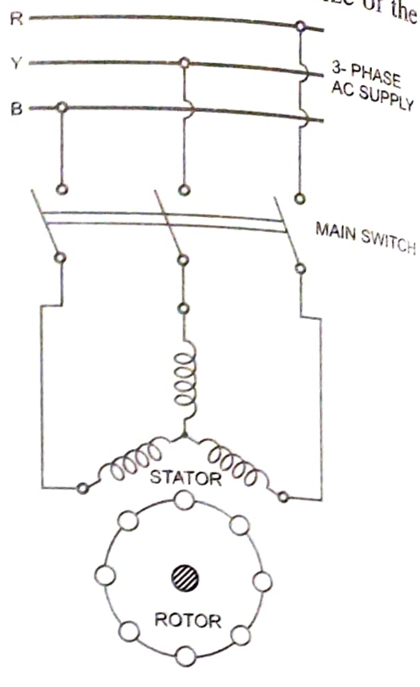


Fig. 14.19

The push button type direct-on-line starter, which is very common in use, is shown in Fig. 14.20. It is simple, inexpensive and easy to instal and maintain. It consists of a set of 'start' and 'stop' push buttons, a contactor (an electromagnet) with its associated contacts and usually an overload and undervoltage protection devices. The start button is a momentary contact switch that is held normally open by a spring. The stop button is held normally closed by a spring. When the start button is pressed the operating coil (or main contactor) gets energized through the overload relay contacts OL (normally closed). This closes the three main contacts M that connects the motor to the supply. At the same time a set of auxiliary or maintaining contacts MC are closed. When the maintaining contacts MC close, a new circuit is established through stop button, maintaining contacts MC and operating coil. Since operating coil circuit is now maintained by the auxiliary contacts MC, the start button may be released. When the stop button is pressed, the operating coil gets de-energized, thereby opening all main contacts and auxiliary contacts.

If the supply fails or line-voltage drops below a certain value, the main contacts and the maintaining contacts are both opened. Upon return of the supply, the contactor cannot close until the start button is again closed. Because a contactor that is controlled by a three-wire control circuit maintains the interruption of the circuit even after the supply is restored, it is said to provide

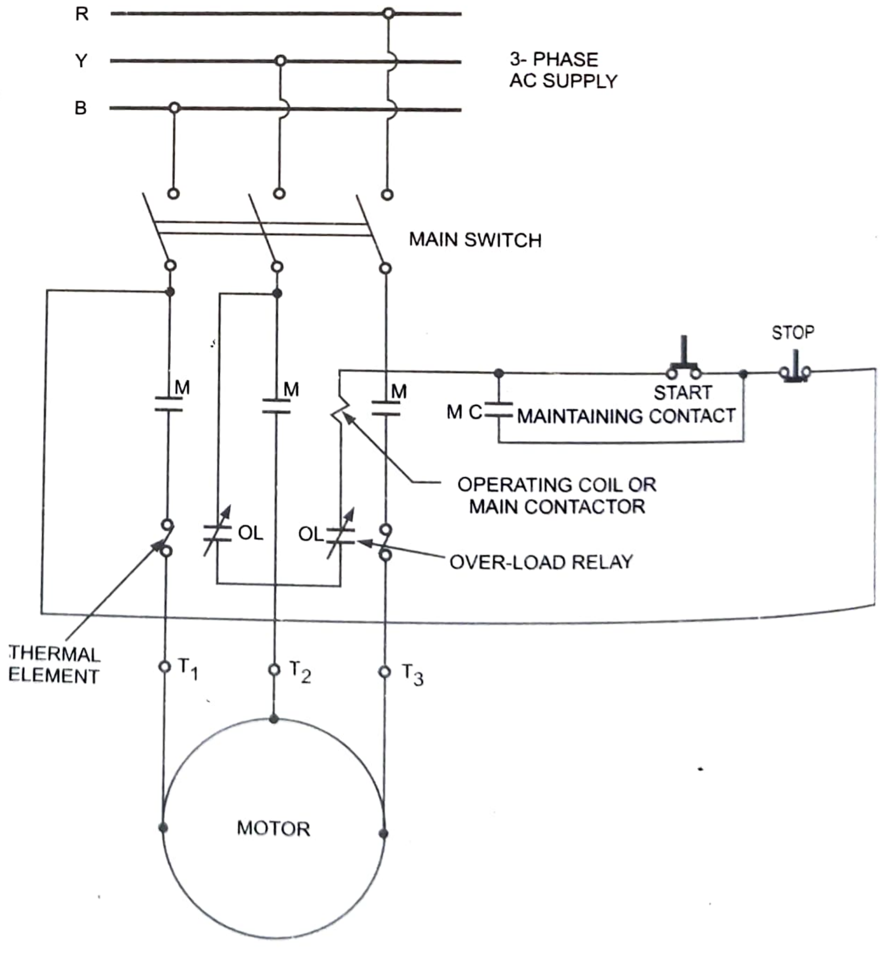


Fig. 14.20 *Wiring Diagram of a Direct-on-Line Starter With Protective Devices*

When the motor is connected directly across the supply mains, the starting current is equal to the short-circuit current. I_{SC}

$$\therefore \text{ Starting torque, } T_{st} = T_f \left(\frac{I_{SC}}{I_f}\right) s_f \quad (14.30)$$

2. Primary Resistor (or Reactor) Starting. This method of starting of a polyphase cage motor is very simple and provides smooth acceleration of the motor. In this method of starting of a 3-phase squirrel cage induction motor reduced voltage is obtained by means of resistors (or reactors) that are connected in series with each stator lead, as shown in Fig. 14.21, during the starting period. The voltage drop in resistors (or reactors) causes a reduced voltage across the motor terminals. As the motor picks up the speed, the resistors (or reactors) are cut out in steps and finally short circuited when the motor attains the operating speed.

Although the initial cost of reactors is high in comparison to that of resistors, reactor starting is preferred because this method incurs small power losses and is more effective* in reducing the voltage applied to the stator at starting.

The advantages and disadvantages of this method of starting of cage motors are given below:

Advantages. 1. Smooth acceleration.
2. High power factor during start.
3. Less expensive than auto-transformer starter in lower output ratings.
4. Closed transition starting.
5. Available with as many as 7 accelerating points.

Disadvantages 1. Resistors give off heat.
2. Low torque efficiency.
3. Starting duration usually exceeds 5 seconds, so needs expensive resistors.
4. Starting voltage is difficult to adjust to meet varying conditions.

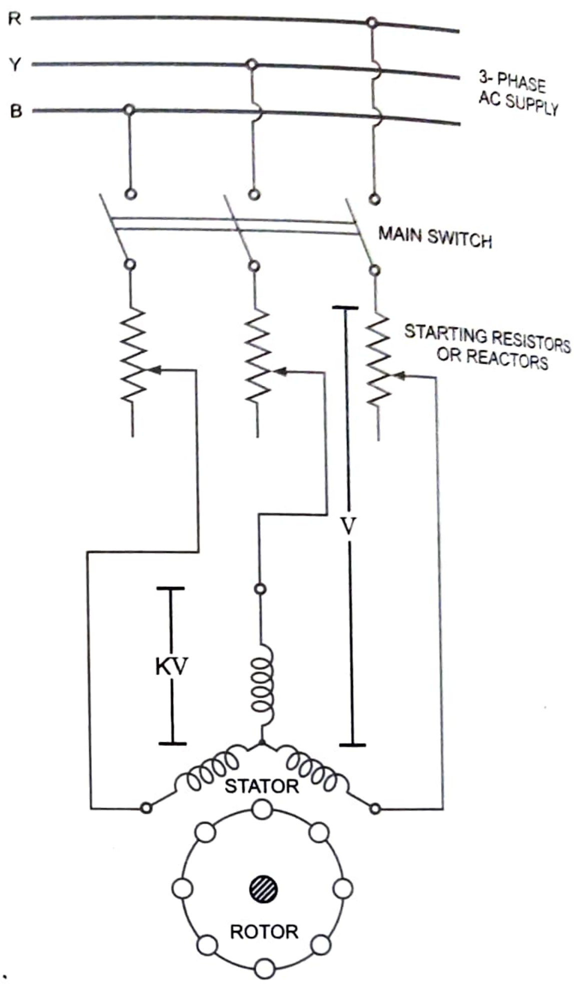


Fig. 14.21

If the normal supply phase voltage = V volts and by using line resistance starter the voltage is reduced to KV volts, then starting current is also reduced in the same ratio *i.e.* starting current $I_{st} = KI_{SC}$ where I_{SC} is the short-circuit current.

$$\text{Starting torque, } T_{st} = T_f \times \left(\frac{I_{st}}{I_f}\right)^2 s_f = T_f \times K^2 \left(\frac{I_{SC}}{I_f}\right)^2 s_f \quad ...(14.31)$$

$$= K^2 \times \text{Torque obtained by switching the motor directly.}$$

* The power factor of an induction motor is quite low at start and if reactors are used for reducing voltage across the motor terminals, the voltage drop across the reactors will be nearly in phase with the supply voltage and so the net reduction in the applied voltage to the stator will be more. On the other hand in case of resistance starting, the voltage drop across the resistors will be nearly in quadrature with the applied voltage and so the net reduction in the applied voltage to the stator terminals will be less.

3. Auto-Transformer Starting. In auto-transformer starting method the reduced voltage is obtained by taking tappings at suitable points from a three phase auto-transformer, as shown in Fig. 14.22. The auto-transformers are generally tapped at the 50, 60 and 80 per cent points, so that adjustment at these voltages may be made for proper starting torque requirements. Since the contacts frequently break large values of current, arcing is sometimes quenched effectively by having them assembled to operate in an oil bath.

Auto-transformer starters may be either manually or magnetically operated.

The manual auto-transformer starter is essentially a multi-pole double-throw switch. It consists of three sets of contacts starting, running (both stationary) and the movable contacts (the contacts attached to the operating handle). The operating handle is spring loaded lever mounted on the outside of a steel cabinet to stand vertically in the "off" position. When the operating handle is moved to the start position, the movable contacts are moved against the starting contacts. This energizes the star-connected auto-transformer and impresses reduced voltage (50, 60 or 80 per cent according to the setting on auto-transformer) across the motor. After the motor has accelerated to about full speed, the operating handle is moved to the run position. This instantly opens the starting contacts (or disconnects the auto-transformer from the line) and connects the motor directly to the line through the running contacts. A latch, fixed to the mechanism, is made to drop into a notch so that the operator is prevented from throwing the handle accidently to the run position first, however, when the handle is quickly pushed from the start to the 'run' position, the latch is kicked up to make the lever free for its forward motion. The operating handle is held in the run position by an electromagnet or undervoltage (latch) coil until the stop button is pressed. If the supply fails or supply voltage drops to low value, the electromagnet will release and trip the holding mechanism. Overload protection is provided by thermal overload relays.

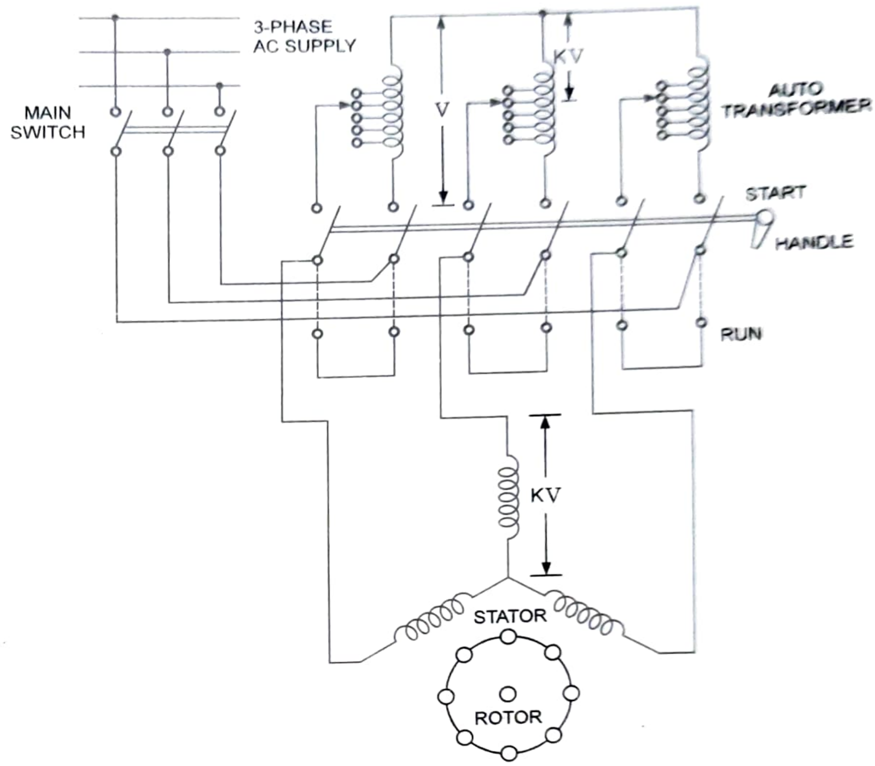


Fig. 14.22 *Auto-Transformer Starter*

Let the motor be started by an auto-transformer having transformation ratio, K. If I_{SC} is the starting current when normal voltage is applied, and applied voltage to stator winding at starting = KV

$$\text{then motor input current, } I_{st} = K\, I_{SC} \qquad \text{....(14.32)}$$

$$\text{Supply current} = \text{Primary current of auto-transformer}$$

$$= K \times \text{secondary current of auto-transformer} = K^2 I_{SC}$$

$$\text{Starting torque, } T_{st} = T_f \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = T_f K^2 \left(\frac{I_{SC}}{I_f}\right)^2 \times s_f \qquad \text{...(14.33)}$$

$$= K^2 \times \text{Torque obtained by direct switching.}$$

Hence the line current and the starting torque are reduced in the square ratio.

The advantages of this method of starting of cage induction motors lies in the fact that the voltage is reduced by transformation and not by dropping the voltage in the resistors (or reactors) and, therefore, the current and power drawn from the supply mains are also reduced in comparison to primary resistor (or reactor) starting. The internal losses of the starter itself are small during long starting periods. Other advantages of this method are (*i*) availability of highest torque per ampere of supply current (*ii*) adjustment of starting voltage by selection of proper tap on the auto-transformer (*iii*) suitability for long starting periods (*iv*) closed transition starting and (*v*) motor current larger than supply current.

The drawbacks of such starters are low power factor and higher cost in case of lower output rating motors.

This method can be employed for starting of star-connected as well as delta-connected motors.

For starting of large cage motors (of output rating exceeding 20 kW) this method of starting is often used.

4. Star-Delta Starting. This method of starting of cage induction motors is based upon the principle that with 3 windings connected in star, the voltage across each winding is $1/\sqrt{3}$ *i.e.* 57.7 % of the line to line voltage whereas the same winding connected in delta will have full line-to-line voltage across each.

The star-delta starter connects the three stator windings in star across the rated supply voltage at the starting instant. After the motor attains speed the same windings, through a change-over switch, are reconnected in delta across the same supply voltage.

The basic diagram of connection is shown in Fig. 14.23. Air break star-delta starter with single phasing preventive and overload relay is shown in Fig. 14.24. The starter is also provided with a mechanical interlocking device to prevent the handle from being put in the "Run" position first.

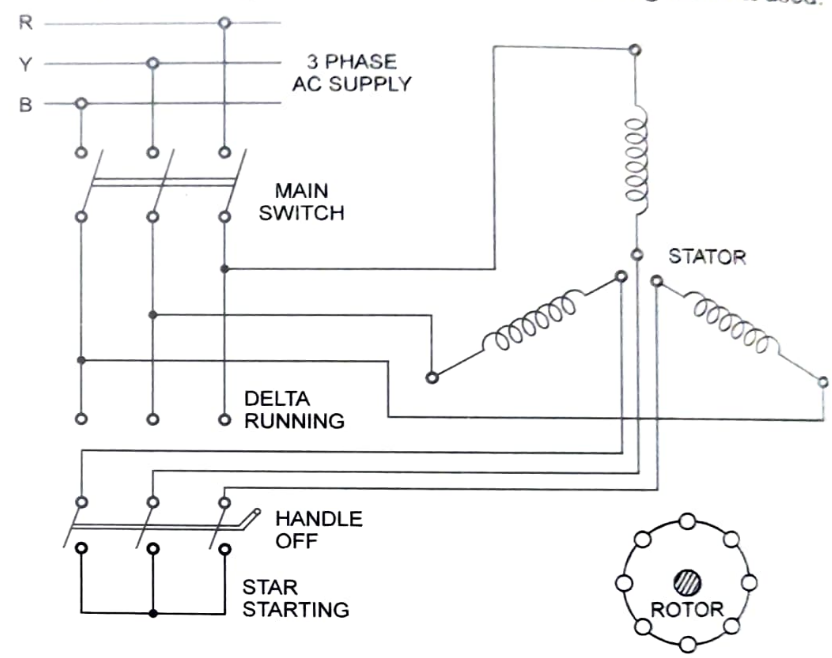


Fig. 14.23 *Star-Delta Starter*

Before putting the starter into service, the starter is mounted in vertical position and magnet armature, which is tied up to avoid damage in transit, is released.

For starting the handle is moved to START position and quickly to RUN position after motor has accelerated.

For stopping of motor, STOP push-button is used.

The load indicator may be set at full-load rated current of motor when thermal overload trips will be operated at approximately 20 to 25 % overload.

Since at starting instant, the stator windings are connected in star, voltage across each phase winding is reduced to $1/\sqrt{3}$ of line voltage and, therefore, starting current per phase becomes equal to $I_{SC}/\sqrt{3}$.

Starting line current by connecting the stator windings in star at the starting instant

$$= \text{Starting motor current per phase} = I_{SC}/\sqrt{3}.$$

Starting line current by direct switching with stator windings connected in delta $= \sqrt{3}\ I_{SC}$.

$$\therefore \quad \frac{\text{Line current with star-delta starting}}{\text{Line current with direct switching}} = \frac{I_{SC}/\sqrt{3}}{\sqrt{3}\, I_{SC}} = \frac{1}{3}$$

Hence by star-delta starting line current is reduced to one-third of line current with direct switching.

$$\text{Starting torque, } T_{st} = T_f\left(\frac{I_{st}}{I_f}\right)^2 s_f = T_f\left[\frac{I_{SC}/\sqrt{3}}{I_f}\right]^2 s_f = \frac{1}{3}T_f\left(\frac{I_{SC}}{I_f}\right)^2 s_f = \frac{1}{3} \times \text{torque obtained by direct switching} \quad ...(14.34)$$

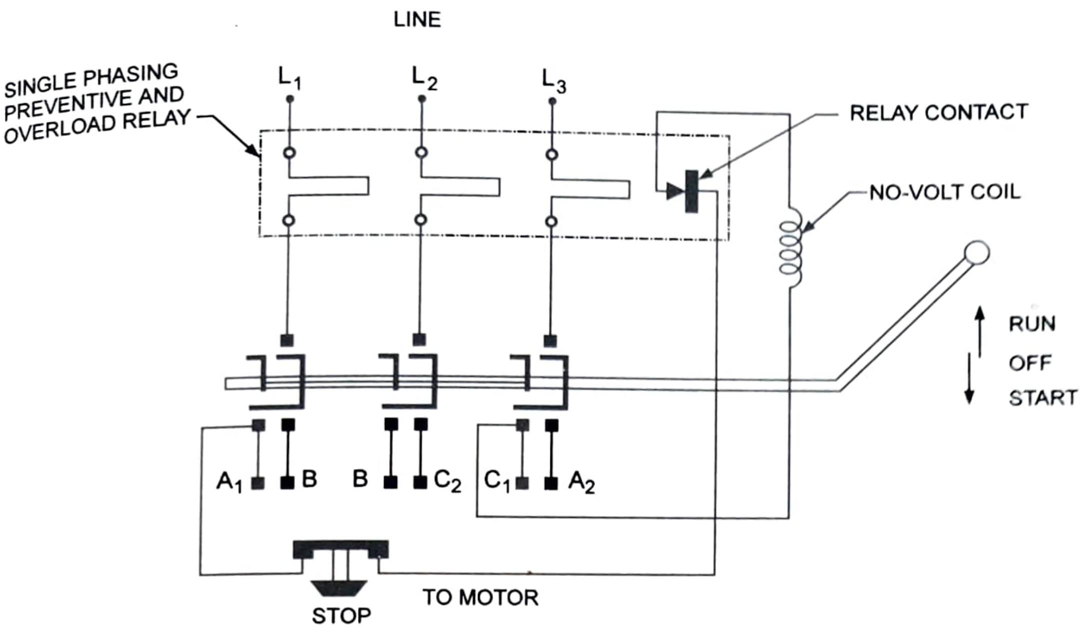


Fig. 14.24 *Air Break Star-Delta Starter With Single Phasing Preventive and Overload Relay*

Hence with star-delta switching, the starting torque is also reduced to one-third of starting torque obtained with direct switching.

This method of starting of cage motors is simple, cheap, effective and efficient since no power is lost in auxiliary components. This method is also suitable for high inertia and long acceleration loads.

This method needs a motor to be delta-connected for normal operation and all the six terminals of the 3-phase stator windings are to be brought out. The reduction in voltage is fixed and starting torque is also low. So this method is limited to application where high starting torque is not the essential requirement e.g. machine tools, pumps, motor-generator sets etc. This method is unsuitable for line voltage exceeding 3,000 V, because of excess number of stator turns required for delta connection.

Such starters are employed for starting 3-phase squirrel cage induction motors of rating between 4 and 20 kW.

Precaution With Star-Delta Starting. The initial current flowing when the motor is started in star is 57.7 % of the short-circuit current in delta together with a transient in each phase. The transient currents decay rapidly but the steady state is not reached until the motor has attained 70 per cent of its synchronous speed. The change-over from star to delta connection should not be made until the motor attains about 90 per cent of synchronous speed, otherwise there will be a current surge considerably greater than full-load current which may even be greater than the standstill current with star connection.

Example 14.21. A small 3-ϕ induction motor has a short-circuit current equal to 4 times the full-load current. Determine the starting torque as a percentage of full-load torque if full-load slip is 2.5 %.

Solution:

Short-circuit current, $I_{SC} = 4\, I_f$

Full-load slip, $s_f = 0.025$

$$\text{Starting torque, } T_{st} = T_f \left(\frac{I_{SC}}{I_f}\right)^2 s_f = T_f \times (4)^2 \times 0.025 = 0.4\, T_f \text{ or } 40\ \% \text{ of full-load torque. } \textbf{Ans.}$$

Example 14.22. A small 3-phase induction motor has a short-circuit current 5 times of full-load current and full-load slip 5 %. Determine the starting torque and starting current if starting resistance starter is used to reduce the impressed voltage to 60 % of normal voltage.

Solution:

Starting current, $I_{st} = 0.6 \times 5\, I_f = 3\, I_f$ **Ans.**

$$\text{Starting torque, } T_{st} = T_f \left(\frac{I_{st}}{I_f}\right)^2 \times s_f = T_f \times (3)^2 \times 0.05 = 0.45\, T_f \text{ or } 45\ \% \text{ of full-load torque. } \textbf{Ans.}$$

Chapter 13

Three-Phase Synchronous Machines

Inside this Chapter

13.1 INTRODUCTION

A synchronous machine is an ac machine in which the rotor moves at a speed which bears a constant relationship to the frequency of currents, in the armature winding. A synchronous machine is one of the important types of electric machines. Large ac networks operating at constant frequency of 50 Hz rely almost exclusively on *synchronous generators,* also called the *alternators*, for the supply of electrical energy. Private, stand-by and peak-load plants with diesel or gas turbine prime movers also have synchronous generators. Synchronous motors provide constant speed industrial drives with the possibility of power factor correction. Synchronous machines are generally constructed in larger sizes. Small size alternators are not economical. The modern trend is to build alternators of very large sizes capable of generating 500 MVA or even more. The synchronous motor is rarely built in small sizes owing to superior performance characteristics and economical construction of induction motors.

13.1.1. Operating Principle. The operating principle of a synchronous machine is fundamentally the same as that of a dc machine, but, unlike the latter, in the synchronous machine there is no need to rectify the time varying emf which is induced in the armature winding. Consequently a synchronous machine does not require a commutator. It is, in fact, quite possible to use a dc generator as an alternator by placing a set of collector rings on the shaft and connecting these rings to the proper points on the armature winding; brushes riding on the rings can then be connected to the load. But unlike dc generator, they are to be driven at a very definite constant speed as the frequency of generated emf is determined by that speed. The latter is usually referred to as the *synchronous speed,* for which reason these machines are frequently called the *synchronous generators*.

Synchronous generators, because of absence of commutator, are comparatively simple and possess several important advantages over the dc generators.

13.1.2. Classification of Synchronous Machines. Synchronous machines, according to their applications, may be *synchronous generators* or *synchronous motors*. A synchronous generator is a synchronous machine which receives mechanical energy from a prime mover (steam turbine, hydraulic turbine or diesel engine) to which it is mechanically coupled and delivers electrical energy. A synchronous motor receives electrical energy from ac supply main and drives mechanical load.

The synchronous machines may be *single-*, *two-* or 3-*phase* types. In three-phase machines three windings may be connected either in star or delta. Large ac machines are invariably 3-phase type.

Based on the construction of the machines, the synchronous machines may be classified as (*i*) rotating armature type and (*ii*) rotating field type.

Since it is immaterial for generation of an induced emf whether a conductor moves across a magnetic field or vice versa, synchronous generators may be constructed with either the armature or the field structure as the revolving member.

Rotating armature type alternator looks very much like a dc generator except that there are 3 slip rings in place of commutator (or 4 slip rings if it is desired to provide a connection to the generator neutral). In such generators the required magnetic field is produced by dc electromagnets placed on the stationary member called the *stator*, and the current generated is collected by means of brushes and slip rings on the revolving member, called the *rotor*. Such an arrangement is economical for the small low-voltage generators. Rotating armature type alternators are built only in small ratings up to about 200 or 250 kVA because the voltage generated is comparatively low and the current to be collected by the brushes small, no difficulty being experienced in collecting such a current. Such machines are suitable for small power plants, isolated lighting plants, where medium or small size machines are required.

Practically all medium and large machines are always constructed with revolving field. The advantages of stationary armature and revolving field system are given below:

1. It is easier to insulate stationary armature winding for very high voltage e.g. as high as 33,000 volts.
2. The load circuit can be connected directly with the fixed terminals of the stator (or armature winding) without passing through slip rings and brushes.
3. The armature winding can be more easily braced in a rigid frame to prevent any deformation which could be developed by the mechanical stresses set up due to short-circuit currents and the high centrifugal forces brought into play.
4. The armature winding is cooled more readily because the stator core can be made large enough with many air passages or cooling ducts for forced air circulation.
5. Only two slip rings are required for the supply of direct current to the rotor and since the exciting current is to be supplied at low voltage of 125 or 250 V, there is no difficulty in insulating them.
6. Since the exciting current is relatively small, the slip rings and the brush gear need be of only light construction.
7. Due to simple, light and robust construction of the rotor, higher speed of rotating dc field is possible.

Since in dc machines, the commutator makes necessary that either the armature should be rotating one, or brushes should revolve with the field, so it is convenient to have armature as a rotating member in dc machines.

Revolving field alternator with essential parts is shown in Fig. 13.1.

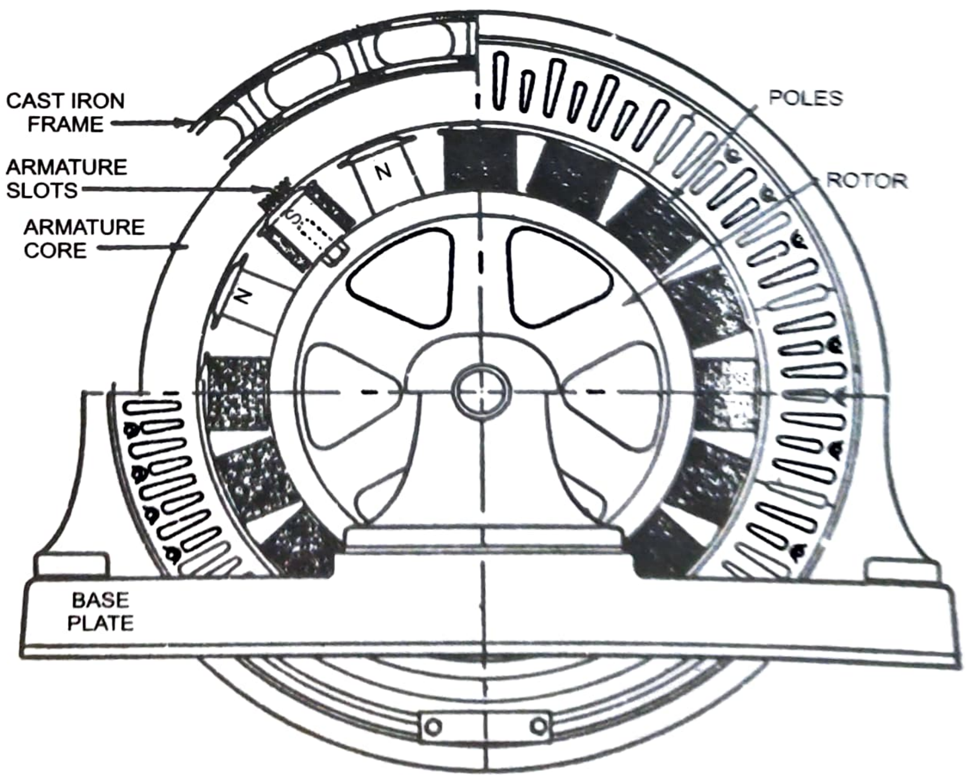


Fig. 13.1 *Revolving Field Salient Pole Type Alternator*

The synchronous machines may be classified as (*i*) salient pole machines and (*ii*) cylindrical rotor machines depending upon the type of construction used for the rotor. The salient pole construction is used for generators and motors of all ranges of output and up to all but the higher speeds. Medium-and large-sized generators for the highest speeds are of the cylindrical rotor type.

The synchronous generators, based on the type of prime movers to which they are mechanically coupled, may be classified as (*i*) turbo-generators, (*ii*) hydrogenerators and (*iii*) diesel engine driven generators.

13.2 CONSTRUCTION

Synchronous machine consists essentially of two parts namely the armature (or stator) and the field magnet system (or rotor).

1. Stator. The armature is an iron ring, formed of laminations of special magnetic iron or steel alloy (silicon steel) having slots on its inner periphery to accommodate armature conductors and is known as *stator*. The whole structure is held in a frame which may be of cast iron or welded steel plates. The field rotates in between the stator, so that flux of the rotating field cuts the core of the stator continuously and therefore causes eddy current loss in the stator core. To minimize the eddy current loss, the stator core is laminated. The laminations are stamped out in complete rings (for smaller machines) or in segments (for larger machines) and insulated from each other with paper or varnish. The stampings also have openings which make axial and radial ventilating ducts to provide efficient cooling. A general view of stator and frame is shown in Fig. 13.2.

Slots provided on the stator core are mainly of two types (*i*) open slots and (*ii*) semi-closed slots, as shown is Figs 13.3 (*a*) and 13.3 (*b*) respectively.

The open slots are more commonly used because the coils can be form-wound and insulated prior to being placed in the slots giving least expenditure and more satisfactory winding method. This type of slots also facilitate in removal and replacement of defective coils. But this type of slots have disadvantage of distributing the air gap flux into branches or tufts which tends to produce ripples in the emf wave. The semi-closed type slots are better in this respect but do not permit the use of form-wound coils. Totally closed slots are rarely used.

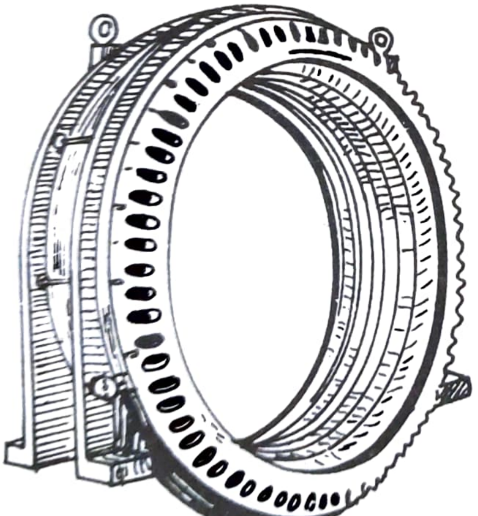
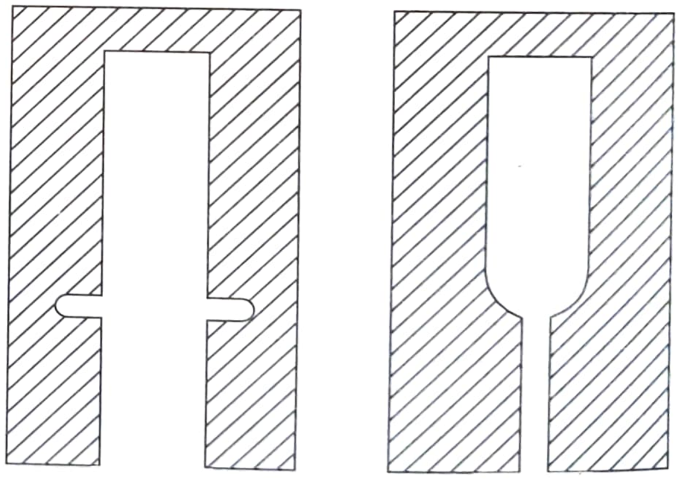


Fig. 13.2



(*a*) *Open Slot* (*b*) *Semi-Closed Slot*

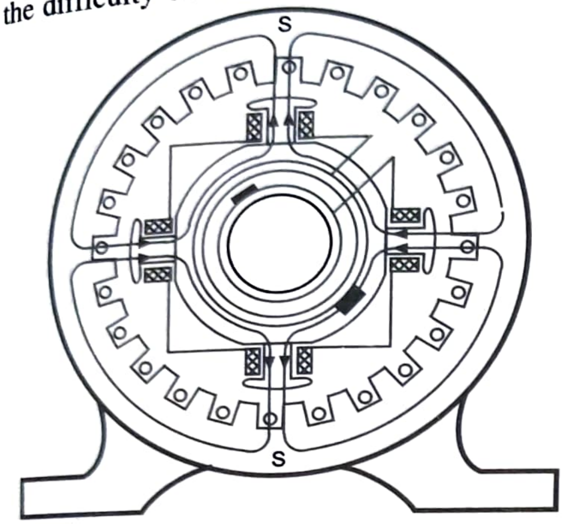
Fig. 13.3

2. Rotor. The field system is just like that of a dc generator which is excited from a separate source of 125 or 250 V dc supply. The excitation is usually provided from a small dc shunt or compound generator, *known as an exciter*, mounted on the shaft of the alternator itself. The field system of the alternator is rotated within the armature ring and is known *as rotor*. The exciting current is supplied to the rotor through two slip rings and brushes. The polarities of the field produced are alternately North and South.

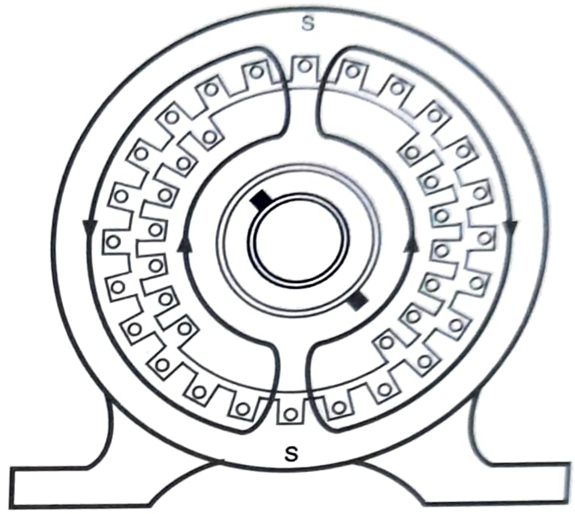
The power rating of the exciter is ordinarily 0.3 to 1% of power rating of synchronous-generator. The rated voltage of the exciter is usually between 125 and 250 volts.

Rotors are of two types namely (*i*) salient-pole type and (*ii*) smooth cylindrical type or non-salient pole type. Both types are shown in Fig. 13.4.

Salient Pole Type. The rotor of this type is used almost entirely for low- and moderate-speed alternators, since it is least expensive and provides ample space for the field ampere-turns. Salient poles cannot be employed in high speed generators on account of very high peripheral speed (100 to 170 metres per second) and the difficulty of obtaining sufficient mechanical strength.



(a) Salient Pole Type Field Structure



(b) Non-Salient Pole Type Field Structure

Fig. 13.4

The salient poles are made of thick steel laminations riveted together and are fixed to rotor by a dovetail joints. The pole faces are usually provided with slots for damper windings. These dampers are useful in preventing the hunting. The pole faces are so shaped that the radial air gap length increases from the pole centre to the pole tips so that the flux distribution over the armature is sinusoidal and wave-form of generated emf is sinusoidal. The field coils are placed on the pole-pieces and connected in series. The ends of the field windings are connected to a dc source through slip rings carrying brushes and mounted on the shaft of the field structure.

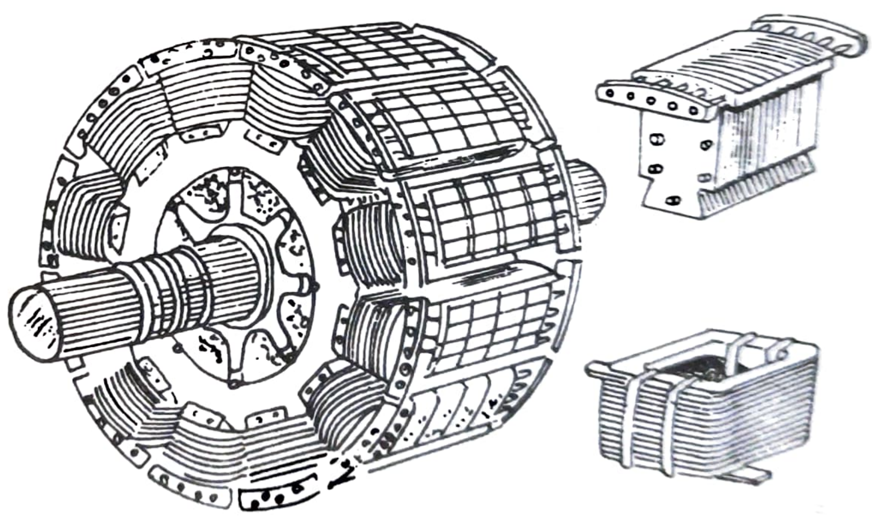


Fig. 13.5 *Salient Pole Field Structure*

The salient pole field structure has the following special features :

(*i*) They have large diameter and short axial length.

(*ii*) The pole shoes cover about 2/3 of pole pitch.

(*iii*) These are employed with hydraulic turbines or diesel engines. The speed is 100 to 375 rpm.

Smooth Cylindrical or Non-Salient Pole Type. The rotors of this type are used in very high-speed alternators (driven by steam turbines). To reduce the peripheral velocity, the diameter of the rotor is reduced and axial length is increased. Such rotors have two or four poles.

It consists of a cylindrical steel forging which is suitably worked mechanically and treated thermally. The forging has radial slots in which the field copper, usually in strip form, is placed. The coils are held in place by steel or bronze wedges and coil ends are fastened by metal rings. The slots over certain portions of the core are omitted to form pole faces, as shown in Fig. 13.7. Each slot is provided with a ventilation hole at the bottom. General view of an assembled smooth cylindrical rotor is shown in Fig. 13.6.

The non-salient field structure has the following special features :

(*i*) They are of small diameter and of very long axial length.

(*ii*) Less windage loss.

(*iii*) High operating speed (3,000 rpm).

(*iv*) Robust construction and noiseless operation.

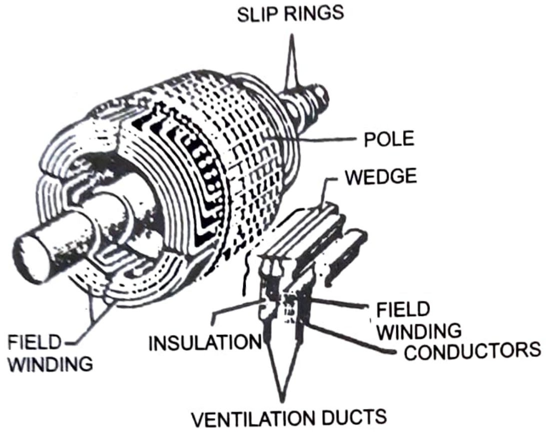


Fig. 13.6 *Non-salient Pole (Cylindrical) Field Structure*

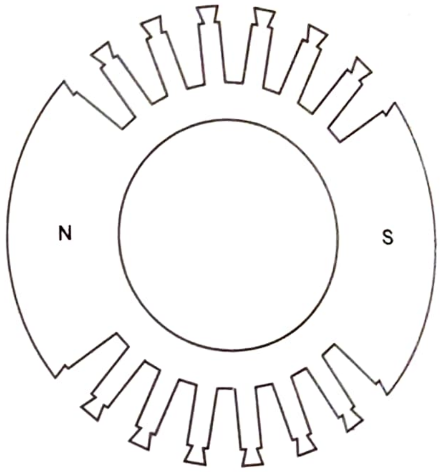


Fig. 13.7

Air Gap. A very small air gap increases the stray-load loss; also the eccentricity in the air gap can result from mechanical difficulties. This also increases the synchronous reactance. A large air gap needs larger excitation. A compromise has to be made. Generally the ratio of air gap to the pole pitch is between 0.008 to 0.02.

13.3 PRODUCTION OF SINUSOIDAL ALTERNATING EMF

When the rotor is rotated by means of some prime mover, the armature conductors cut the magnetic flux, therefore, an emf is induced in the armature conductors, due to electromagnetic induction effect.

When the conductor is opposite the neutral planes, as at A, C and E, induced emf in it is minimum because flux density is minimum there. When the conductor is opposite the middle of the poles, as at B, D and F, induced emf in it is maximum, the direction of induced emf depends upon the name of the pole influencing the conductor at any given instant. Thus an alternating emf is induced in the conductors which goes through one complete cycle in an angular distance equal to twice of the pole pitch. Though the shape of the wave of alternating induced emf is not exactly the sinusoidal but taken as sinusoidal.

13.4 FREQUENCY OF INDUCED EMF

As mentioned above, an emf induced in conductor goes through one complete cycle in an angular distance equal to twice the pole pitch.

If the number of poles on rotor of an alternator is P, then P/2 cycles of emf are completed in one revolution. The number of cycles per second, *known as frequency f,* will be equal to the product of number of cycles of emf per revolution and number of revolutions made per second by the rotor.

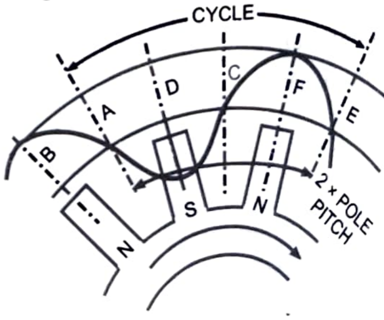


Fig. 13.8

i.e. Frequency, $f = \dfrac{P}{2} \times n$

where n is the number of revolutions made per second by rotor

$$\text{or } f = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120} \qquad ...(13.1)$$

where N is the number of revolutions made per minute by the rotor.

Hence frequency of induced emf or current induced in stator conductors depends upon the number of poles and speed of rotor.

Example 13.1. A 6-pole ac generator is running and producing the frequency of 60 Hz. Calculate the revolutions per minute of the generator. If the frequency is reduced to 20 Hz, how many number of poles will be required if the generator is to be run at the same speed.

Solution:

Frequency generated, f = 60 Hz

Number of poles, P = 6

$$\text{Speed, } N = \frac{120\,f}{P} = \frac{120 \times 60}{6} = 1{,}200 \text{ rpm } \textbf{Ans.}$$

When frequency, f' = 20 Hz

$$\text{Number of poles required, } P' = \frac{120\,f'}{N} = \frac{120 \times 20}{1{,}200} = 2 \textbf{ Ans.}$$

13.5 WINDING FACTOR

The product of pitch factor K_p and distribution factor K_d is referred to the winding factor

$$i.e.\ K_w = K_p K_d \qquad ...(13.2)$$

In a short-pitch winding the induced emfs in the two sides of the coil are not in phase, hence their resultant given by the phasor sum is always less than their arithmetic sum. The ratio of phasor sum of induced emfs per coil to the arithmetic sum of induced emfs per coil is known as *coil pitch factor, coil-span factor* or simply *pitch factor* (K_c or K_p). Pitch factor is given as

$$K_p = \frac{\text{Phasor sum of coil side emfs}}{\text{Arithmetic sum of coil side emfs}}$$

$$= \frac{2E \cos \alpha/2}{2E} = \cos\frac{\alpha}{2} \qquad ...(13.3)$$

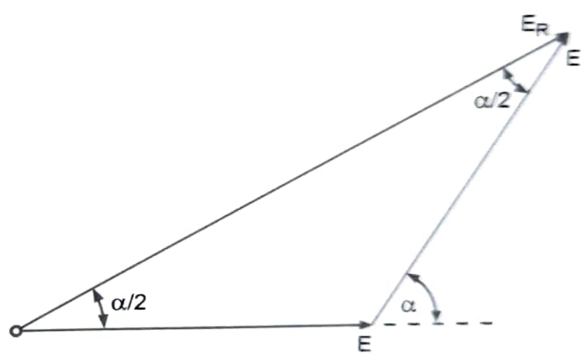


Fig. 13.9

where α is the phase angle between the induced emfs in the two sides of the coil and is given as (when coil span is reduced by one slot)

$$\alpha = \frac{180°}{n} \quad \text{where } n \text{ is the number of slots per pole}$$

It is always less than unity.

The ratio of the phasor sum of the emfs induced in all the coils distributed in a number of slots under one pole to the arithmetic sum of the emfs induced (or to the resultant of emfs induced in all coils concentrated in one slot under one pole) is known as breadth factor (K_b) or distribution factor (K_d)

or distribution factor,

$$K_d = \frac{\text{EMF induced in distributed winding}}{\text{EMF induced if the winding would have been concentrated}}$$

$$= \frac{\sin\frac{m\beta}{2}}{m \sin\frac{\beta}{2}} \qquad ...(13.4)$$

where m is number of slots per pole per phase and β is angular displacement between the slots and is given as

$$\beta = \frac{180°}{\text{Number of slots per pole, } n}$$

The distribution (or breadth) factor is always less than unity.

Example 13.2. An alternator has 9 slots per pole. The coil span is 8 slots. Find the pitch factor for fundamental frequency.
[Rajasthan Technical Univ. Electrical Machines-II, 2011]

Solution: Number of slots per pole, $n = 9$

$$\text{Angular displacement between the slots, } \beta = \frac{180°}{n} = \frac{180°}{9} = 20° \text{ (electrical)}$$

$$\text{Coil span} = \frac{180° \times \text{coil span in terms of slots}}{\text{Number of slots per pole}} = \frac{180 \times 8}{9} = 160°$$

$$\text{Chording angle, } \alpha = 180° - \text{coil span} = 180° - 160° = 20°$$

Pitch factor for the fundamental frequency

$$k_p = \text{Cos}\frac{\alpha}{2} = \text{Cos}\frac{20°}{2} = 0.9848 \textbf{ Ans.}$$

Example 13.3. Calculate the distribution factor for a 3-phase distributed single layer winding of the armature of an alternator. The alternator has 2 poles and a total of 18 slots.
[G.G.S.I.P. Univ. Electromechanical Energy Conversion-II, May-2011]

Solution: Number of slots per pole, $n = \frac{18}{2} = 9$

$$\text{Number of slots per pole per phase, } m = \frac{n}{\text{Number of phases}} = \frac{9}{3} = 3$$

$$\text{Angular displacement between the slots, } \beta = \frac{180°}{n} = \frac{180°}{9} = 20° \text{ (electrical)}$$

$$\text{Distribution factor, } k_d = \frac{\text{Sin}\frac{m\beta}{2}}{m \sin\frac{\beta}{2}} = \frac{\text{Sin}\frac{3 \times 20°}{2}}{3 \sin\frac{20°}{2}} = \frac{1}{3}\frac{\sin 30°}{\sin 10°} = 0.96 \textbf{ Ans.}$$

13.6 EMF EQUATION

Let Z_p = Number of conductors in series per phase
P = Number of poles
Φ = Useful flux per pole in webers
N = Rotational speed in rpm

and f = Frequency in hertz and is equal to $\frac{NP}{120}$

The flux cut by any conductor while passing from the centre of one inter polar gap to the centre of the next is Φ webers and since during the movement, the emf wave completes half cycle *i.e.* the time taken is $\frac{1}{2f}$ seconds, therefore, the average rate of cutting the flux,

$$\frac{d\phi}{dt} = \frac{\Phi}{1/2f} = 2f\Phi \text{ Wb/s}$$

Hence average emf induced in each conductor = $2f\Phi$ volts

Average emf per phase, E_{av}/phase = Number of conductors in series/phase arranged in one slot/pole × average emf induced per conductor

$$= Z_p \times 2f\Phi = 2\text{T} \times 2f\Phi = 4\,\Phi f \text{T volts} \qquad \because Z_p = 2\text{T (turns)}$$

For distributed winding the average value of emf per phase will be K_d times the above value

$$i.e.\ E_{av} / \text{phase} = 4 K_d\ \Phi f T \text{ volts}$$

For short-pitched winding the true average value of emf per phase will be K_p times the above value

$$i.e.\ E_{av}/\text{phase} = 4 K_d K_p\ \Phi f T \text{ volts}$$

$$\text{and } E_{rms}/\text{phase} = \text{Form factor, } K_f \times E_{av}/\text{phase} = 4 K_f K_d K_p\ \Phi f T \text{ volts}$$

For sinusoidal wave of emf, $K_f = 1.11$

$$E_{rms} / \text{phase} = 4.44 K_d K_p\ \Phi f T \text{ volts} \quad ...(13.5)$$

For full-pitched and concentrated windings, $K_p = 1$ and $K_d = 1$

If the alternator is star-connected, as usually,

$$\text{Line voltage, } E_L = \sqrt{3}\ E_{rms}/\text{phase} = \sqrt{3} \times 4.44 K_d K_p\ \Phi f T \text{ volts} \quad ...(13.6)$$

For full-pitched and concentrated windings, $K_p = 1$ and $K_d = 1$

Example 13.4. A 4-pole alternator has an armature with 25 slots and 8 conductors per slot and rotates at 1,500 rpm and flux per pole is 0.05 Wb. Calculate the emf generated if winding factor is 0.96 and all conductors are in series.

[Anna Univ. Electrical Machines-II, November/December-2012]

Solution: Flux per pole, $\Phi = 0.05$ Wb

$$\text{Frequency, } f = \frac{PN}{120} = \frac{4 \times 1,500}{120} = 50 \text{ Hz}$$

Number of conductors connected in series,

$$Z_p = \text{Number of slots} \times \text{number of conductors per slot} = 25 \times 8 = 200$$

$$\text{Number of turns, T} = \frac{Z_p}{2} = \frac{200}{2} = 100$$

$$\text{Winding factor, } K_w = K_d K_p = 0.96$$

$$\text{Generated emf, } E = 4.44 \times K_w \times \Phi \times f \times T \text{ volts} = 4.44 \times 0.96 \times 0.05 \times 50 \times 100 = 1,065.6 \text{ V} \quad \textbf{Ans.}$$

Example 13.5. A 3-phase, 4-pole, star-connected synchronous generator runs at 1,500 rpm. The stator has 80 slots and 18 conductors per slot. The flux in the stator yoke is 0.006 Wb. Determine generated phase and line voltages, if the winding factor is 0.96. *[G.B. Technical Univ. Electromechanical Energy Conversion-II, 2012-13]*

Solution:

$$\text{Frequency, } f = \frac{PN}{120} = \frac{4 \times 1,500}{120} = 50 \text{ Hz}$$

$$\text{Winding factor, } k_w = k_d k_p = 0.96$$

$$\text{Flux per pole, } \Phi = 0.006 \text{ Wb}$$

$$\text{Number of turns, } T = \frac{\text{Number of slots} \times \text{number of conductors per slot}}{2 \times \text{number of phases}} = \frac{80 \times 18}{2 \times 3} = 240$$

$$\text{Generated phase voltage, } E_p = 4.44\, k_w \Phi f T = 4.44 \times 0.96 \times 0.006 \times 50 \times 240 = 306.9 \text{ V} \quad \textbf{Ans.}$$

$$\text{Generated line voltage, } E_L = \sqrt{3} \times E_p = \sqrt{3} \times 306.9 \text{ V} = 531.5 \text{ V} \quad \textbf{Ans.}$$

13.7 ROTATING MAGNETIC FIELDS

A rotating magnetic field is that field which is constant in magnitude but whose axis of direction rotates in space as field system of a dc machine. With a stationary field system the magnetic field is stationary in space, but if the field system is rotated at a certain speed, its magnetic field will rotate with it at the same speed.

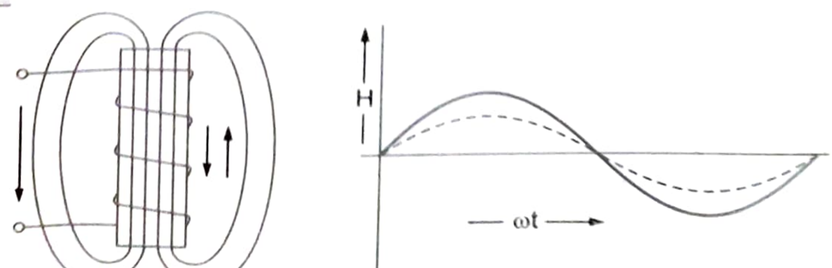


Fig. 13.10 *Alternating Magnetic Field*

The magnetic field produced by single-phase alternating current is an *alternating magnetic field*, the field acting along a fixed axis, varying in magnitude periodically and changing its direction alternately positive and negative (Refer to Fig. 13.10).

13.7.1. Ferraris Principle. The magnetic field produced by single-phase alternating current is an alternating magnetic field which, by Ferraris principle, can be resolved into two rotating fields of half its amplitude and rotating in opposite directions at synchronous speed.

Consider two rotating magnetic fields OA_1 and OA_2, each having magnitude of H units and travelling in opposite directions with angular velocity ω, as shown in Fig. 13.11.

Let both the fields start travelling from axis OX at time $t = 0$.

After time t seconds the angle through which fields OA_1 and OA_2 have rotated, $\theta = \omega t$ radians.

i.e. Field represented by vector OA_1 has moved in counter-clockwise direction through an angle $\theta = \omega t$ from axis OX and field represented by vector OA_2 has moved in clockwise direction through same angle θ, because both fields are travelling with same angular velocity ω.

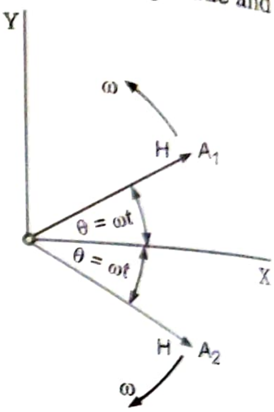


Fig. 13.11

Resolving the magnetic fields represented by vectors OA_1 and OA_2 along axis X and axis Y, we get

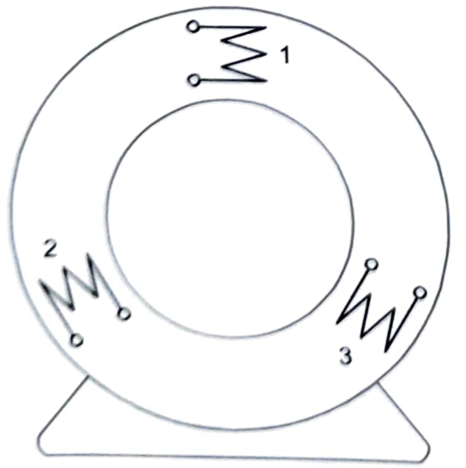
$$\text{X-component, } H_x = OA_1 \cos\theta + OA_2 \cos\theta = H\cos\theta + H\cos\theta = 2H\cos\theta = 2H\cos\omega t$$

$$\text{Y-component, } H_y = OA_1 \sin\theta - OA_2 \sin\theta = H\sin\theta - H\sin\theta = 0$$

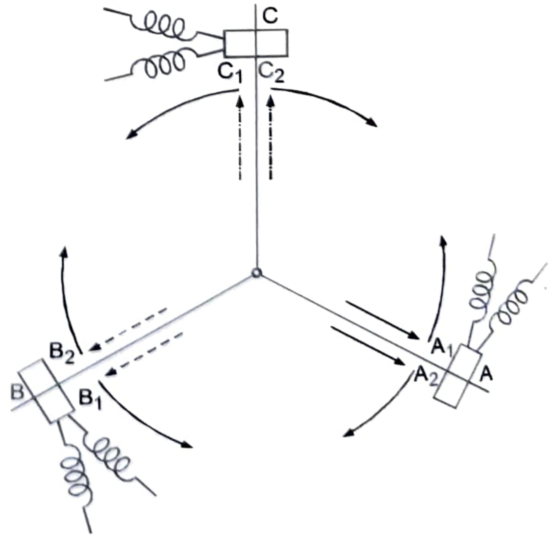
Hence resultant magnetic field is 2H cos ωt along X-axis. It is, therefore, obvious that two rotating magnetic fields, travelling in opposite directions with the same angular velocity, result in an alternating field of twice their amplitude. *Conversely an alternating field can be replaced exactly by two rotating fields of half its amplitude travelling in opposite directions at synchronous speed.*

13.8 PRODUCTION OF 3-PHASE ROTATING MAGNETIC FIELD

Consider three similar coils A, B and C displaced in space by 120°, as shown in Fig. 13.12, and connected to 3-phase ac supply. Let each of alternating fields due to currents in coils A, B and C be resolved into two components OA_1 and OA_2, OB_1 and OB_2 and OC_1 and OC_2 respectively travelling with angular velocity ω in the directions shown in Fig. 13.12, where $\omega = 2\pi f$, f being the supply frequency.



(a) Simple Stator of a Rotating Machine Featuring Three Spatially Positioned Coils at 120° Degrees



(b)

Fig. 13.12

Consider the instant when the current in coil A is maximum. At this instant both of the components OA_1 and OA_2 of the alternating field produced by the current in coil A are along the axis of the coil A *i.e.* along OA. The current in coil B is 120° behind the instant of its maximum value, therefore, each of its components OB_1 and OB_2 will have to rotate through 120° in order to reach the axis of the coil B *i.e.* along OB. Hence components OB_1 and OB_2 are along OC and OA respectively. The current in coil C is 240° being the instant of its maximum value, therefore, each of components OC_1 and OC_2 of the field produced by current in coil C will have to rotate through 240° in order to reach the axis of coil C *i.e.* along OC. Hence at this instant components OC_1 and OC_2 are along OB and OA respectively.

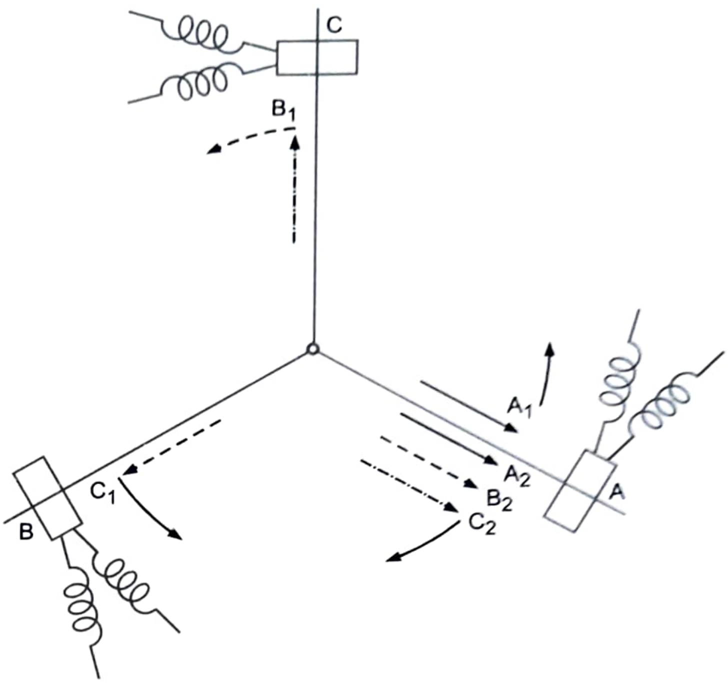


Fig. 13.13

From Fig. 13.13 it is clear that components OA_1, OB_1 and OC_1 are rotating in counter-clockwise direction with same angular velocity ω but are 120° apart, therefore, their resultant is always zero. Components OA_2, OB_2 and OC_2 are rotating in clockwise direction with same angular velocity ω and also points in same direction, therefore, resultant gives a pure rotating field rotating at synchronous speed.

The direction of rotation is the same as the direction of phase sequence *i.e.* first current in coil A attains its maximum value, then current in coil B attains its maximum value and then current in coil C attains its maximum value, as shown in Fig. 13.14. Hence to reverse the direction of rotation of the magnetic field, it is necessary to change the phase sequence which can be done by interchanging any two of the terminals.

For proving the establishment of rotating magnetic field by three-phase currents by considering the direction of flow of currents through three phase windings at several successive instants, let us again consider a simplified stator core with three equally spaced phase windings. The time diagrams for currents in phase windings A, B and C are shown in Fig. 13.14. The different instants are marked off at 60° intervals on the current waves in Fig. 13.14.

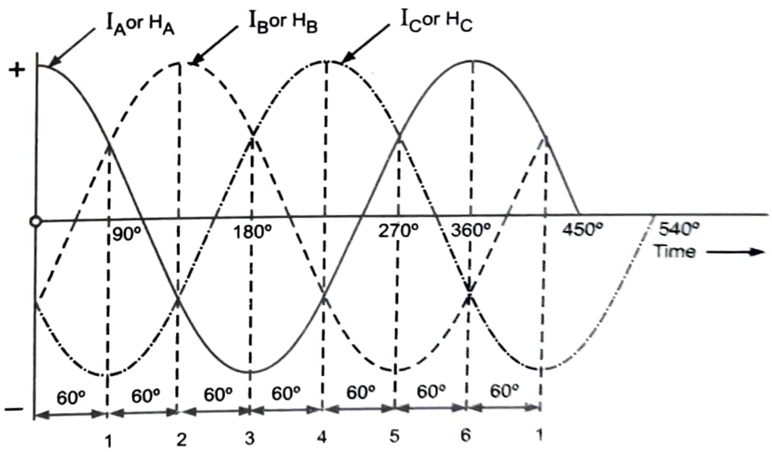


Fig. 13.14

Mathematical Proof. The above fact can also be proved mathematically as below:

The time diagrams for currents in coils A, B and C are shown in Fig. 13.14. Coils A, B and C establish alternating (pulsating) fields along their respective axis *i.e.* along axis OA, OB and OC respectively. Since phase difference between the currents flowing through coils A, B and C respectively is 120°, therefore, phase difference between the magnetic fields H_A, H_B and H_C produced is 120° (electrical).

Let each of the coil produce an alternating field of maximum strength H_{max} along its own axis then instantaneous values of magnetic fields produced by coils A, B and C with respect to time are given as below:

$$H_A = H_{max} \cos \omega t \text{ along axis OA}$$
$$H_B = H_{max} \cos (\omega t - 120°) \text{ along axis OB}$$
$$H_C = H_{max} \cos (\omega t - 240°) \text{ along axis OC}$$

The resultant magnetic field H_R at any instant is the combination of above fields, taking into account the directions as well as magnitude. Resolving these three magnetic fields horizontally and vertically we get

$$H_{Rh} = H_A + H_B \cos 120^\circ + H_C \cos 240^\circ$$

$$= H_{max} \cos \omega t - \frac{1}{2} H_{max} \cos (\omega t - 120^\circ) - \frac{1}{2} H_{max} \cos (\omega t - 240^\circ)$$

$$= H_{max} \cos \omega t - \frac{1}{2} H_{max} [\cos (\omega t - 120^\circ) + \cos (\omega t - 240^\circ)]$$

$$= H_{max} \cos \omega t - \frac{1}{2} H_{max} [2 \cos (\omega t - 180^\circ) \cos 60^\circ]$$

$$= H_{max} \cos \omega t + \frac{1}{2} H_{max} \cos \omega t = \frac{3}{2} H_{max} \cos \omega t$$

$$H_{Rv} = H_A \sin 0^\circ + H_B \sin (-120^\circ) + H_C \sin (-240^\circ)$$

$$= 0 - \frac{\sqrt{3}}{2} H_{max} \cos (\omega t - 120^\circ) + \frac{\sqrt{3}}{2} H_{max} \cos (\omega t - 240^\circ)$$

$$= \frac{\sqrt{3}}{2} H_{max} [\cos (\omega t - 240^\circ) - \cos (\omega t - 120^\circ)]$$

$$= \frac{\sqrt{3}}{2} H_{max} [2 \sin (\omega t - 180^\circ) \sin 60^\circ] = \frac{3}{2} H_{max} \sin \omega t$$

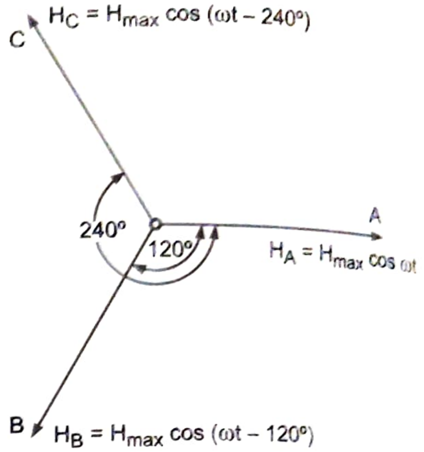


Fig. 13.15

The resultant field, H_R

$$= \sqrt{(H_{Rh})^2 + (H_{Rv})^2} = \sqrt{\left(\frac{3}{2} H_{max} \cos \omega t\right)^2 + \left(\frac{3}{2} H_{max} \sin \omega t\right)^2} = \frac{3}{2} H_{max}$$

Inclination of the resultant field is given by

$$\theta = \text{Tan}^{-1} \frac{H_{Rv}}{H_{Rh}} = \text{Tan}^{-1} \frac{\frac{3}{2} H_{max} \sin \omega t}{\frac{3}{2} H_{max} \cos \omega t} = \omega t$$

It shows that the resultant magnetic field due to three phases is of constant magnitude (3/2 times the maximum strength of magnetic field produced by each phase separately) and travels in space with a uniform angular velocity ω radians per second. *Hence resultant field is of constant magnitude and is rotating at synchronous speed.*

The above principle is not only applicable to synchronous machines but to all machines with polyphase stator windings.

13.9 SYNCHRONOUS MOTORS

A synchronous motor has the same relationship to an alternator as a dc motor has to a dc generator *i.e.* if an alternator is supplied ac power it is capable of rotating as a motor and doing mechanical work. If the mechanical power supplied to a rotating alternator is removed while the dc field remains energized, and an ac supply is then connected across the armature terminals, torque will be developed and the alternator will continue to rotate at a speed determined by the ac supply frequency and number of poles on the synchronous machine. Changes in mechanical load within the machine's rating will not cause a change in speed.

In case of a dc motor the field and armature, both, are supplied from dc supply mains, since both require direct current. But in case of a synchronous motor the field structure is to be energized by direct current, as in case of an alternator, whereas the armature winding is connected to a 3-phase ac supply mains. Such a machine, therefore, requires two sources of supply, viz., an ac source to supply the power for driving the armature and a dc source to excite the field. DC excitation may be provided either from an exciting plant dc system or, if no direct current is available, from separate dc generators. Direct-connected exciters are fre-