Three-Phase Induction Motors

4.1 INTRODUCTION

Three-phase induction motor is the most popular type of a.c. motor. It is very commonly used for industrial drives since it is cheap, robust, efficient and reliable. It has good speed regulation and high starting torque. It requires little maintenance. It has a reasonable overload capacity.

4.2 CONSTRUCTION

A three-phase induction motor essentially consists of two parts : the *stator* and the *rotor*. The stator is the stationary part and the rotor is the rotating part. The stator is built up of high-grade alloy steel laminations to reduce eddy-current losses. The laminations are slotted on the inner periphery and are insulated from each other. These laminations are supported in a stator frame of cast iron or fabricated steel plate. The insulated stator conductors are placed in these slots. The stator conductors are connected to form a three-phase winding. The phase winding may be either star or delta-connected [Fig. 4.1(*a*)].

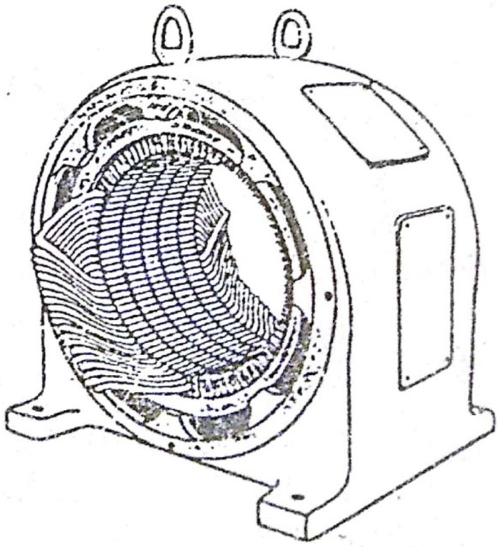


Fig. 4.1 (*a*) Induction motor stator with double-layer winding partly wound.

Scanned by CamScanner

The rotor is also built up of thin laminations of the same material as stator. The laminated cylindrical core is mounted directly on the shaft or a spider carried by the shaft. These laminations are slotted on their outer periphery to receive the rotor conductors. There are *two* types of induction motor rotors :

(*a*) Squirrel-cage rotor or simply cage rotor.

(*b*) Phase wound or wound rotor. Motors using this type of rotor are also called slip-ring motors.

4.2.1 Cage Rotor

It consists of a cylindrical laminated core with slots nearly parallel to the shaft axis, or *skewed*. Each slot contains an uninsulated bar conductor of aluminium or copper. At each end of the rotor, the rotor bar conductors are short-circuited by heavy end rings of the same material. The conductors and the end rings form a cage of the type which was once commonly used for keeping squirrels ; hence its name. A cage rotor is shown in Fig. 4.1(*b*).

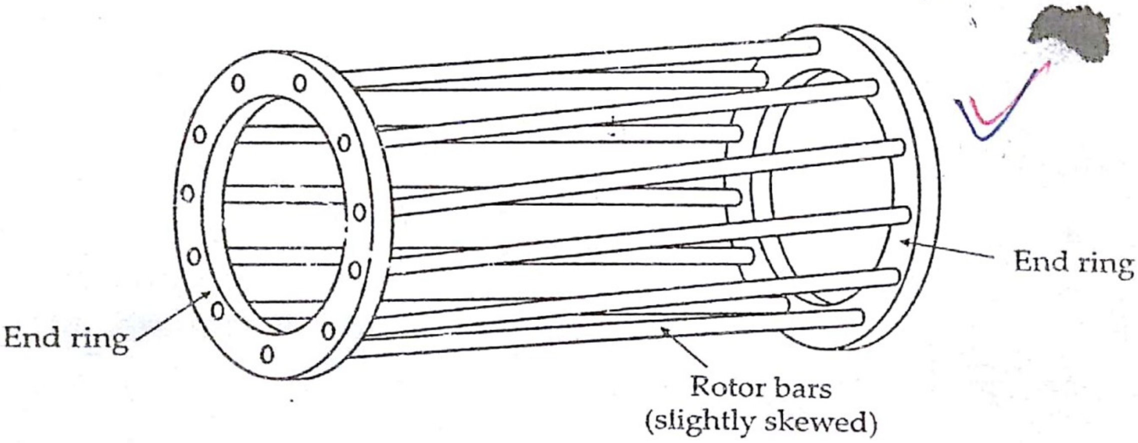


Fig. 4.1 (*b*) Cage rotor.

The skewing of cage rotor conductors offers the following advantages :

1. More uniform torque is produced and the noise is reduced during operation.
2. The *locking* tendency of the rotor is reduced. During locking, the rotor and stator teeth attract each other due to magnetic action.

4.2.2 Wound Rotor or Slip Ring Rotor

The wound rotor consists of a slotted armature. Insulated conductors are put in the slots and connected to form a three-phase double layer distributed winding similar to the stator winding. The rotor windings are connected in star.

The open ends of the star circuit are brought outside the rotor and connected to three insulated slip rings. The slip rings are mounted on the shaft with brushes resting on them. The brushes are connected to three variable resistors connected in star. The purpose of slip rings and brushes is to provide a means for connecting external resistors in the rotor circuit.

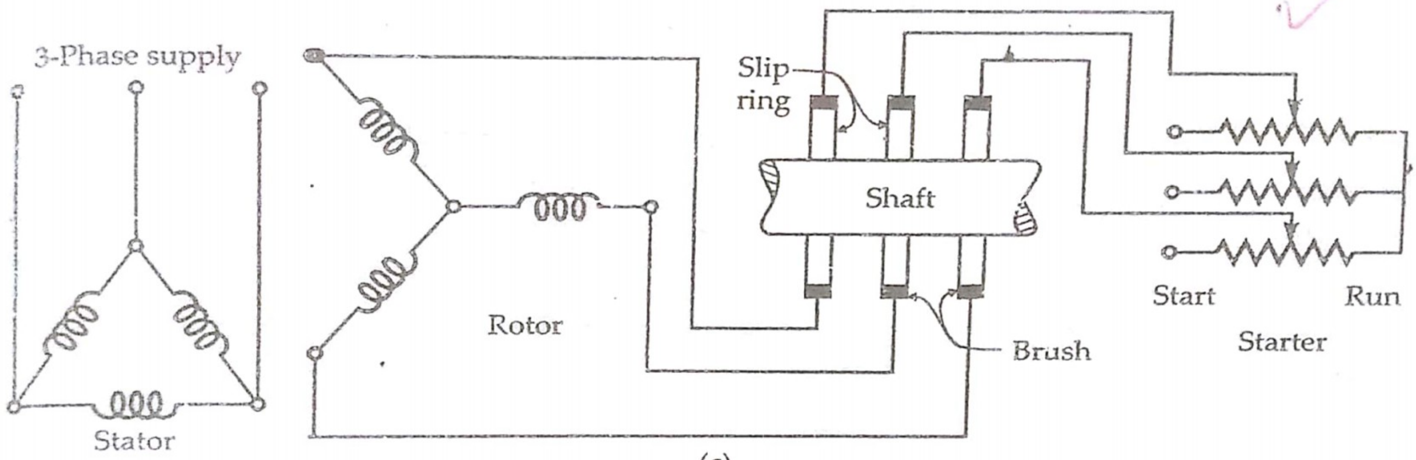
Scanned by CamScanner

The resistors enable the variation of each rotor phase resistance to serve two purposes :

(*a*) to increase the starting torque and decrease the starting current from the supply.

(*b*) to control the speed of the motor.

A slip ring induction motor is shown in Fig. 4.2(*a*) and (*b*).



(*a*)

Scanned by CamScanner

4.5 PRINCIPLE OF OPERATION OF A THREE-PHASE INDUCTION MOTOR

For the sake of simplicity, let us consider one conductor on the stationary rotor as shown in Fig. 4.6(*a*). Let this conductor be subject to the rotating magnetic field produced when a three-phase supply is connected to the three-phase winding of the stator. Let the rotation of the magnetic field be clockwise. A magnetic field moving clockwise has the same effect as a conductor moving anticlockwise in a stationary field. By Faraday's law of electromagnetic induction, a voltage will be induced in the conductor. Since the rotor circuit is complete, either through the end rings or an external resistance the induced voltage causes a current to flow in the rotor conductor. By right-hand rule we can determine the direction of induced current in the conductor. Since the magnetic field is rotating clockwise, and the conductor is stationary we can *assume* that the conductor is in motion in the anticlockwise direction with respect to the magnetic field. By right hand rule the direction of the induced current is outwards (shown by dot) as given in Fig. 4.6(*b*). The current in the rotor conductor produces its own magnetic field [Fig. 4.6(*c*)].

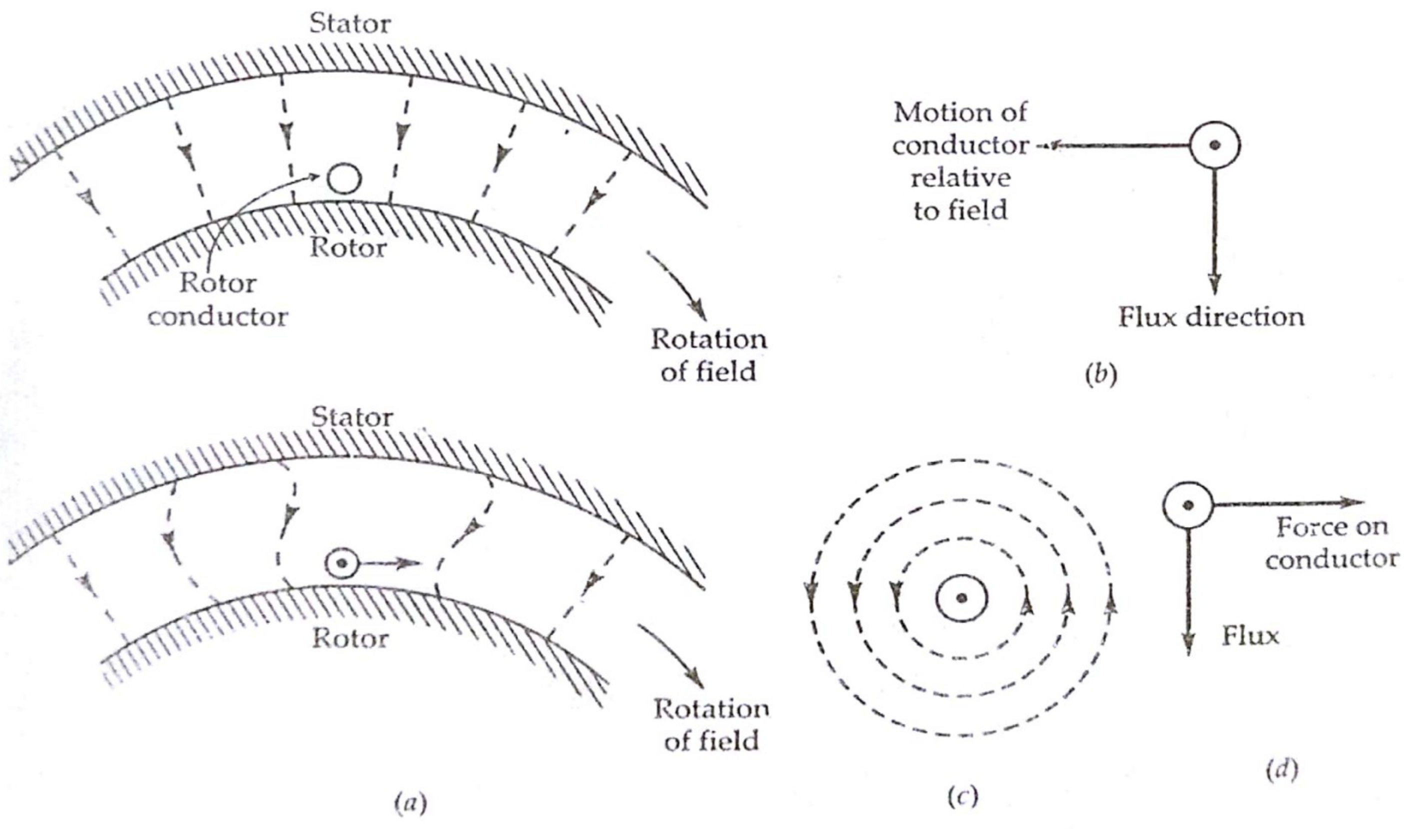


Fig. 4.6 Production of torque

We know that when a conductor carrying current is put in a magnetic field a force is produced on it. Thus, a force is produced on the rotor conductor. The direction of this force can be found by left-hand rule [Fig. 4.6(*d*)]. It is seen that the force acting on the conductor is in the same direction as the direction of the

Scanned by CamScanner

4.4 PRODUCTION OF ROTATING FIELD

When 3-phase windings displaced in space by 120° are supplied by 3-phase currents displaced in time by 120°, a magnetic flux is produced which rotates in space.

4.4.1 Analytical Method

Consider three identical coils located on axes physically at 120° in space as shown in Fig. 4.3(*a*). Let each coil be supplied from one phase of a balanced 3-phase supply. Each coil will produce an alternating flux along its own axis. Let the instantaneous fluxes be given by

$$\Phi_1 = \Phi_m \sin \omega t \tag{4.4.1}$$

$$\Phi_2 = \Phi_m \sin(\omega t - 120°) \tag{4.4.2}$$

$$\Phi_3 = \Phi_m \sin(\omega t + 120°) \tag{4.4.3}$$

The resultant flux produced by this system may be determined by resolving the components with respect to the physical axes as shown in Fig. 4.3(*b*).

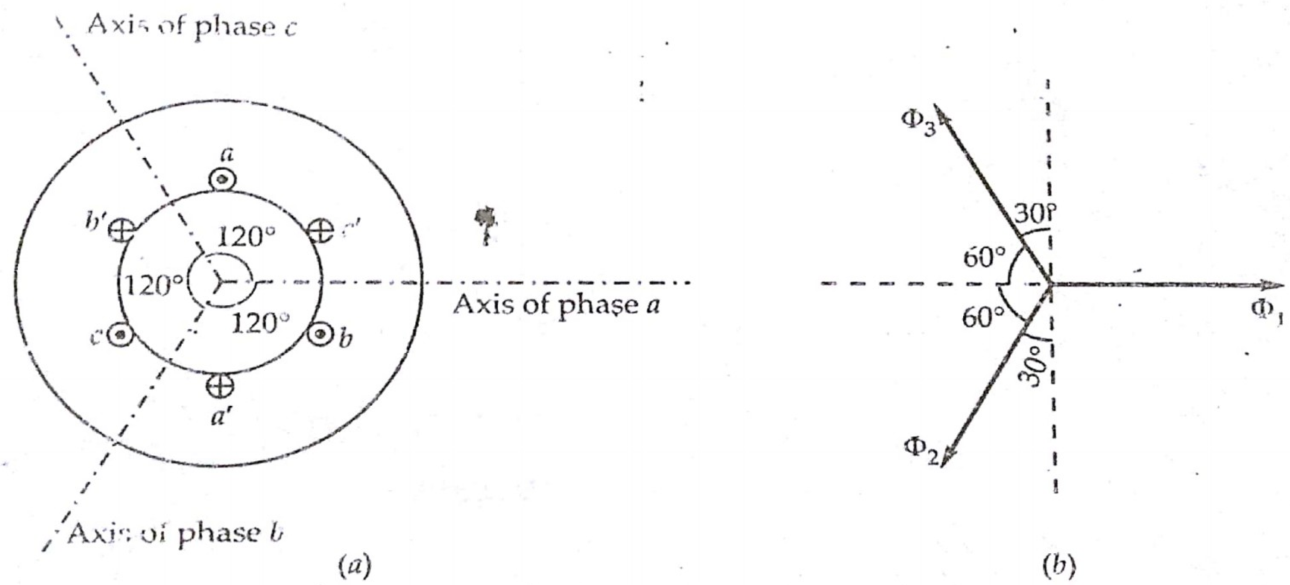


Fig. 4.3

The resultant horizontal component of flux is given by

$$\Phi_h = \Phi_1 - \Phi_2 \cos 60° - \Phi_3 \cos 60° = \Phi_1 - (\Phi_2 + \Phi_3)\cos 60°$$

$$= \Phi_1 - \tfrac{1}{2}(\Phi_2 + \Phi_3) = \Phi_m \sin \omega t - \tfrac{1}{2}[\Phi_m \sin(\omega t - 120°) + \Phi_m \sin(\omega t + 120°)]$$

$$= \Phi_m \sin \omega t - \frac{\Phi_m}{2}(\sin \omega t \cos 120° - \cos \omega t \sin 120° + \sin \omega t \cos 120° + \cos \omega t \sin 120°)$$

$$= \Phi_m \sin \omega t - \frac{\Phi_m}{2} \times (2 \sin \omega t)(-\tfrac{1}{2})$$

$$\text{or } \Phi_h = \frac{3}{2}\Phi_m \sin \omega t \tag{4.4.4}$$

Scanned by CamScanner

The resultant vertical component of flux is given by

$$\Phi_v = 0 - \Phi_2 \cos 30° + \Phi_3 \cos 30°$$

$$= \cos 30° [-\Phi_m \sin(\omega t - 120°) + \Phi_m \sin(\omega t + 120°)]$$

$$= \frac{\sqrt{3}}{2}\Phi_m [-(\sin \omega t \cos 120° - \cos \omega t \sin 120°)$$

$$+ (\sin \omega t \cos 120° + \cos \omega t \sin 120°)]$$

$$= \frac{\sqrt{3}}{2}\Phi_m (2 \cos \omega t \sin 120°) = \frac{\sqrt{3}}{2}\Phi_m \times 2 \cos \omega t \times \frac{\sqrt{3}}{2}$$

or $$\Phi_v = \frac{3}{2}\Phi_m \cos \omega t \qquad (4.4.5)$$

The components Φ_h and Φ_v are shown in Fig. 4.3(c).

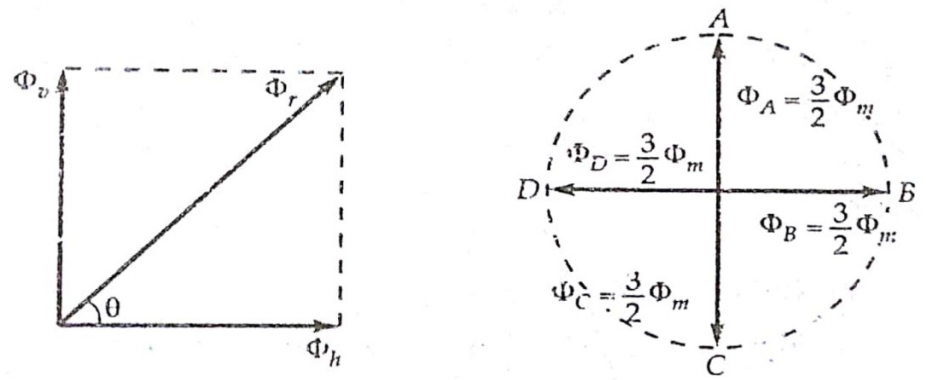


Fig. 4.3 (c) (d)

Resultant flux

$$\Phi_r = \sqrt{\Phi_h^2 + \Phi_v^2} = \sqrt{\left(\frac{3}{2}\Phi_m \sin \omega t\right)^2 + \left(\frac{3}{2}\Phi_m \cos \omega t\right)^2}$$

$$= \frac{3}{2}\Phi_m \sqrt{(\sin^2 \omega t + \cos^2 \omega t)} = \frac{3}{2}\Phi_m \qquad (4.4.6)$$

Also,

$$\tan\theta = \frac{\Phi_v}{\Phi_h} = \left(\frac{3}{2}\Phi_m \cos \omega t\right) \div \left(\frac{3}{2}\Phi_m \sin \omega t\right) = \cot \omega t = \tan\left(\frac{\pi}{2} - \omega t\right)$$

$$\therefore \qquad \theta = \frac{\pi}{2} - \omega t \qquad (4.4.7)$$

Equation (4.4.6) shows that the resultant flux Φ_r is independent of time. It is a constant flux of magnitude equal to $\frac{3}{2}$ times the maximum flux per phase.

Equation (4.4.7) shows that angle θ is dependent on time.

From Eq. (4.4.7), $\theta = 90° - \omega t$,

(a) At $\omega t = 0°$, $\theta = 90°$ corresponding to position A in Fig. 4.3(d).

(b) At $\omega t = 90°$, $\theta = 0°$ corresponding to position B.

(c) At $\omega t = 180°$, $\theta = -90°$ corresponding to position C.

(d) At $\omega t = 270°$, $\theta = -180°$ corresponding to position D.

Scanned by CamScanner

Speed and Slip:

1. An induction motor cannot run at synchronous speed
2. If rotor starts rotating at synchronous speed, there would be no cutting of flux by the rotor conductors and there would be no generated voltage, no current & no torque
3. Rotor speed is therefore slightly less than synchronous speed.
4. The difference b/w synchronous speed and actual rotor speed is known as slip speed.

$$\text{Slip speed} = N_S - N_R$$

$$\boxed{\text{Slip, } s = \frac{N_S - N_R}{N_S}}$$

$N_S \rightarrow$ Synchronous Speed
$N_R \rightarrow$ Rotor Speed

Torque of an Induction motor:

Torque developed by the rotor of an induction motor is directly proportional to
1. Rotor current I_{2s}
2. Stator flux per pole ϕ
3. Power factor of rotor ckt $\cos\phi_2$

$$T \propto \phi \, I_{2s} \cos\phi_{2s}$$

$\because \quad E_{20} \propto \phi$

$\therefore \quad T = K E_{20} I_{2s} \cos\phi_{2s}$

$$T = K E_{20} \frac{E_{2s}}{Z_{2s}} \frac{R_2}{Z_{2s}}$$

$$T = \frac{K E_{20} \, s E_{20} \, R_2}{Z_{2s}^2}$$

$$T = \frac{K s R_2 E_{20}^2}{\sqrt{R_2^2 + X_{2s}^2}}$$

$$\boxed{T = \frac{K s R_2 E_{20}^2}{\sqrt{R_2^2 + s^2 X_{20}^2}}}$$

(a) At standstill conditions

→ E_{20} = Emf Induced per phase of the rotor at standstill

→ R_2 = Resistance per phase of the rotor

→ X_{20} = Reactance per phase of the rotor at standstill

(b) At slip s

→ E_{2s} = Induced emf per phase in rotor at slip s

$$E_{2s} = s E_{20}$$

→ X_{2s} = Rotor winding reactance per phase at slip s

$$X_{2s} = s X_{20}$$

→ $I_{2s} = \frac{E_{2s}}{Z_{2s}}$ (current per phase at slip s)

→ $\cos\phi_{2s} = \frac{R_2}{Z_{2s}}$

14.19. TORQUE-SLIP CURVE

The full load torque developed by an induction motor is given by the expression ;

$$T = \frac{3}{\omega_s} \frac{SE_{2s}^2 R_2}{[R_2^2 + (SX_{2s})^2]}$$

To draw the torque-slip or torque-speed curve the following points are considered :

(*i*) At synchronous speed (N_s) ; slip, $S = 0$ and torque $T = 0$.

(*ii*) When rotor speed is very near to synchronous speed *i.e.* when the slip is very low the value of the term $(SX_{2s})^2$ is very small in comparison to R_2^2 [*i.e.* $(SX_{2s})^2 << R_2^2$)] and is neglected.

Therefore, torque is given by the expression ;

$$T = \frac{3}{\omega_s} \frac{SE_{2s}^2 R_2}{R_2^2} = KS$$

or $\qquad T \propto S$

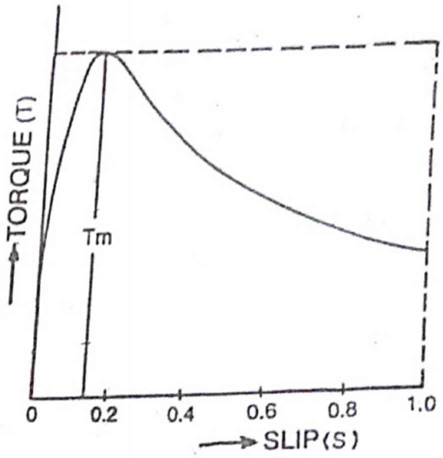


Fig. 14.17

Thus, at low values of slip, torque is approximately proportional to slip S and the torque-slip curve is a straight line, as shown in fig. 14.17.

(*iii*) As the slip increases torque increases and attains its maximum value when $S = R_2/X_{2s}$. *This maximum value of torque is also known as* **break down** *or* **pul out torque.**

(*iv*) With further increase in slip due to increase in load beyond the point of maximum torque *i.e.* when slip is high, the value of term $(SX_{2s})^2$ is very large in comparison to R_2^2 [*i.e.* $(SX_{2s})^2 >> R_2^2$]. Therefore, R_2^2 is neglected as compared to $(SX_{2s})^2$ and the torque is given by the expression

$$T = \frac{3}{\omega_s} \frac{SE_{2s}^2 R_2}{S^2 X_{2s}^2} = K' \frac{1}{S} \quad \textbf{or} \quad T \propto \frac{1}{S}$$

Thus, at higher values of slip (*i.e.* the slip beyond that corresponding to maximum torque), torque is approximately inversely proportional to slip S and the torque-slip curve is a rectangular hyperbola, as shown in fig. 14.17.

Thus, with the increase of slip beyond the point of maximum torque, due to increase in load, torque decreases. The result is that the motor could not pick-up the load and slows down and eventualiy stops.

Scanned by CamScanner