## THREE-PHASE INDUCTION MOTORS UNIT-3

The induction machine finds wide application as a motor in industries. Infact more than 85% of industrial motors are induction motors. Induction motors are singly fed motors, i.e., ac supply given to the stator only. (whereas Synchronous motors require ac supply for the stator and dc supply to the rotor). The current in the rotor, in the case of Induction motors, is by induction from the stator.

### Construction of Induction motors

The stator of an induction motor is similar to that of a synchronous machine and is wound for three phases. Modern practice is to use double-layer winding. There are two types of rotors: i) Squirrel cage rotor and ii) slip-ring rotor (wound rotor).

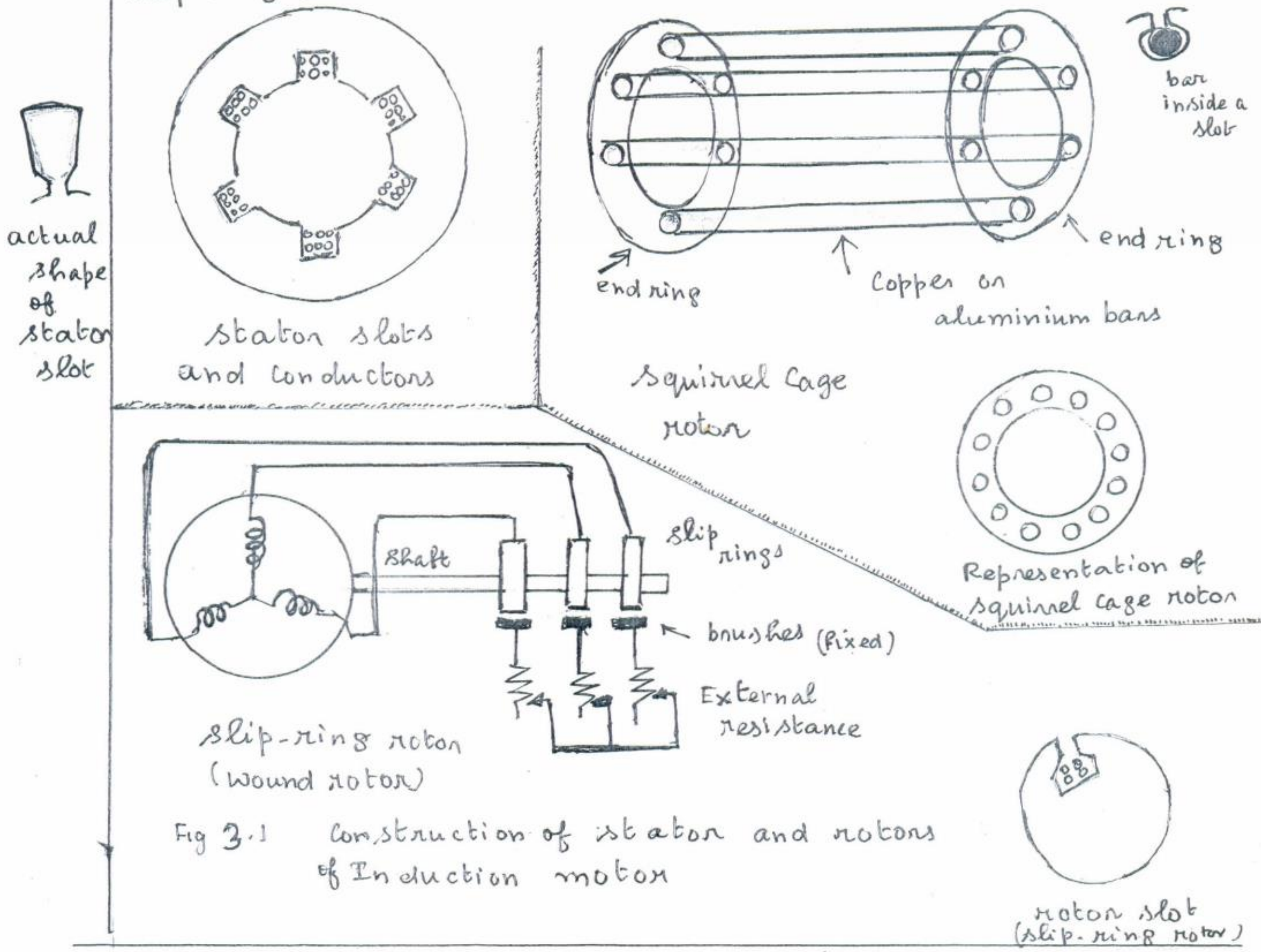



Fig 3.1 Construction of stator and rotors of Induction motor

The rotor core is of laminated construction with slots suitably punched for accommodating the rotor bars (squirrel cage rotor) or rotor winding (slip-ring rotor).

**Wound-rotor**

The winding of a wound rotor is polyphase with coils placed in slots of the rotor core. It is similar to that of the stator except that the number of slots is different. The three-phase rotor is wound for the same number of poles as the stator, and the winding is connected in star. Three leads are brought out through slip rings mounted on the shaft. External connections are taken through fixed carbon brushes making contact with moving slip rings. External resistance can be included in the rotor circuit for reducing the starting current and increasing the starting torque.

**Squirrel-cage rotor**

The squirrel-cage rotor has solid bars of conducting material (copper or aluminium) placed in rotor slots and shorted through end rings on both sides. There are no external terminals for the squirrel cage rotor. The squirrel cage induction motor has low starting torque. The starting torque of a squirrel-cage motor can be improved by employing either a double-cage rotor or a deep-bar rotor.

The slots in the induction machine are semi-closed so as to increase the permeance of the airgap. This reduces the magnetising current needed to set up the rotating magnetic field.

**Comparison**

The squirrel cage rotor is not made for any specific number of poles. The rotor construction is simple, cheap, robust and maintenance free compared to wound rotor. The wound rotor is used for high torque applications such as lifts, cranes and elevators. The squirrel cage rotor is used for lathes, fans, water pumps, grinders etc.
The speed of a wound rotor motor can be controlled by rotor resistance. (but not squirrel cage motor)

## Principle of operation of 3-phase Induction Motor

When three-phase supply is given to the three-phase stator winding, a rotating field of constant magnitude ($= 1.5\, I_m T_{ph}$) is produced. The speed of the rotating magnetic field $= N_s$ rpm ($120 f/p$).

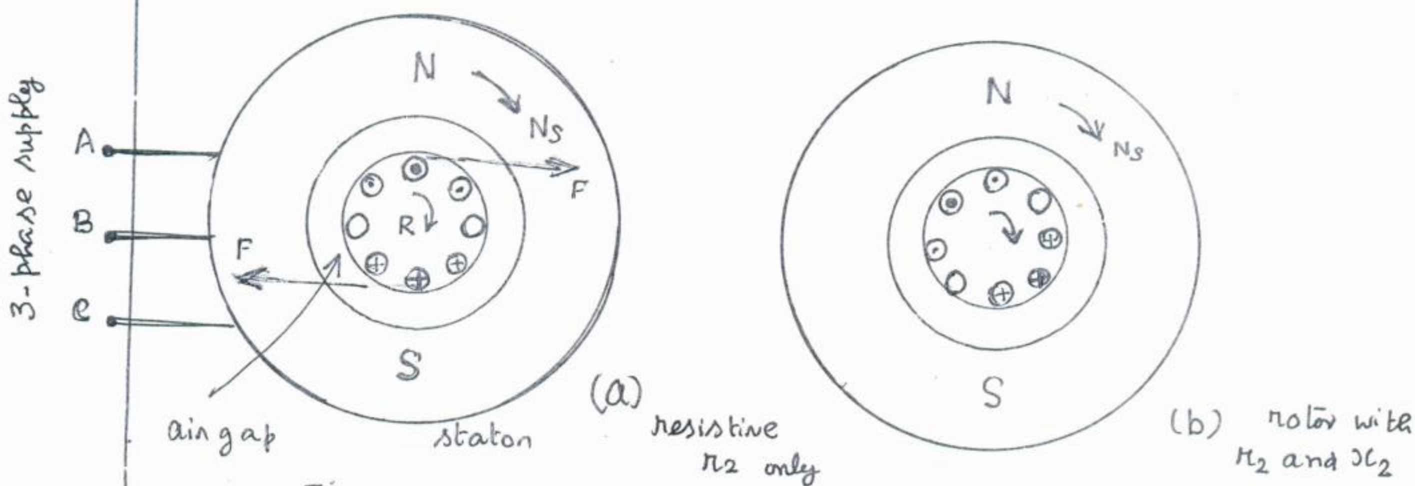



Fig 3.2 Explaining the rotation of the rotor

The rotating magnetic field induces EMF in the rotor bars. This EMF causes an induced current. This induced current interact with the rotating field and a torque is produced on the rotor.

RMF: rotating Magnetic Field

See Fig above: A two-pole motor is considered. The stator rotating field produces flux $\Phi_m$. The axis of the flux at one instant (North at the top and South at the bottom) rotating clock wise is shown.

The polarity of the induced current in the rotor can be found by Right Hand rule. (Assume the rotor to be resistive). Note larger dots and crosses. The consequent mechanical force produced on the rotor bars (LEft Hand rule) rotates the rotor in the same direction as the RMF. The torques on all the bars are not the same, however all the torques are in the same direction.

The rotor rotates at a speed $N < N_s$. So it is called asynchronous motor.

If $N = N_s$, the rotor EMF, current and torque will become zero. So the rotor can not run at synchronous speed.

At starting $(N = 0)$, the rotor frequency, $f_2 = f$.
At no-load $N$ is closed to $N_s$. When the motor is loaded $N$ reduces.

$$\text{slip} = \frac{N_s - N}{N_s}, \quad \%\ \text{slip} = \frac{N_s - N}{N_s} \times 100$$

or $N = N_s(1-s)$.

$N$ = Speed of the rotor
$N_s$ = Speed of RMF $(120f/P)$

$$N_s - N = \frac{120 f_2}{P}$$

$\therefore$ Divide both sides by $N_s$

$$\frac{N_s - N}{N_s} = \frac{120 f_2}{P N_s} = \frac{f_2}{f} = s$$

$$\therefore f_2 = sf$$

Example: A 4-pole, 3-phase, 50 Hz induction motor runs at 1440 rpm. calculate the slip and rotor frequency at this speed.

Solution

$$N_s = \frac{120 f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

$N = 1440$ rpm. $\therefore S = \dfrac{N_s - N}{N_s} = \dfrac{1500 - 1440}{1500}$

$$= 0.04 \quad (4\%)$$

rotor frequency, $f_2 = sf = 0.04 \times 50 = 2$ Hz

Note: In the running condition, the rotor frequency (frequency of the rotor EMF and current) is very small.

$E_{2r} = S E_2$

As the rotor starts running from (stand still) Zero speed, the rotor EMF also reduces proportional to $(N_s - N)$, i.e., proportional to slip.

Rotor EMF in the running condition with slip, S = S × rotor EMF at stand still

$X_{2r} = S X_2$

As the rotor starts running from zero speed, the rotor reactance also reduces proportional to slip.

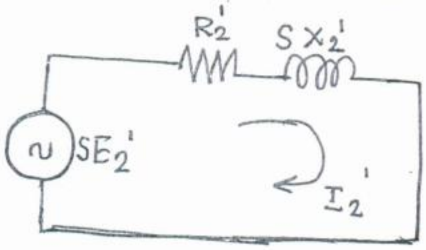
Rotor reactance in the running condition with slip, S = S × rotor reactance at stand still

$S = 1$ at starting

The rotor EMF, current and impedance can be represented in terms of stator (similar to secondary quantities are represented in terms of primary in a transformer).

The rotor equivalent circuit can be represented as follows:

Fig 3.3



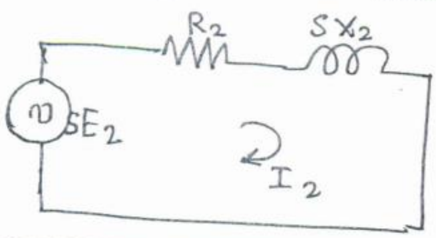

$$I_2' = \frac{S E_2'}{R_2' + j S X_2'} \quad ; \quad R_2' = K^2 R_2, \quad X_2' = K^2 X_2, \quad SE_2' = SE_1$$

The transformation ratio $= k = \dfrac{E_1}{E_2} = \dfrac{K_{w1} T_{ph1}}{K_{w2} T_{ph2}}$

OR

in terms of actual values

Fig 3.4




$$I_2 = \frac{S E_2}{R_2 + j S X_2}$$

Rotor power factor $= \cos\phi_2 = \dfrac{R_2}{\sqrt{R_2^2 + S^2 X_2^2}}$

Ex

A 3-phase, 4-pole, 50 Hz, slip ring Induction motor has a star connected rotor winding. At rated stator voltage the open circuit EMF between slip rings = 100 V. $R_2 = 0.3\ \Omega$ and $X_2 = 1.0\ \Omega$ per phase. Its full load speed is 1425 rpm. Calculate the rotor current and Power factor at i) starting ii) full load condition.

Soln

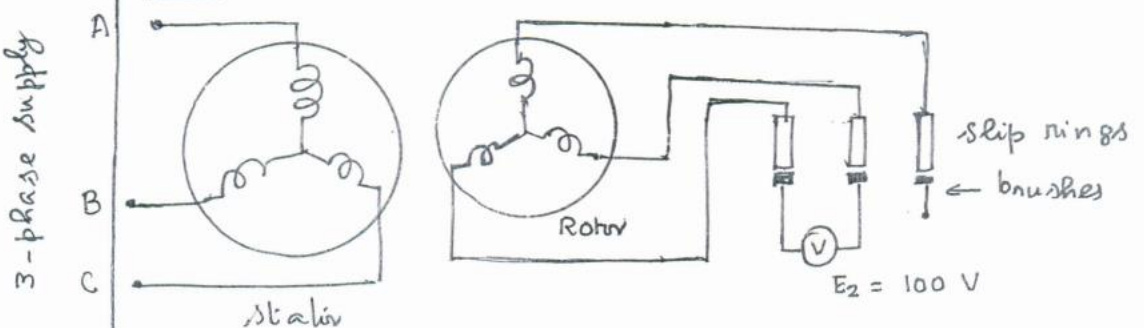



Fig. 3.5

Soln :

As long as rotor is open, there can not be a rotor current and the rotor can not run.

i) At starting

$E_{2\,line} = 100\ V,\quad E_{2\,ph} = \frac{100}{\sqrt{3}} = 57.73\ V$

rotor current per phase $= \frac{E_2}{Z_2} = \frac{57.73}{\sqrt{0.3^2 + 1.0^2}} = \frac{57.73}{1.044} = 55.3\ A$

Power factor $= \frac{R_2}{Z_2} = \frac{0.3}{1.044} = 0.287$

ii) At full load condition

$S = \frac{N_S - N}{N_S} = \frac{1500 - 1425}{1500} = 0.05$

$N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm

$E_{2r\,line} = S E_{2\,line} = 0.05 \times 100 = 5.0\ V$

$E_{2r}$ phase $= \frac{5.0}{\sqrt{3}} = 2.887\ V$

rotor current $= \frac{2.887}{\sqrt{0.3^2 + (0.05 \times 1)^2}} = \frac{2.887}{0.304} = 9.5\ A$

Power factor $= 0.3 / 0.304 = 0.987$

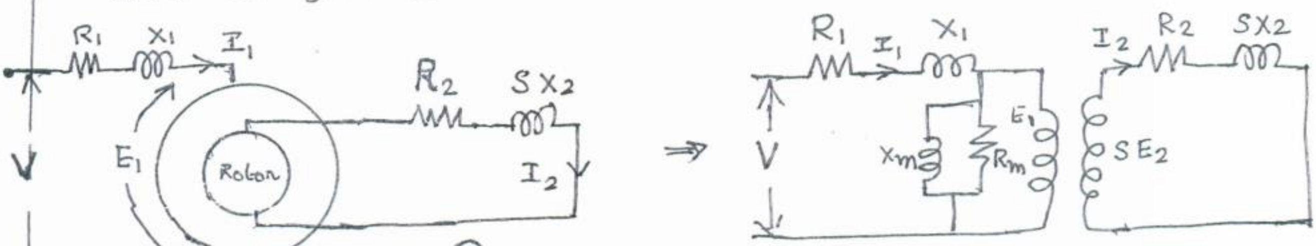
## Equivalent circuit of 3-phase Induction Motor

Note: i) The induction motor is a generalised transformer in which $f_2 = sf$, and the rotor EMF = $sE_2$ and rotor reactance = $sX_2$

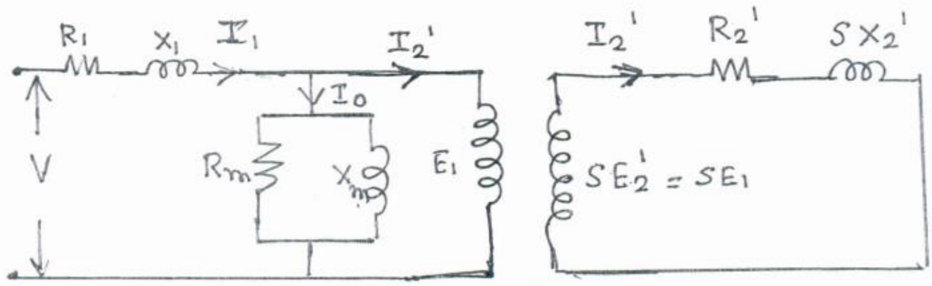
ii) Like in a transformer, the magnetizing component, $I_m$ of the stator current lags the induced EMF by $90°$.

iii) The core loss component is in phase with $E_1$.

The equivalent circuit can now be drawn on a per phase basis as follows:

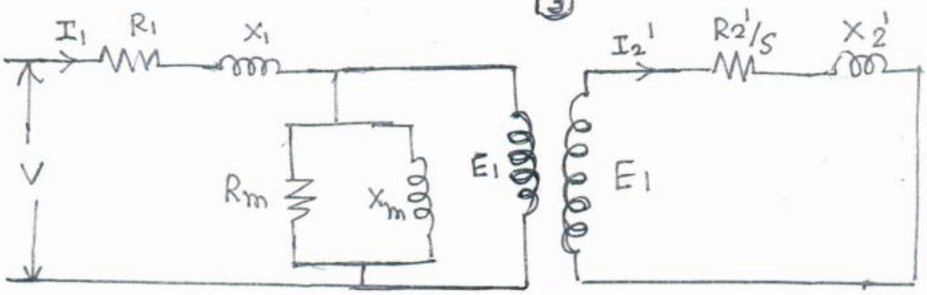



① ② K : 1




Transforming the rotor quantities in stator terms 1:1

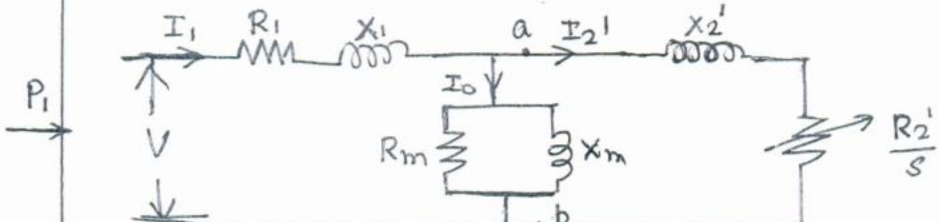
③




Dividing the rotor quantities by S 1:1

④

In ④ both stator and rotor have the same frequency




Removing the ideal windings and combining the stator and rotor

⑤

Fig. 3.6 Derivation Equivalent circuit

In Fig. 3.6 (5), the power transferred to the rotor is $= P_2$

$$I_2'^2 \frac{R_2'}{S} = I_2'^2 R_2' + I_2'^2 R_2' \frac{(1-S)}{S}$$

$=$ Rotor copper loss $+$ Mechanical power developed

Approximate Equivalent circuit

As an approximation the shunt branch can be shifted to the input terminals.

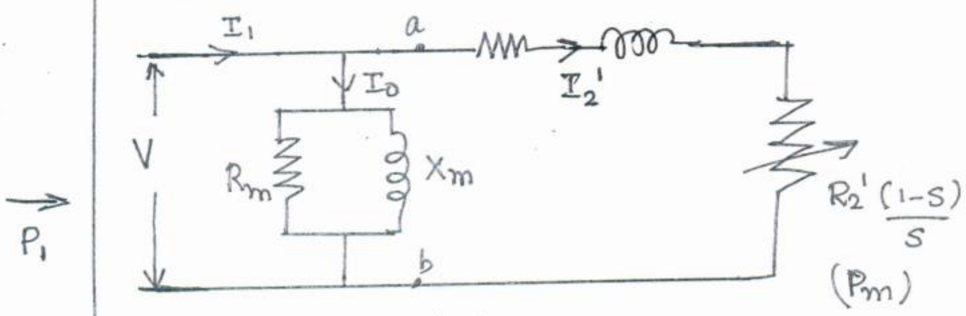



Fig. 3.7 Approximate Equivalent circuit.

$P_2 =$ Power crossing the terminals ab in Fig 3.6 (5) $= P_1 -$ stator copper loss

$=$ Power crossing the air gap

$=$ Power input to the rotor

$$P_2 = I_2'^2 \frac{R_2'}{S} = \frac{\text{Rotor copper loss}}{\text{slip}}$$

$$\therefore \; P_m = I_2'^2 R_2' \frac{(1-S)}{S} = P_2(1-S)$$

$$\therefore \; \boxed{P_2 : P_m : P_c :: 1 : (1-S) : S}$$

## TORQUE

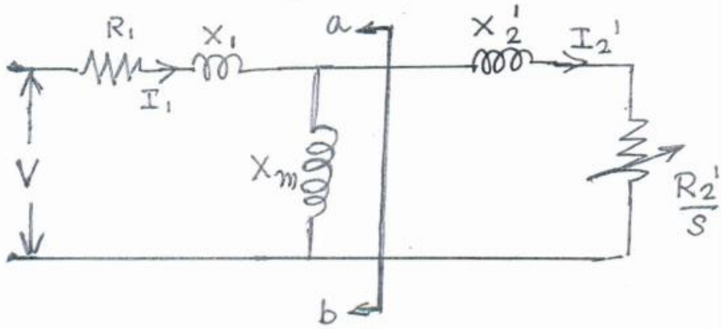
$$T = \frac{P_m}{2\pi N/60} = \frac{P_2(1-S)}{2\pi \frac{N_S(1-S)}{60}} = \frac{P_2}{(2\pi N_S/60)} = \frac{P_2}{\omega_s} \text{ Nm}$$

$\therefore$ $P_2$ itself is called Torque in synchronous watts

The net mechanical power output and torque are obtained by subtracting Friction, Windage and stray losses.

## Torque - slip characteristics

Consider the equivalent circuit shown in Fig.




Find the Thevenin equivalent to the left of ab in the circuit

$$Z_{TH} = (R_1 + jX_1) \parallel jX_m = R_{TH} + jX_{TH}$$

$$V_{TH} = V\left[\frac{jX_m}{R_1 + j(X_1 + X_m)}\right]$$

The circuit then reduces to the following Fig.

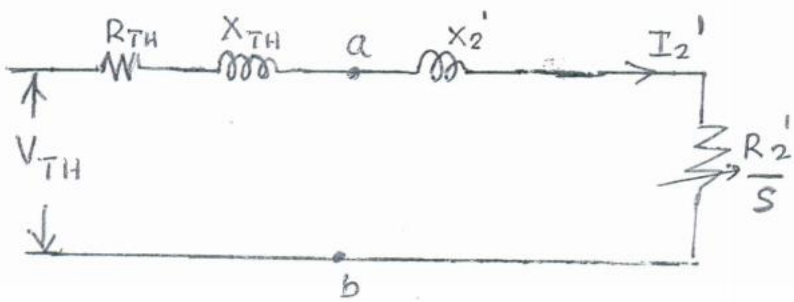



Fig. Thevenin Equivalent circuit of induction motor

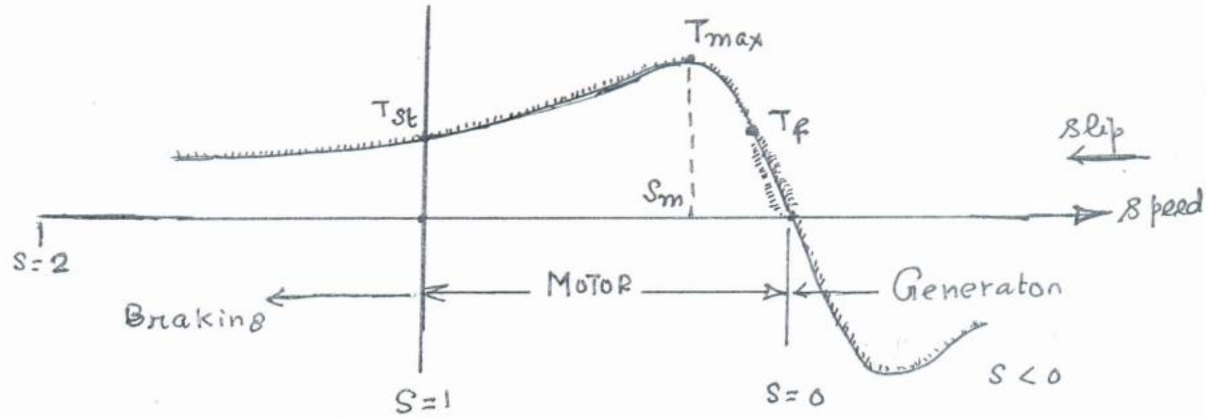
$$I_2'^2 = \frac{V_{TH}^2}{\left(R_{TH} + \frac{R_2'}{s}\right)^2 + \left(X_{TH} + X_2'\right)^2}$$

$$T = \frac{3}{W_s} I_2'^2 \frac{R_2'}{s}$$

$$= \frac{3}{W_s} \frac{V_{TH}^2 \left(R_2'/s\right)}{\left(R_{TH} + \frac{R_2'}{s}\right)^2 + \left(X_{TH} + X_2'\right)^2}$$

Note: $T \propto (\text{Voltage})^2$

The torque-slip characteristic is shown in Fig below:




Note:

MOTOR

At $S=0$, $T=0$

$S=S_m$, $T=T_{max}$ (Maximum torque)

$S=1$, $T=T_{st}$ (starting torque)

$S=S_f$, $T=T_f$ (Full load torque)

From $S=0$ to $S=S_f$ (Torque-slip characteristic is almost linear)

$S_f$ is usually between 2 to 7 %.

$S=0$ to $S=S_m$ : stable region

$S=S_m$ to $S=1$ : unstable region

Gen : $S<0$ : i.e, when the rotor is driven by a prime mover above synchronous speed, the induction machine acts as a generator feeding power to the supply.

Brake : $S>1$ : The motor runs in the opposite direction to the rotating magnetic field ($N$ is negative)

i.e $\dfrac{N_S - N}{N_S}$ becomes $\dfrac{N_S-(-N)}{N_S}$ which is $>1$.