Unit -I

Three Phase Induction Motors

Introduction

The three-phase induction motors are the most widely used electric motors in industry. They run at essentially constant speed from no-load to full-load. However, the speed is frequency dependent and consequently these motors are not easily adapted to speed control. We usually prefer d.c. motors when large speed variations are required. Nevertheless, the 3-phase induction motors aresimple, rugged, low-priced, easy to maintain and can be manufactured with characteristics to suit most industrial requirements. In this chapter, we shall focus our attention on the general principles of 3-phase induction motors.

8.1 Three-Phase Induction Motor

Like any electric motor, a 3-phase induction motor has a stator and a rotor. The stator carries a 3-phase winding (called stator winding) while the rotor carries a short circuited winding (called rotor winding). Only the stator winding is fed from 3-phase supply. The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction and hence the name. The induction motor may be considered to be a transformer with a rotating secondary and it can, therefore, be described as a "transformertype"a.c. machine in which electrical energy is converted into mechanicalenergy.

Advantages

(i) It has simple and rugged construction.
(ii) It is relatively cheap.
(iii) It requires little maintenance.
(iv)It has high efficiency and reasonably good power factor.
(v) It has self-starting torque.

Disadvantages

(i) It is essentially a constant speed motor and its speed cannot be changedeasily.
(ii) Its starting torque is inferior to d.c. shunt motor.

Construction

A 3-phase induction motor has two main parts (i) stator and (ii) rotor. The rotor is separated from the stator by a small air-gap which ranges from 0.4 mm to 4 mm, depending on the power of the motor.

1. Stator

It consists of a steel frame which encloses a hollow, cylindrical core made up of thin laminations of silicon steel to reduce hysteresis and eddy current losses. A number of evenly spaced slots are provided on the inner periphery of the laminations. The insulated connected to form a balanced 3-phase star or delta connected circuit. The 3-phase stator winding is wound for a definite number of poles as per requirement of speed. Greater the number of poles, lesser is the speed of the motor and vice-versa. When 3-phase supply is given to the stator winding, a rotating magnetic field of constant magnitude is produced. This rotating field induces currents in the rotor by electromagnetic induction.

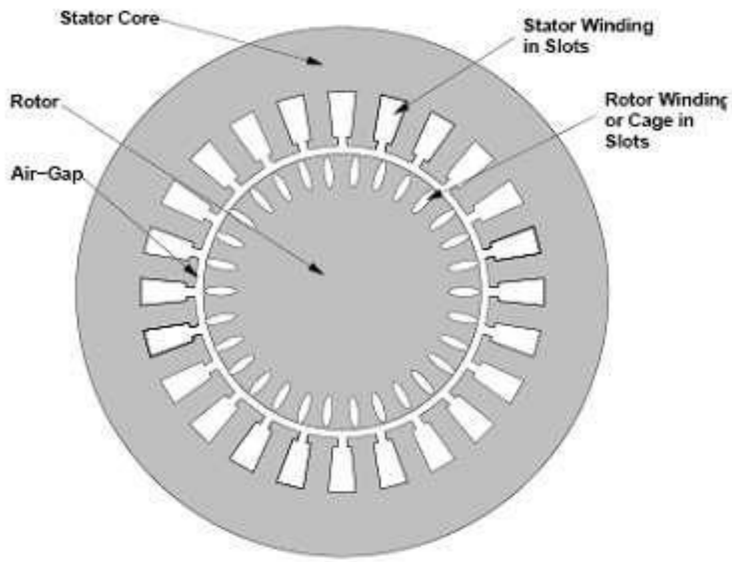
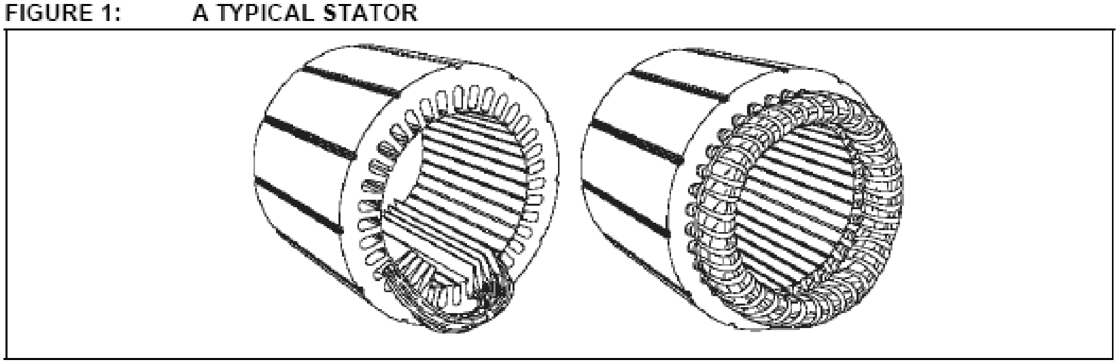


FIGURE 1: A TYPICAL STATOR

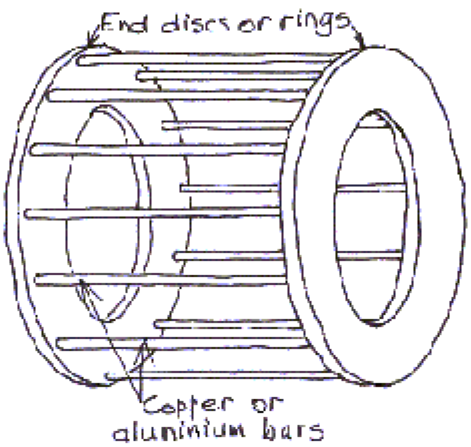


2. Rotor

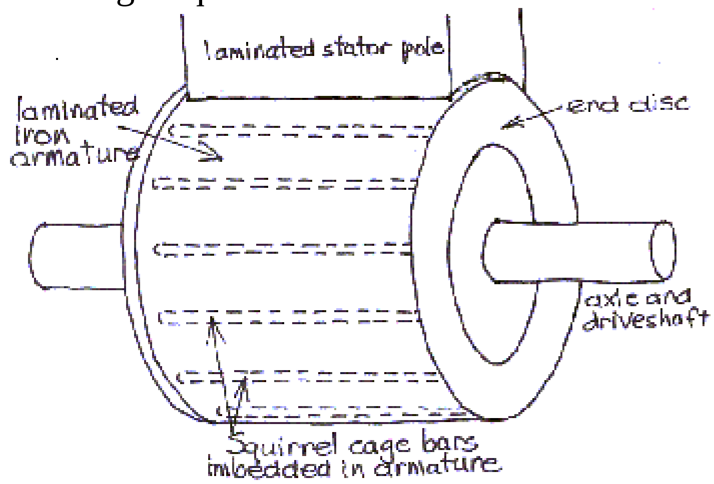
The rotor, mounted on a shaft, is a hollow laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

(i) Squirrel cage type
(ii) Wound type

Squirrel cage rotor. It consists of a laminated cylindrical core having parallel slots on its outer periphery. One copper or aluminum bar is placed in each slot. All these bars are joined at each end by metal rings called end rings. This forms a permanently short-circuited winding which is indestructible. The entire construction (bars and end rings) resembles a squirrel cage and hence the name. The rotor is not connected electrically to the supply but has current induced in it by transformer action from the stator. Those induction motors which employ squirrel cage rotor are called squirrel cage induction motors. Most of 3-phase induction motors use squirrel cage rotor as it has a remarkably simple and robust construction enabling it to operate in the most adverse circumstances. However, it suffers from the disadvantage of a low starting torque. It is because the rotor bars are permanently short-circuited and it is not possible to add any external resistance to the rotor circuit to have a large starting torque.

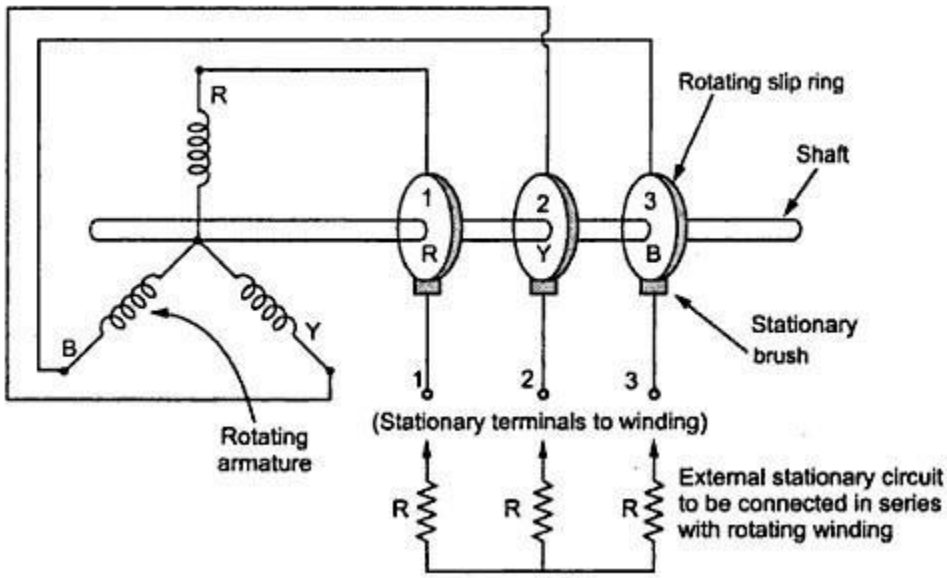


"Squirrel cage" rotor



Induction motor rotor

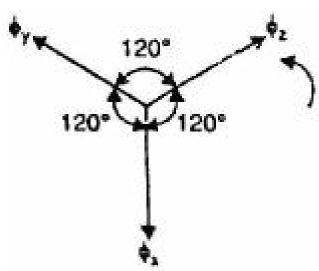
(ii) **Wound rotor**. It consists of a laminated cylindrical core and carries a 3- phase winding, similar to the one on the stator. The rotor winding is uniformly distributed in the slots and is usually star-connected. The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring. The three brushes are connected to a 3-phase star-connected rheostat as shown in fig. At starting, the external resistances are included in the rotor circuit to give a large starting torque. These resistances are gradually reduced to zero as the motor runs up to speed. The external resistances are used during starting period only. When the motor attains normal speed, the three brushes are short-circuited so that the wound rotor runs like a squirrel cage rotor.



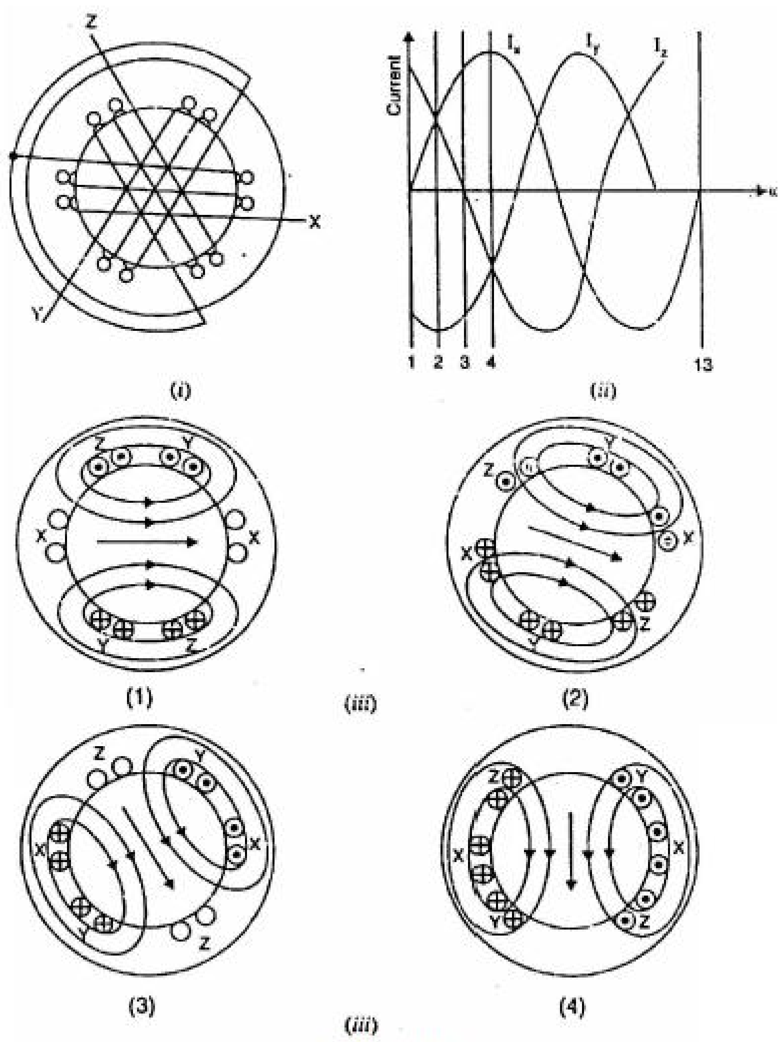
8.3 Rotating Magnetic Field Due to 3-Phase Currents

When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating Held. It can be shown that magnitude of this rotating field is constant and is equal to 1.5 ϕ_m where ϕ_m is the maximum flux due to any phase To see how rotating field is produced, consider a 2-pole, 3i-phase winding as shown in Fig. (8.6 (i)). The three phases X, Y and Z are energized from a 3-phase source and currents in these phases are indicated as I_x, I_y and produced by these currents are given by:

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin (\omega t - 120°)$$
$$\phi_z = \phi_m \sin (\omega t - 240°)$$

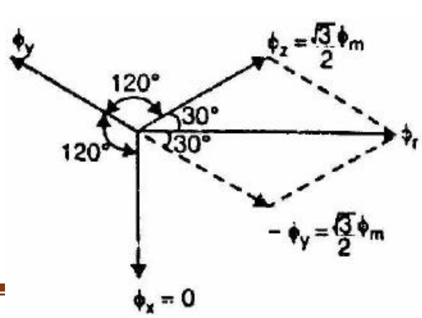


Here ϕ_m is the maximum flux due to any phase. Fig. (8.5) shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 ϕm.



At instant 1, the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:

At instant 1, $\omega t = 0°$. Therefore, the three fluxes are given by;



$$\phi_x = 0; \qquad \phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

The phasor sum of $-\phi_y$ and ϕ_z is the resultant flux ϕ_r [See Fig. (8.7)]. It is clear that:

$$\text{Resultant flux, } \phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 2 \times \frac{\sqrt{3}}{2}\phi_m \times \frac{\sqrt{3}}{2} = 1.5\ \phi_m$$

It follows from the above discussion that a 3-phase supply produces a rotating field of constant value (= 1.5 ϕ_m, where ϕ_m is the maximum flux due to any phase).

Speed of rotating magnetic field

The speed at which the rotating magnetic field revolves is called the synchronous speed (N_s). Referring to Fig. (8.6 (ii)), the time instant 4 represents the completion of one-quarter cycle of alternating current I_x from the time instant 1. During this one quarter cycle, the field has rotated through 90°. At a time instant represented by 13 or one complete cycle of current I_x from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, fur P poles, the rotating field makes one revolution in P/2 cycles of current.

$\therefore$ Cycles of current = P/2 × revolutions of field

or Cycles of current per second = P/2 × revolutions of field per second

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

f = P/2*Ns/60 = PNs/120

or Ns= 120*f / P

The speed of the rotating magnetic field is the same as the speed of the alternator that is supplying power to the motor if the two have the same number of poles. Hence the magnetic flux is said to rotate at synchronous speed.

Principle of Operation

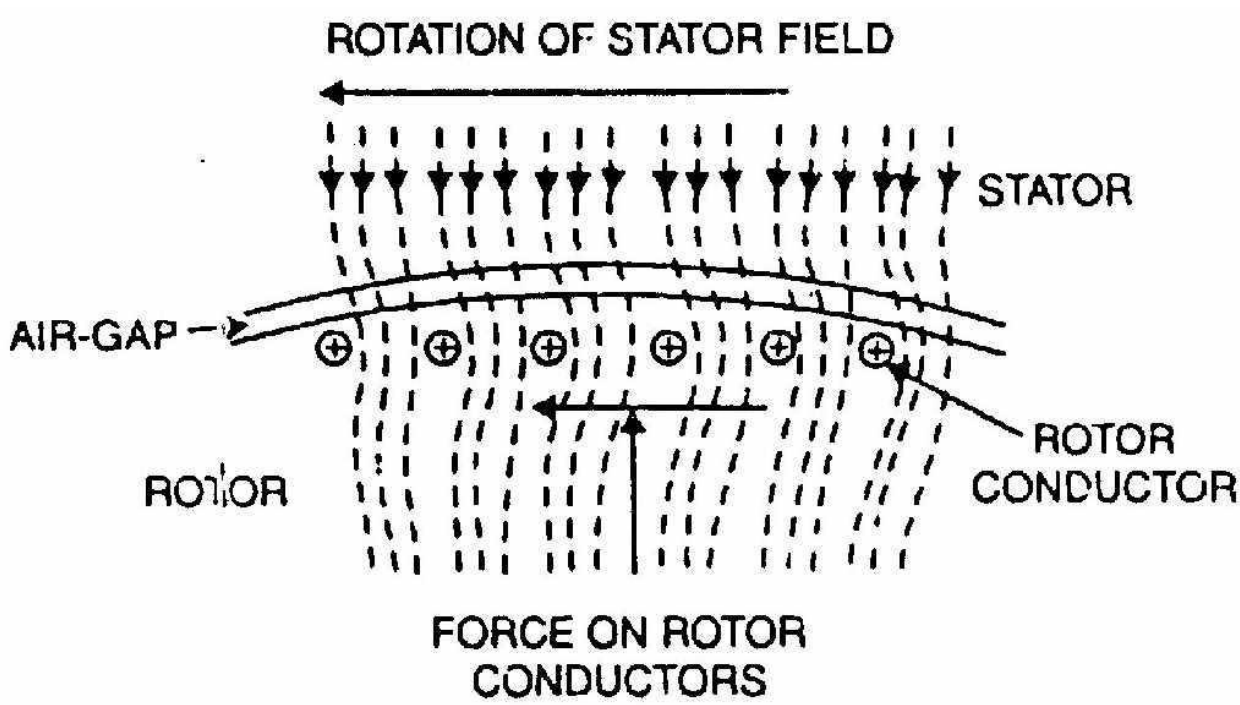
Consider a portion of 3-phase induction motor as shown in Fig. Theoperation of the motor can be explained as under:

(i) When 3-phase statorwinding is energized froma 3-phase supply, arotatingmagnetic field isset up which rotates roundthe stator at synchronousspeed N_s (= 120 f/P).

(ii) The rotating field passesthrough the air gap andcuts the rotor conductors,which as yet, arestationary. Due to the relative speed between the rotating flux and thestationary rotor, e.m.f.s are induced in the rotor conductors. Since therotor circuit is short-circuited, currents start flowing in the rotorconductors.

(iii) The current-carrying rotor conductors are placed in the magnetic fieldproduced by the stator. Consequently, mechanical force acts on the rotorconductors. The sum of the mechanical forces on all the rotor conductorsproduces a torque which tends to move the rotor in the same direction asthe rotating field.

(iv) The fact that rotor is urged to follow the stator field (i.e., rotor moves inthe direction of stator field) can be explained by Lenz's law. Accordingto this law, the direction of rotor currents will be such that they tend tooppose the cause producing them. Now, the cause producing the rotorcurrents is the relative speed between the rotating field and the stationaryrotor conductors. Hence to reduce this relative speed, the rotor startsrunning in the same direction as that of stator field and tries to catch it.



Slip:

We have seen above that rotor rapidly accelerates in the direction of rotating field. In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the suitor field speed (N_s). This difference in speed depends upon load on the motor.

The difference between the synchronous speed N_s of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.,

% Slip = (Ns - N)/Ns *100

(i) The quantity $N_s - N$ is sometimes called slip speed.

(ii) When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.

(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

Rotor Current Frequency

The frequency of a voltage or current induced due to the relative speed between a vending and a magnetic field is given by the general formula;

Frequency = PN /120

Where N = Relative speed between magnetic field and the winding

P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is $N_s - N$. Consequently, the rotor current frequency f' is given by;

$$f' = \frac{(N_s - N)P}{120}$$

$$= \frac{sN_sP}{120} \qquad \left(\because s = \frac{N_s - N}{N_s}\right)$$

$$= sf \qquad \left(\because f = \frac{N_sP}{120}\right)$$

i.e., Rotor current frequency = Fractional slip x Supply frequency

(i) When the rotor is at standstill or stationary (i.e., s = 1), the frequency of rotor current is the same as that of supply frequency ($f' = sf = 1 \times f = f$).

(ii) As the rotor picks up speed, the relative speed between the rotating flux and the rotor decreases. Consequently, the slip s and hence rotor current frequency decreases.

Note. The relative speed between the rotating field and stator winding is $N_s - 0 = N_s$. Therefore, the frequency of induced current or voltage in the stator winding is $f = N_s P/120$—the supply frequency.

Effect of Slip on the Rotor Circuit

When the rotor is stationary, s = 1. Under these conditions, the per phase rotor e.m.f. E_2 has a frequency equal to that of supply frequency f. At any slip s, the relative speed between stator field and the rotor is decreased. Consequently, the rotor e.m.f. and frequency are reduced proportionally to sE_s and sf respectively. At the same time, per phase rotor reactance X_2, being frequency dependent, is reduced to sX_2.

Power Stages in an Induction Motor

The input electric power fed to the stator of the motor is converted into mechanical power at the shaft of the motor. The various losses during the energy conversion are:

1. Fixed losses

(i) Stator iron loss
(ii) Friction and windage loss

The rotor iron loss is negligible because the frequency of rotor currents under normal running condition is small.

2. Variable losses

(i) Stator copper loss
(ii) Rotor copper loss

Fig. shows how electric power fed to the stator of an induction motor suffers losses and finally converted into mechanical power.

The following points may be noted from the above diagram:

(i) Stator input, P_i = Stator output + Stator losses
= Stator output + Stator Iron loss + Stator Cu loss

(ii) Rotor input, P_r = Stator output

It is because stator output is entirely transferred to the rotor through air gap by electromagnetic induction.

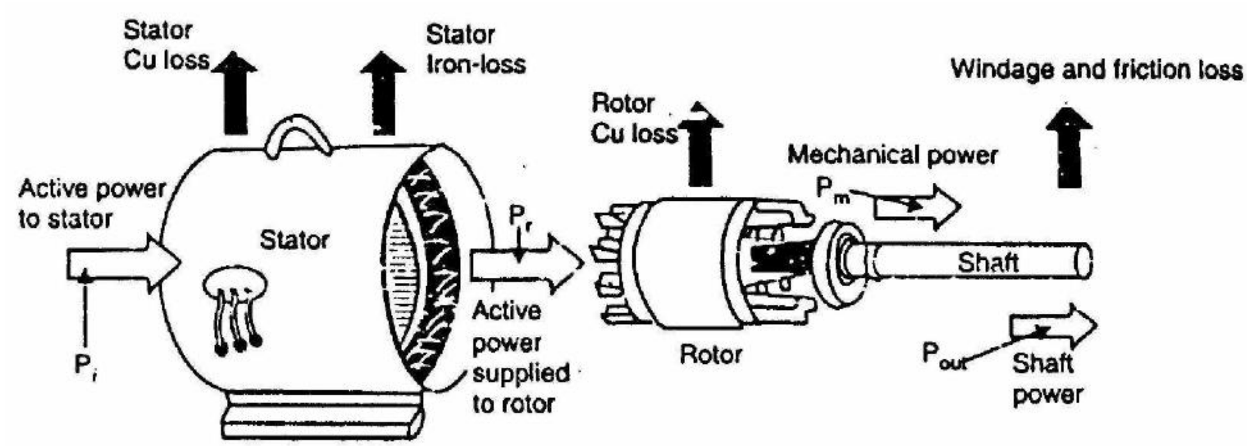
(iii) Mechanical power available, $P_m = P_r$ – Rotor Cu loss

This mechanical power available is the gross rotor output and will produce a gross torque T_g.

(iv) Mechanical power at shaft, $P_{out} = P_m$ – Friction and windage loss

Mechanical power available at the shaft produces a shaft torque T_{sh}.

Clearly, $P_m - P_{out}$ = Friction and windage loss



Induction Motor Torque

The mechanical power P available from any electric motor can be expressed as:

$$P = \frac{2\pi N T}{60} \quad \text{watts}$$

where N = speed of the motor in r.p.m.
T = torque developed in N-m

$$\therefore \qquad T = \frac{60}{2\pi}\frac{P}{N} = 9.55\frac{P}{N} \text{ N - m}$$

If the gross output of the rotor of an induction motor is P_m and its speed is N r.p.m., then gross torque T developed is given by:

$$T_g = 9.55\frac{P_m}{N} \text{ N - m}$$

$$\text{Similarly,} \qquad T_{sh} = 9.55\frac{P_{out}}{N} \text{ N - m}$$

Note. Since windage and friction loss is small, $T_g = T_{sh}$,. This assumption hardly leads to any significant error.

8.26 Rotor Output

If T_g newton-metre is the gross torque developed and N r.p.m. is the speed of the rotor, then,

$$\text{Gross rotor output} = \frac{2\pi N T_g}{60} \quad \text{watts}$$

If there were no copper losses in the rotor, the output would equal rotor input and the rotor would run at synchronous speed N_s.

$$\therefore \quad \text{Rotor input} = \frac{2\pi N_s T_g}{60} \quad \text{watts}$$

$$\therefore \quad \text{Rotor Cu loss} = \text{Rotor input} - \text{Rotor output}$$

$$= \frac{2\pi T_g}{60}(N_s - N)$$

(i) $$\frac{\text{Rotor Cu loss}}{\text{Rotor input}} = \frac{N_s - N}{N_s} = s$$

$$\therefore \quad \text{Rotor Cu loss} = s \times \text{Rotor input}$$

(ii) Gross rotor output, P_m = Rotor input – Rotor Cu loss

$$= \text{Rotor input} - s \times \text{Rotor input}$$

$$\therefore \quad P_m = \text{Rotor input}\,(1 - s)$$

(iii) $$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s = \frac{N}{N_s}$$

(iv) $$\frac{\text{Rotor Cu loss}}{\text{Gross rotor output}} = \frac{s}{1 - s}$$

It is clear that if the input power to rotor is P_r then s P_r is lost as rotor Cu loss and the remaining $(1 - s)P_r$ is converted into mechanical power. Consequently, induction motor operating at high slip has poor efficiency.

$$\frac{\text{Gross rotor output}}{\text{Rotor input}} = 1 - s$$

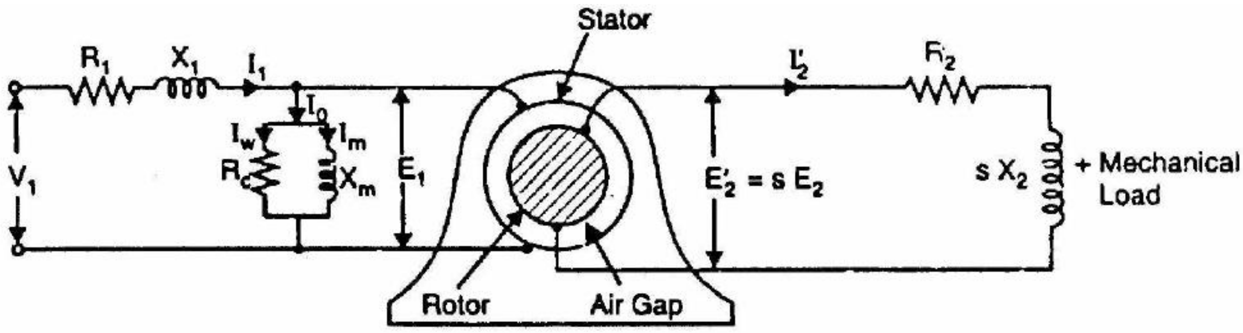
If the stator losses as well as friction and windage losses arc neglected, then,
Gross rotor output = Useful output
Rotor input = Stator input

$$\therefore \quad \frac{\text{Useful output}}{\text{Stator output}} = 1 - s = \text{Efficiency}$$

Hence the approximate efficiency of an induction motor is 1 – s. Thus if the slip of an induction motor is 0.125, then its approximate efficiency is = 1 – 0.125 = 0.875 or 87.5%.

Equivalent Circuit of 3-Phase Induction Motor at Any Slip

In a 3-phase induction motor, the stator winding is connected to 3-phase supply and the rotor winding is short-circuited. The energy is transferred magnetically from the stator winding to the short-circuited, rotor winding. Therefore, an induction motor may be considered to be a transformer with a rotating secondary (short-circuited). The stator winding corresponds to transformer primary and the rotor finding corresponds to transformer secondary. In view of the similarity of the flux and voltage conditions to those in a transformer, one can expect that the equivalent circuit of an induction motor will be similar to that of a transformer. Fig. shows the equivalent circuit (though not the only one) per phase for an induction motor. Let us discuss the stator and rotor circuits separately.



Stator circuit. In the stator, the events are very similar to those in the transformer primal y. The applied voltage per phase to the stator is V_1 and R_1 and X_1 are the stator resistance and leakage reactance per phase respectively. The applied voltage V_1 produces a magnetic flux which links the stator winding (i.e., primary) as well as the rotor winding (i.e., secondary). As a result, self-induced e.m.f. E_1 is induced in the stator winding and mutually induced e.m.f. E'_2(= s E_2 = s K E_1 where K is transformation ratio) is induced in the rotor winding. The flow of stator current I_1 causes voltage drops in R_1 and X_1.

$\therefore\ V_1 = -E_1 + I_1(R_1 + j X_1)$ ... phasor sum

When the motor is at no-load, the stator winding draws a current I_0. It has two components viz., (i) which supplies the no-load motor losses and (ii) magnetizing component I_m which sets up magnetic flux in the core and the airgap. The parallel combination of R_c and X_m, therefore, represents the no-load motor losses and the production of magnetic flux respectively.

$I_0 = I_w + I_m$

Rotor circuit. Here R_2 and X_2 represent the rotor resistance and standstill rotor reactance per phase respectively. At any slip s, the rotor reactance will be s X_2 The induced voltage/phase in the rotor is $E'_2 = s E_2 = s K E_1$. Since the rotor winding is short-circuited, the whole of e.m.f. E'_2 is used up in circulating the rotor current I'_2.

$$\therefore E'_2 = I'_2 (R_2 + j s X_2)$$

The rotor current I'_2 is reflected as I''_2 (= K I'_2) in the stator. The phasor sum of I''_2 and I_0 gives the stator current I_1.

It is important to note that input to the primary and output from the secondary of a transformer are electrical. However, in an induction motor, the inputs to the stator and rotor are electrical but the output from the rotor is mechanical. To facilitate calculations, it is desirable and necessary to replace the mechanical load by an equivalent electrical load. We then have the transformer equivalent circuit of the induction motor.

It may be noted that even though the frequencies of stator and rotor currents are different, yet the magnetic fields due to them rotate at synchronous speed N_s. The stator currents produce a magnetic flux which rotates at a speed N_s. At slip s, the speed of rotation of the rotor field relative to the rotor surface in the direction of rotation of the rotor is

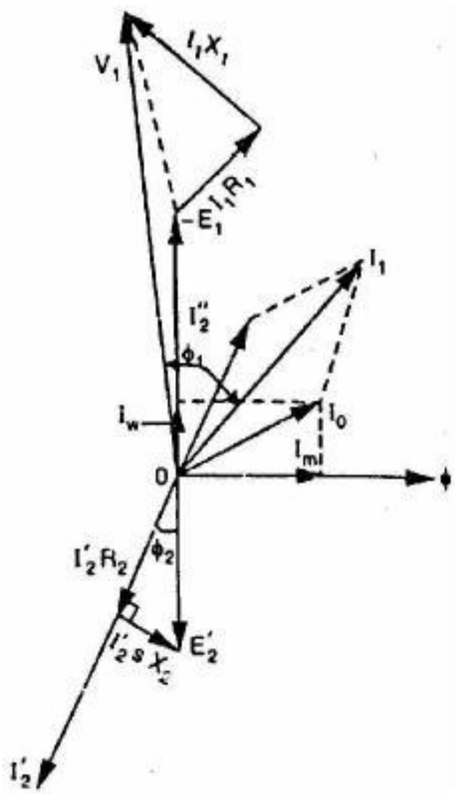
$$= \frac{120\ f'}{P} = \frac{120\ s\ f}{P} = s\ N_s$$

But the rotor is revolving at a speed of N relative to the stator core. Therefore, the speed of rotor field relative to stator core

$$= sN_s + N = (N_s - N) + N = N_s$$

Thus no matter what the value of slip s, the stator and rotor magnetic fields are synchronous with each other when seen by an observer stationed in space. Consequently, the 3-phase induction motor can be regarded as being equivalent to a transformer having an air-gap separating the iron portions of the magnetic circuit carrying the primary and secondary windings.

Fig. shows the phasor diagram of induction motor.



Equivalent Circuit of the Rotor:

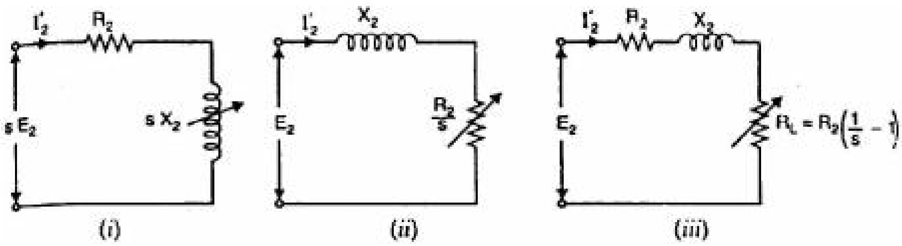
We shall now see how mechanical load of the motor is replaced by the equivalent electrical load. Fig. (i) shows the equivalent circuit per phase of the rotor at slip s. The rotor phase current is given by;

$$I'_2 = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

Mathematically, this value is unaltered by writing it as:

$$I'_2 = \frac{E_2}{\sqrt{(R_2/s)^2 + (X_2)^2}}$$

As shown in Fig.(ii), we now have a rotor circuit that has a fixed reactance X_2 connected in series with a variable resistance R_2/s and supplied with constant voltage E_2. Note that Fig.(ii) transfers the variable to the resistance without altering power or power factor conditions.



The quantity R_2/s is greater than R_2 since s is a fraction. Therefore, R_2/s can be divided into a fixed part R_2 and a variable part $(R_2/s - R_2)$ i.e.,

$$\frac{R_2}{s} = R_2 + R_2\left(\frac{1}{s} - 1\right)$$

(i) The first part R_2 is the rotor resistance/phase, and represents the rotor Cu loss.

(ii) The second part $R_2\left(\frac{1}{s} - 1\right)$ is a variable-resistance load. The powerdelivered to this load represents the total mechanical power developed inthe rotor. Thus mechanical load on the induction motor can be replaced bya variable-resistance load of $R_2\left(\frac{1}{s} - 1\right)$ value. This is

$$\therefore \quad R_L = R_2\left(\frac{1}{s} - 1\right)$$

Induction Motor Torque Equation

The gross torque T_g developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi N_s}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi N_s}$$

Now $\quad \text{Rotor input} = \frac{\text{Rotor Cu loss}}{s} = \frac{3(I'_2)^2 R_2}{s}$

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s\,E_2}{\sqrt{R_2^2 + (s\,X_2)^2}} = \frac{s\,K\,E_1}{\sqrt{R_2^2 + (s\,X_2)^2}}$$

where $\quad K = \text{Transformation ratio} = \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2\,E_2^2 R_2}{R_2^2 + (s\,X_2)^2} \times \frac{1}{s} = \frac{3\,s\,E_2^2 R_2}{R_2^2 + (s\,X_2)^2}$$

$$\text{Rotor input} = 3 \times \frac{s^2\ K^2\ E_1^2 R_2}{R_2^2 + (s\,X_2)^2} \times \frac{1}{s} = \frac{3\,s\,K^2 E_1^2 R_2}{R_2^2 + (s\,X_2)^2}$$

$$T_g = \frac{\text{Rotor input}}{2\pi\,N_s} = \frac{3}{2\pi\,N_s} \times \frac{s\,E_2^2 R_2}{R_2^2 + (s\,X_2)^2}$$

$$= \frac{3}{2\pi\,N_s} \times \frac{s\,K^2\ E_1^2 R_2}{R_2^2 + (s\,X_2)^2}$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.