Poly-phase Induction Motors

1-1 Introduction

The direct-current (dc) and synchronous motors have one thing in common: both are the doubly-fed type. These motors have direct current in their field windings and alternating current (ac) in their armature windings. Since the electrical power is delivered directly to the armature of a dc motor via a commutator, it can also be referred to as a conduction motor.

Considering a motor in which the rotor receives its power not by conduction but by induction and is therefore called an induction motor. A winding that receives its power exclusively by induction constitutes a transformer. Therefore, an induction motor is a transformer with a rotating secondary winding. From the above discussion, the following must be evident:

1. An induction motor is a singly-fed motor. Therefore, it does not require a commutator, slip-rings, or brushes. In fact, there are no moving contacts between the stator and the rotor. This results in a motor that is rugged, reliable, and almost maintenance free.
2. The absence of brushes eliminates the electrical loss due to the brush voltage drop and the mechanical loss due to friction between the brushes and commutator or the slip-rings. Thus, an induction motor has a relatively high efficiency.
3. An induction motor carries alternating current in both the stator and the rotor windings.
4. An induction motor is a rotating transformer in which the secondary winding receives energy by induction while it rotates.

1-2 Types of Induction Motors

There are two basic types of induction motors: *single-phase induction motors* and *poly-phase induction motors*.

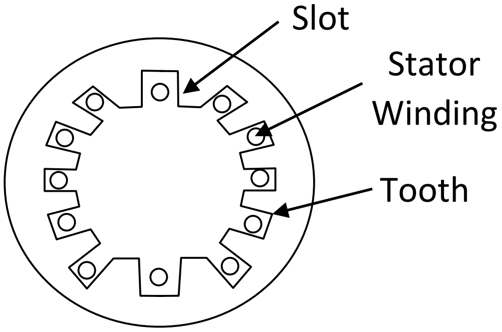
Single-phase induction motors are favored for domestic applications. A large number of these motors are built in the fractional horse power range. We will discuss single-phase induction motors in section 2. On the other hand, poly-phase induction motors cover the entire spectrum of horsepower ratings and are preferably installed at locations where a polyphaser power source is easily accessible. Owing to the widespread generation and transmission of three-phase power, most poly-phase induction motors are of the three-phase type.

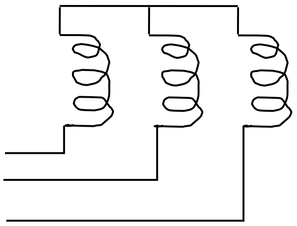
1-3 Construction

A 3 phase induction motor has two main parts (a) stator and (b) rotor. The rotor is separated from the stator by a small air-gap**.**

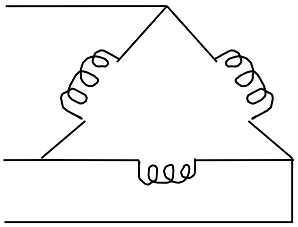
a) Stator:

The stator of an I.M. is the same as that of a synchronous machine. It is made from cylindrical core made up of thin laminations of steel (to reduce hysteresis and eddy current losses) with slots in the inner periphery. The stator carries a poly-phase winding in these slots. For a 3-ph I.M. the winding is connected in star or delta connection.





Star



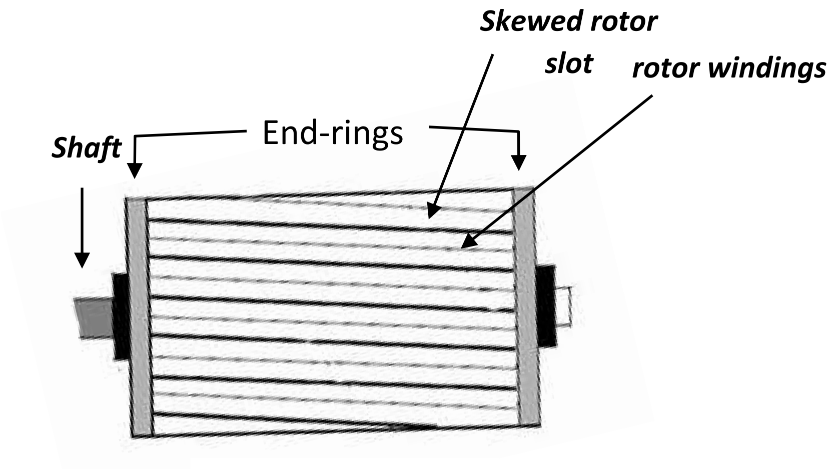
Delta

b) Rotor:

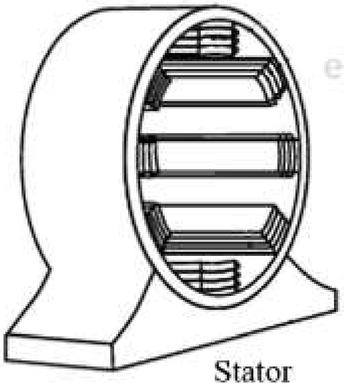
The rotor, mounted on a shaft, is a laminated core having slots on its outer periphery. The winding placed in these slots (called rotor winding) may be one of the following two types:

1) Squirrel-Cage rotor, or 2) Wound rotor.

1- Squirrel-Cage Rotor:



Squirrel-Cage Rotor



The rotor consists of a cylindrical laminated core with parallel slots for carrying the rotor bars. These bars are short-circuited by two end-rings. The rotor slots are not quite parallel to the shaft but are given slight skew.

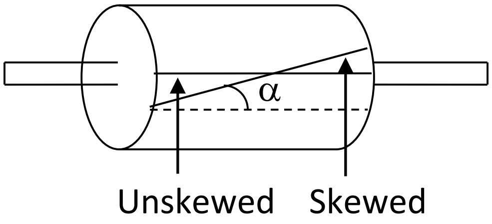
The advantages of skewing are:

1. It makes the motor run quietly by reducing the magnetic hum.
2. It reduces the locking tendency of the rotor. The tendency of the rotor teeth to remain under the stator teeth due to direct magnetic attraction between them.

The magnetic hum is reduced because the air gap in a skewed rotor is more constant reluctance resulting in a more uniform torque and a quieter motor.

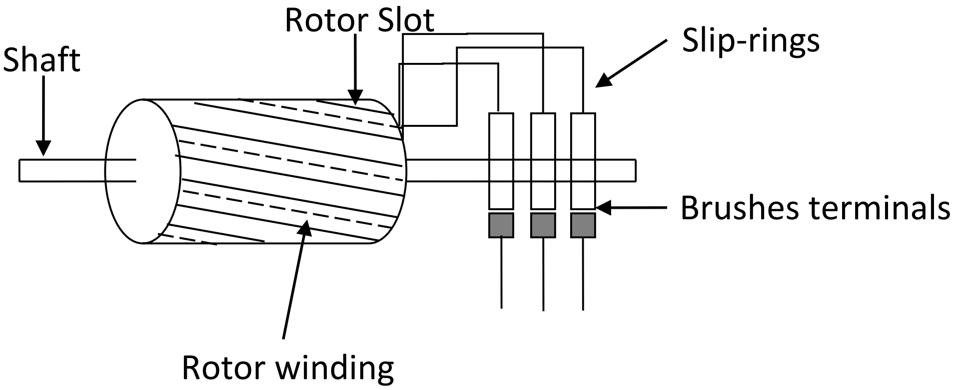
The skewing factor = K_S = The voltage induced in the skewed inductor / The voltage induced in the unskewed inductor

$$K_S = \frac{2E_m \sin\left(\frac{\alpha}{2}\right)}{E_m \alpha} = \frac{\sin\left(\frac{\alpha}{2}\right)}{\frac{\alpha}{2}}$$



Where: E_m is the max. voltage / unit angle of the skewed inductor (V/rad.), and α is the angle of skew.

2-Wound Rotor:



The rotor core is laminated with skewed slots on its outer periphery. The rotor is provided with 3-ph, double-layer, distributed windings. The rotor is wound to have the same number of poles as for the stator. The 3-ph windings are connected in star formation. The terminals of the rotor star-winding are connected to slip-rings mounted on the shaft.

1-4 Principle of Operation

When a 3-ph I.M. is supplied with a 3-ph supply, a rotating field will produce. Such rotating field will cut the rotor conductors with speed equal to the synchronous speed, and as a result of this, a 3-ph emf will be produced with frequency equal to the supply frequency. This emf will send a current through the closed rotor circuit with a direction such as to oppose the very cause producing it, i.e., the rotation of the field. Therefore, the rotor starts running in the same direction as that of the flux and tries to catch up with the rotating flux. This will continue until the speed near the synchronous speed and therefore, the emf and the current will reduce. The difference between these two speeds is called slip (S).

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

The frequency of the rotor emf depends upon the relative speed or on slip-speed, i.e.,

$$N_S - N = \frac{120 f_{rotor}}{2p} \rightarrow SN_S = \frac{120 f_{rotor}}{2p} \rightarrow S * \frac{120 f}{2p} = \frac{120 f_{rotor}}{2p}$$

$$\rightarrow f_{rotor} = Sf$$

Speed of the rotor field with respect to stator$= N_{s\cdot rotor} + N = \frac{120Sf}{2p} + N =$

$$SN_S + N = \left(\frac{N_S - N}{N_S}\right) N_S + N = N_S - N + N = N_S$$

EXAMPLE. 1

A 208-V, 60-Hz, 4-pole, three-phase induction motor has a full-load speed of 1755 rpm.

Calculate:

(a) its synchronous speed,

(b) the slip, and

(c) the rotor frequency.

SOLUTION:

(a) The synchronous speed of the induction motor is

$$N_s = \frac{120 \times 60}{4} = 1800 \text{ rpm}$$

(b) At full load, the slip is

$$s = \frac{1800 - 1755}{1800} = 0.025 \qquad \text{or} \qquad 2.5\%$$

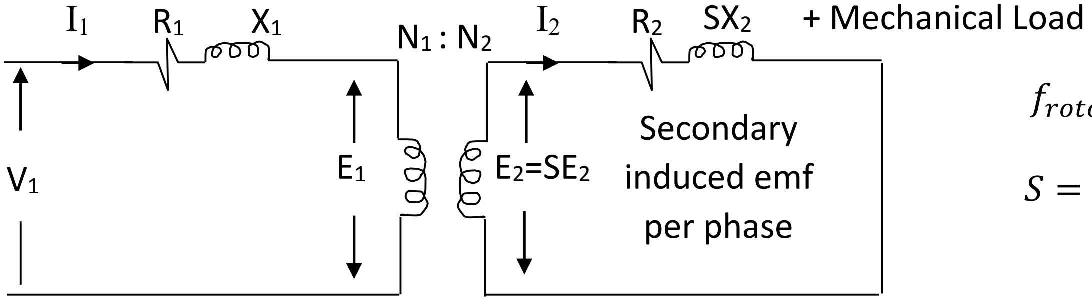
(c) The rotor frequency at full load is

$$f_r = 0.025 \times 60 = 1.5 \text{ Hz}$$

1-5 The Equivalent Circuit:

In an induction motor, 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 equivalent circuit of a 3-ph I.M. has a certain similarity with the equivalent circuit of 3-ph transformer.



$$f_{rotor} = Sf$$

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

The main difference between the induction motor and transformer lies in the fact that the rotor voltage and its frequency are both proportional to slip s. If f is the stator frequency, E2 is the per phase rotor e.m.f. at standstill and X2 is the standstill rotor reactance/phase, then at any slip s, these values are:

Rotor e.m.f./phase, E'2 = s E2

Rotor reactance/phase, X'2 = sX2

Rotor frequency, f' = sf

Where,

V_1= per-phase the applied stator voltage

R_1= per-phase stator winding resistance

X_1= per-phase stator winding leakage reactance

R_2= per-phase rotor winding resistance

X_2=S X_2 = per-phase rotor winding leakage reactance at slip s

E_1= per-phase induced emf in the stator winding

E_2=SE_2= per-phase induced emf in the rotor winding at slip s

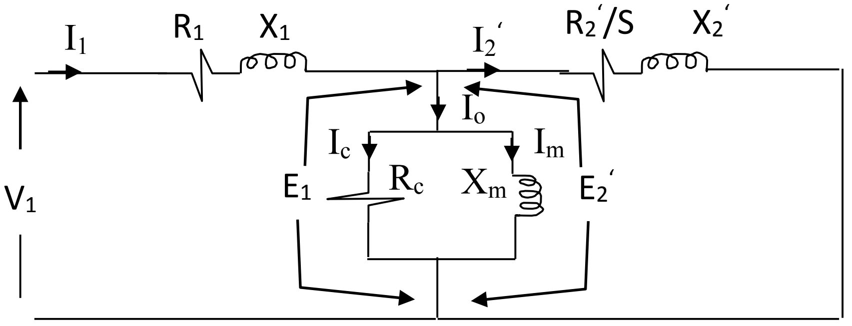
I_1= per-phase current supplied by the source

I_2= per-phase rotor winding current

N_1 = actual turns per phase of the stator winding

N_2 = actual turns per phase of the rotor winding

It is possible to reduce this circuit to:



Where,

Xm = per-phase magnetization reactance

R_c = per-phase equivalent core-loss resistance

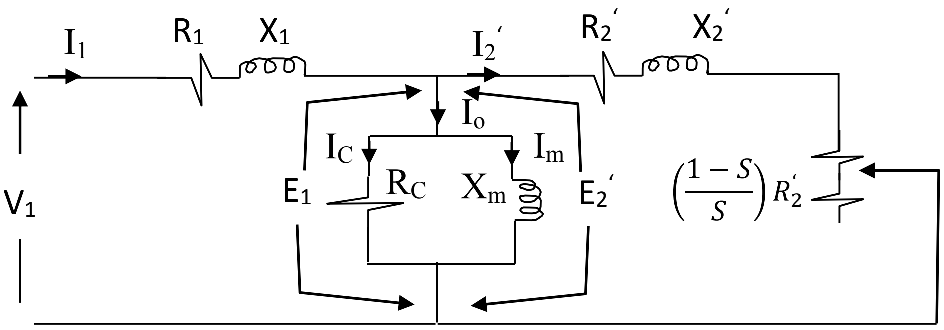
I_m = per-phase magnetization current

I_c = per-phase core-loss current

$$I_0 = I_c + I_m$$

$$R_2' = R_2\left(\frac{N_1}{N_2}\right)^2, X_2' = X_2\left(\frac{N_1}{N_2}\right)^2, E_2' = E_2\left(\frac{N_1}{N_2}\right), I_2' = I_2\left(\frac{N_2}{N_1}\right)$$

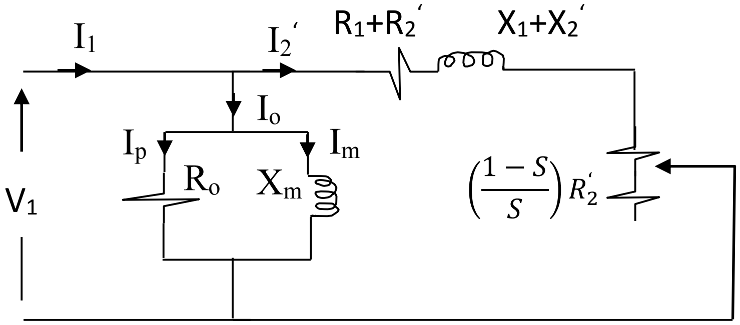
The quantity R_2'/s is greater than R_2' since S is a fraction. Therefore, R_2'/s can be divided into a fixed part R_2' and a variable part (R_2'/s - R_2') i.e.,



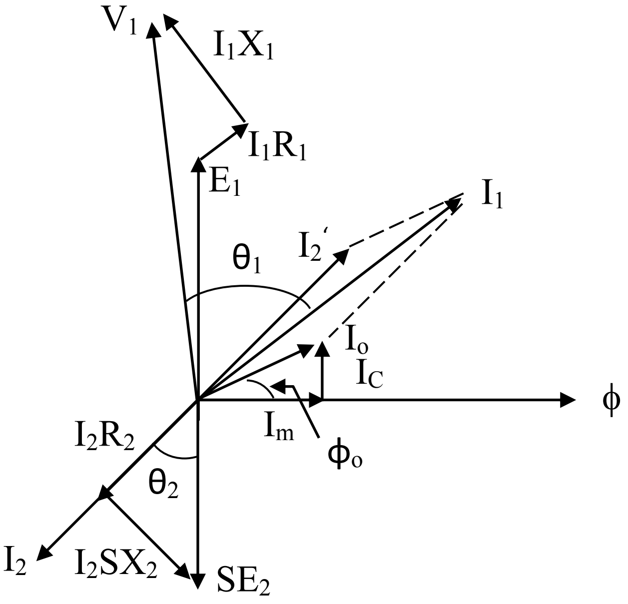
$$R_2'/S = R_2' + \left(\frac{1-S}{S}\right)R_2'$$

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

(ii) The second part is a variable-resistance load. The power delivered to this load represents the total mechanical power developed in the rotor. Thus mechanical load on the induction motor can be replaced by a variable-resistance load of value Also, this circuit can be reduced to:



1-6 3-Ph Induction Motor Phasor Diagram:



1-7 Equivalent circuit calculations

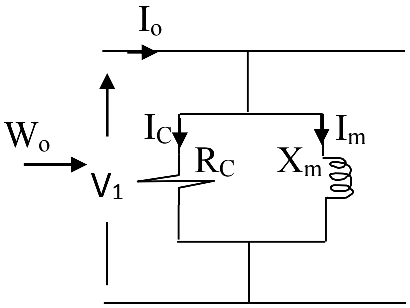
Equivalent circuit parameters can be determined by performing the following two tests on the machine:

No-load test

The motor should run with no-load at rated voltage, the V_o, I_o, and W_o (the voltage, current, and power per phase) must be noted.

$$\text{Cos}\,\emptyset_o = \frac{W_o}{V_o I_o} \rightarrow I_m = I_o \sin \emptyset_o \,, I_C = I_o \cos \emptyset_o$$

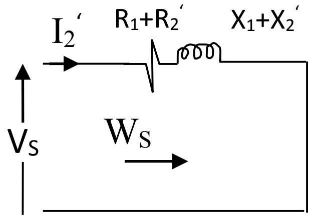
$$R_C = \frac{V_o}{I_C} \,, X_m = \frac{V_o}{I_m}$$



The equivalent circuit of the 3-ph I.M. gets reduced to that shown above since at no-load the slip is very small (normally assumed to be zero).

Blocked-rotor test

In this test the rotor of the machine is held stationary and a reduced voltage (V_S per phase) is applied to the armature winding such that it will allow rated current (I_S) in the armature winding. In blocked-rotor test the equivalent circuit of the machine gets reduced to that shown below:



$$R_1 + R_2' = \frac{W_S}{I_S^2}\ , X_1 + X_2' = \sqrt{\left(\frac{V_S}{I_S}\right)^2 - \left(R_1 + R_2'\right)^2}\ ,$$

$$X_1 = X_2'$$

The dc value of R_1 can be measured by voltmeter-ammeter method ($R_1=R_{1dc}$*1.2(skin effect)).

1-8 Production of Rotating Field:

It can be shown that symmetrical 3-ph windings when supplied from a balance 3-ph power supply produce a rotating field. The figure below shows a 3-ph, 2-pole I.M.

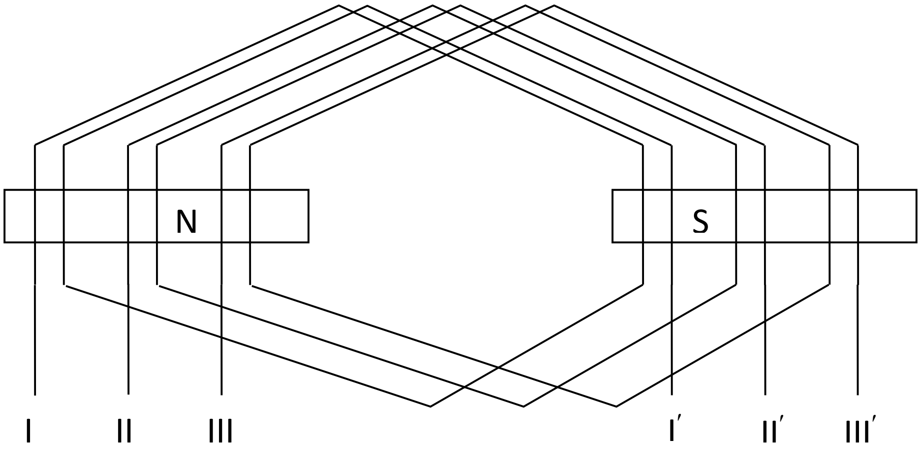


Fig-1-

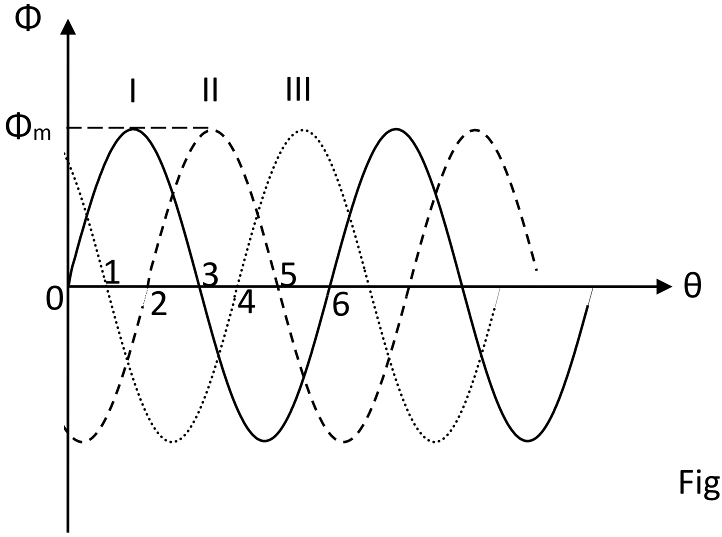


Fig-2- The flux due to the 3-phase

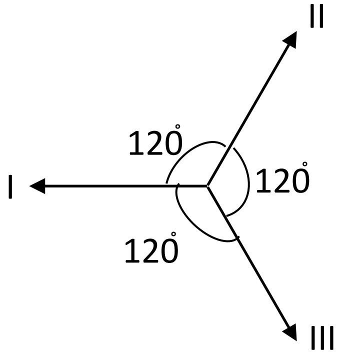
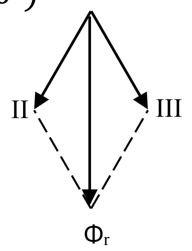


Fig-3- The +ve direction of the fluxes

$\emptyset_1 = \emptyset_m \sin\theta, \emptyset_2 = \emptyset_m \sin(\theta - 120^\circ), \emptyset_3 = \emptyset_m \sin(\theta - 240^\circ)$

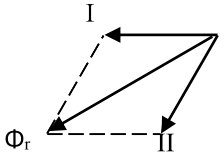
<u>At point 0, θ=0</u>

$\emptyset_1 = 0, \emptyset_2 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$



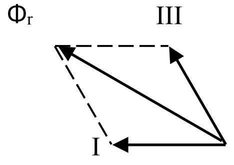
<u>At point 1, θ=60°</u>

$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m, \emptyset_2 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = 0, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$



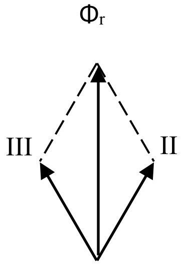
<u>At point 2, θ=120°</u>

$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m, \emptyset_2 = 0, \emptyset_3 = \frac{-\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$



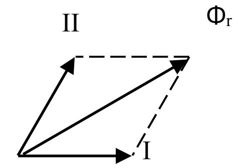
<u>At point 3, θ=180°</u>

$\emptyset_1 = 0, \emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \frac{-\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$



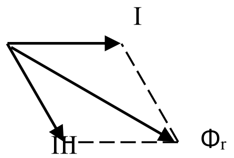
At point 4, θ=240°

$$\emptyset_1 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m, \emptyset_3 = 0, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$$



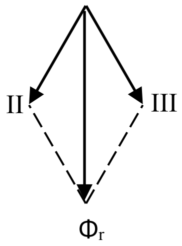
At point 5, θ=300°

$$\emptyset_1 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_2 = 0, \emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$$



At point 6, θ=360°

$$\emptyset_1 = 0, \emptyset_2 = \frac{-\sqrt{3}}{2}\emptyset_m, \emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m, \rightarrow \therefore \emptyset_r = \frac{3}{2}\emptyset_m$$



From this, it is clear that the resultant flux is constant and is rotating with synchronous speed.

in order to change the direction of Rotation of the magnetic field, it is necessary only to change the phase sequence of the applied voltage. For a three-phase supply, this can be done by interchanging any two of the three lines (changing the phase sequence from RST to SRT).

For one current (or flux) cycle → 360° elec. Angle

$$\propto_e = \propto_m * p \rightarrow \propto_m = \frac{\propto_e}{p} \rightarrow \frac{360^\circ}{p} \text{ mech. Angle} \rightarrow \frac{1}{p} \text{ revolution}$$

For f cycles of current (or flux) → $\frac{f}{p}$ revolution/sec

$$\rightarrow \frac{2f}{2p} \text{ revolution/sec}$$

The synchronous speed → $N_S = \frac{120f}{2p}$ r.p.m

1-9 Speed Control of 3-Phase Induction Motors

Since the speed of the I.M. $N = (1 - S)N_S = (1 - S)\frac{120f}{2p}$

Which reveals that the speed N of an induction motor can be varied by changing (i) supply frequency f (ii) number of poles P on the stator and (iii) slip s. The change of frequency is generally not possible because the commercial supplies have constant frequency. Therefore, the practical methods of speed control are either to change the number of stator poles or the motor slip. However, depending on the rotor type the speed can be changed as following:

1. Squirrel cage motors

The speed of a squirrel cage motor is changed by changing the number of stator poles. Only two or four speeds are possible by this method. Two-speed motor has one stator winding that may be switched through suitable control equipment to provide two speeds, one of which is half of the other. For instance, the winding may be connected for either 4 or 8 poles, giving synchronous speeds of 1500 and 750 r.p.m. Four-speed motors are equipped with two separate stator windings each of which provides two speeds. The disadvantages of this method are:

(i) It is not possible to obtain gradual continuous speed control.

(ii) Because of the complications in the design and switching of the interconnections of the stator winding, this method can provide a maximum of four different synchronous speeds for any one motor.

2. Wound rotor motors

The speed of wound rotor motors is changed by changing the motor slip. This can be achieved by; (i) varying the stator line voltage

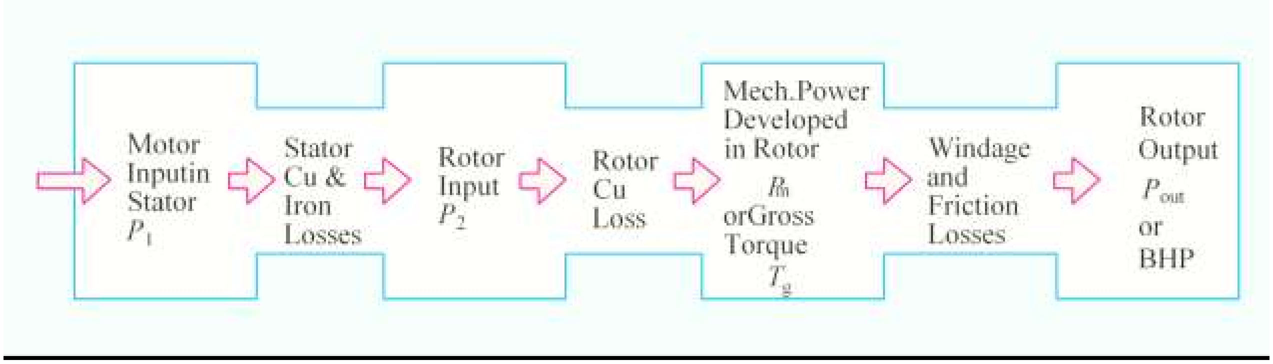
(ii) varying the resistance of the rotor circuit

(iii) inserting and varying a foreign voltage in the rotor circuit

1-10 Power Stages in an Induction Motor

Stator iron loss (consisting of eddy and hysteresis losses) depends on the supply frequency and the flux density in the iron core. It is practically constant. The iron loss of the rotor is, however, negligible because frequency of rotor currents under normal running conditions is always small. Total rotor Cu loss = 3 $I_2^2 R_2$.

Different stages of power development in an induction motor are shown below:



1-11 Torque Developed by an Induction Motor

An induction motor develops gross torque T_g due to gross rotor output P_m.

Its value can be expressed either in terms of rotor input P_2 or rotor gross output P_m as given below:

$$T_g = \frac{P_2}{\omega_s} = \frac{P_2}{2\pi N_s} \qquad \text{in terms of rotor input}$$

$$T_g = \frac{P_m}{\omega} = \frac{P_m}{2\pi N} \qquad \text{in terms of rotor output}$$

The shaft torque T_{sh} is due to output power P_{out} which is less than P_m because of rotor friction and windage losses.

$$T_{sh} = P_{out}/\omega = P_{out}/2\pi N$$

The difference between T_g and T_{sh} equals the torque lost due to friction and windage loss in the motor.

In the above expressions, N and Ns are in r.p.s. However, if they are in r.p.m., the above expressions for motor torque become:

$$
\begin{aligned}
T_g &= \frac{P_2}{2\pi N_s/60} = \frac{60}{2\pi}\cdot\frac{P_2}{N_s} = 9.55\,\frac{P_2}{N_s}\ \text{N-m} \\
&= \frac{P_m}{2\pi N/60} = \frac{60}{2\pi}\cdot\frac{P_m}{N} = 9.55\,\frac{P_m}{N}\ \text{N-m} \\
T_{sh} &= \frac{P_{out}}{2\pi N/60} = \frac{60}{2\pi}\cdot\frac{P_{out}}{N} = 9.55\,\frac{P_{out}}{N}\ \text{N-m}
\end{aligned}
$$