

CHAPTER 10

INDUCTION MOTOR

10.1 INTRODUCTION

Induction motor based on the principle of Electro Magnetic Induction (EMI). Induction motors are of two types.

- (1) 3 phase induction motor
- (2) 1 phase induction motor

10.2 CONSTRUCTION OF THE INDUCTION MOTOR

The Construction of the induction motor mainly consist 2 parts.

- (1) **Stator:** It is the stationary part of the induction machine. The purpose of the field system is to provide the coupling magnetic field. The field system of the induction machine consist the poles and field winding. The type of the field winding depends on the induction motor. For Three phase induction motor: Three phase winding are connected in the stator so 3 phase supply can be provided to the stator which provides the rotating magnetic field.
Single phase induction motor: Single phase winding are connected in the stator so 1 phase supply can be provided to the stator which provide the pulsating magnetic field.

- (2) **Rotor:** It is the rotating part of the induction machine. The purpose of the armature is to rotate the armature winding in the magnetic field. The armature consist the slot on its outer surface. The conductor are placed in these slots and known as armature winding. The rotor of the induction motor is of two types.

Squirrel cage rotor: In this type of rotor the armature winding armature conductor are short circuited internally. Almost 95 % of the induction motor are having squirrel cage rotor. It has the following characteristic

- (1) High efficiency
- (2) Low starting torque
- (3) High starting current
- (4) Cheaper cost
- (5) Speed control by resistance is not possible

Wound rotor: In this type of rotor the armature winding armature conductor are short circuited externally. It has the following characteristic

- (1) Low efficiency
- (2) High starting torque
- (3) Low starting current
- (4) Higher cost
- (5) Speed control by resistance is possible

10.3 PRINCIPLE OF THE INDUCTION MOTOR

The induction motor work on the principle of faraday law of Electro Magnetic induction (EMI). According to this law "If there is the rate of change in the flux link with the winding then EMF will induced in the winding".

10.4 3 PHASE INDUCTION MOTOR

An induction motor which converts 3 phase AC electrical energy into mechanical energy is called 3 phase induction motor. A 3 phase induction motor is shown in fig. 10.1 (a).

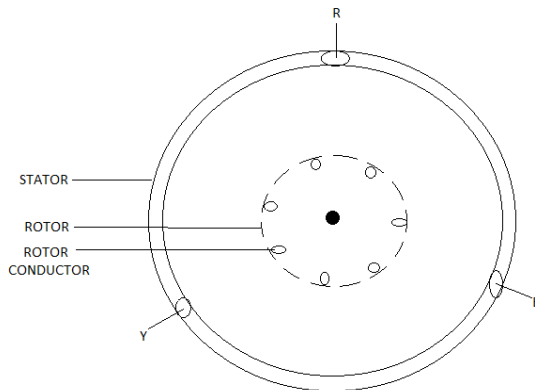


Fig. 10.1 (a)

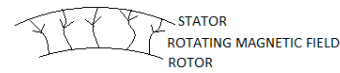


Fig. 10.1 (b)

Working: The working of 3 phase induction motor is follow.

- (1) When a three phase AC supply is given to the stator winding a rotating magnetic field is produce.
A rotating magnetic field is a magnetic field which is rotating by a constant speed called synchronous speed. Rotating magnetic field is shown in fig. 10.1 (b).
- (2) This rotating magnetic field passes through the rotor and cut the rotor conductor.
- (3) Then according to faraday law an EMF is induced in the rotor conductor.
- (4) These rotor conductors are short circuited so a current will start to flow in the rotor conductor.
- (5) Now the rotor conductor is current carrying conductor and placed in the magnetic field so a force will act on the rotor conductor and rotor conductor will rotate.
- (6) There rotor conductor placed on the rotor so finally rotor will rotate.
- (7) Finally 3 phase AC electrical energy is converted in to mechanical energy.

10.5 SLIP

The ratio of slip speed to the synchronous speed is called slip. It is denoted by s.

$$s = \frac{\text{slip speed}}{\text{synchronous speed}}$$

Slip speed: It is the difference between the synchronous speed to rotor speed.

$$N_s - N_r$$

N_s = Synchronous speed (Speed of the rotating magnetic field)

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

f = Supply frequency

P = Number of pole

N_r = Rotor speed

$$s \% = \frac{N_s - N_r}{N_s} \times 100$$

Case 1: If the rotor is stationary, starting time ($N_r = 0$) Then $s = 100\%$

Case 2: If $N_s = N_r$ Then $s = 0$

So the value of slip between

$$0 < s < 1$$

10.6 TORQUE EQUATION OF 3 PHASE INDUCTION MOTOR

The torque produced in 3 phase induction motor depends on three parameters.

- (1) Rotor emf (E_2)
- (2) Rotor current (I_2)
- (3) Rotor power factor ($\cos \phi_2$)

So

$$T \propto E_2 I_2 \cos \phi_2$$

At running condition when slip is s

$$I_2 = \frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}} \quad \text{and} \quad \cos \phi_2 = \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}}$$

So running torque

$$T_r \propto E_2 \times \frac{sE_2}{\sqrt{(R_2)^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{(R_2)^2 + (sX_2)^2}} \propto \frac{sE_2^2 R_2}{(R_2)^2 + (sX_2)^2}$$

$$T_r = \frac{K_1 s E_2^2 R_2}{(R_2)^2 + (sX_2)^2}$$

Where K_1 is the proportionate constant.

E_2 is also constant so defined $K_2 = K_1 E_2^2$

So running torque

$$T_r = \frac{K_2 s R_2}{(R_2)^2 + (sX_2)^2}$$

At starting time when $s = 1$, the starting torque (torque at the time of starting)

$$T_{st} = \frac{K_2 R_2}{(R_2)^2 + (X_2)^2}$$

Condition for maximum torque: The running torque is maximum, when

$$\frac{dT_r}{ds} = 0$$

$$\frac{d}{ds} \left(\frac{K_2 s R_2}{(R_2)^2 + (sX_2)^2} \right) = 0$$

$$\frac{[(R_2)^2 + (sX_2)^2](K_2 R_2) - (K_2 s R_2)(2sX_2)}{[(R_2)^2 + (sX_2)^2]^2} = 0$$

$$[(R_2)^2 + (sX_2)^2] - (2s^2 X_2^2) = 0$$

$$(R_2)^2 = (sX_2)^2$$

$$R_2 = sX_2$$

Maximum Torque

$$T_m = \frac{K_2 s R_2}{(R_2)^2 + (sX_2)^2} = \frac{K_2 s \times sX_2}{(sX_2)^2 + (sX_2)^2} = \frac{K_2 s^2 X_2}{2s^2 X_2^2} = \frac{K_2}{2X_2}$$

$$T_m \propto \frac{1}{X_2}$$

Maximum torque is independent from the slip.

10.7 TORQUE-SLIP CHARACTERISTICS

The curve obtained by plotting torque by varying slip (from 0 to 1) is called the Torque-Slip characteristic shown in fig. 10.2. We know

$$T_r = \frac{K_2 s R_2}{(R_2)^2 + (sX_2)^2}$$

The Torque-Slip curve can be divided into three regions.

- (1) **Low slip region:** When $s = 0$ then $T = 0$, so torque slip characteristic start from origin.
- (2) **Medium slip region ($0 < s < s_m$):** When the value of slip is medium, the term

$$sX_2 < R_2 \quad \text{so} \quad (sX_2)^2 \ll R_2^2$$

So by neglecting $(sX_2)^2$ from R_2^2 then torque

$$T_r \propto \frac{K_2 s R_2}{(R_2)^2} \propto s$$

So torque is linearly increased with slip in medium slip region. This region is stable region.

- (3) **High slip region ($s_m < s < 1$):** When the value of slip is high, the term

$$R_2 < sX_2 \quad \text{so} \quad R_2^2 \ll (sX_2)^2$$

So by neglecting R_2^2 from $(sX_2)^2$ then torque

$$T_r \propto \frac{K_2 s R_2}{(sX_2)^2} \propto \frac{s}{s^2} \propto \frac{1}{s}$$

So torque is inversely proportional with slip in high slip region. This region is unstable region.

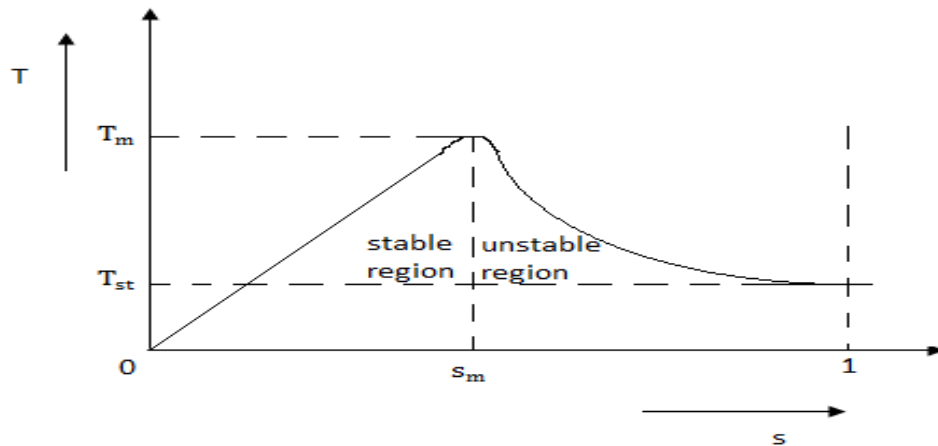


Fig. 10.2

10.8 APPLICATION OF 3 PHASE INDUCTION MOTOR

Applications of 3 phase induction motor are as follow

- (1) Printing machine (2) Flour machine (3) Lifts (4) Cranes (5) Pumps

10.9 1 PHASE INDUCTION MOTOR

An induction motor which converts 1 phase AC electrical energy into mechanical energy is called 1 phase induction motor.

A single phase induction motor is not a self starting motor because when a single phase AC supply is connected to the stator winding, a pulsating magnetic field is produced. This pulsating magnetic field build in one direction, fall to zero and then build up in the opposite direction, torque produced in both the direction is equal and opposite, the resultant torque is zero. So the pulsating magnetic field cannot produce the rotation in the rotor. Therefore single phase induction motor is not a self starting motor.

To make single phase induction motor self starting, we should have to produce a rotating magnetic field. This can be produce by converting a single phase AC supply in to two phase AC supply by using a additional winding called auxiliary winding (starting winding). With the help of auxiliary winding motor temporarily works as a two phase induction motor and produce a rotating magnetic field and makes itself starting.

10.10 TYPES OF INDUCTION MOTOR

It is also called starting method of single phase induction motor. The induction motor is of four types.

10.10.1 Split phase starting:

Construction: The construction of split phase induction motor is shown in fig. 10.3 (a)

- (1) Its stator has two winding main winding and auxiliary winding.
- (2) The main winding and auxiliary winding are 90° in spaces and it is like a two phase induction motor.

- (3) The main winding is highly inductive and auxiliary winding is highly resistive.
- (4) It consist a centrifugal switch by which auxiliary winding connected in the circuit.

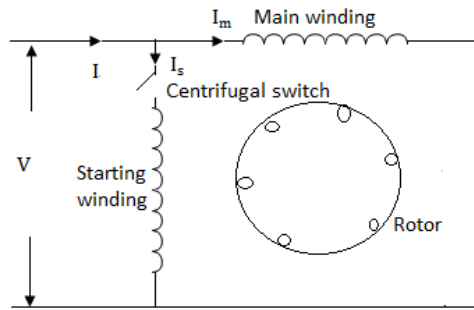


Fig. 10.3 (a)

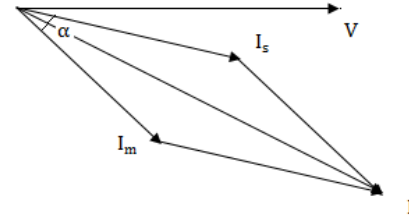


Fig. 10.3 (b)

Working: The working of the split phase induction motor is follow.

- (1) When the stator winding energized from a single phase supply, the main winding carry current (I_m) and auxiliary winding carry current (I_s).
- (2) Since main winding is highly inductive and starting winding is highly resistive, so the current I_m and I_s have a reasonable phase difference α (25° to 30°) between them. So a weak rotating magnetic field is produced. As shown in the fig. 10.3 (b).
- (3) Due to this rotating magnetic field rotor will rotate.
- (4) When the rotor of the motor reach 75% of the synchronous speed, the centrifugal switch is open and motor continue to run on the main winding as a single phase induction motor.

Torque equation: The torque equation of the induction motor is

$$T \propto I_m I_s \sin \alpha$$

Application: The application of the split phase induction motor is follow.

- (1) Fans (2) Blower (3) Washing machine (4) Refrigerators (5) Grinders

10.10.2 Capacitor start motor: The capacitor start motor is shown in fig. 10.4 (a).

In capacitor start motor a capacitor C is connected in series with the auxiliary winding to produce a greater phase difference α (80° to 85°) between the current I_m and I_s .

The value of capacitor is chosen such that current I_s lead current I_m by about 85° which is greater so a strong magnetic field is produced as shown in fig. 10.4 (b). Again when the rotor of the motor reach 75% of the synchronous speed, the centrifugal switch is open and motor continue to run on the main winding as a single phase induction motor.

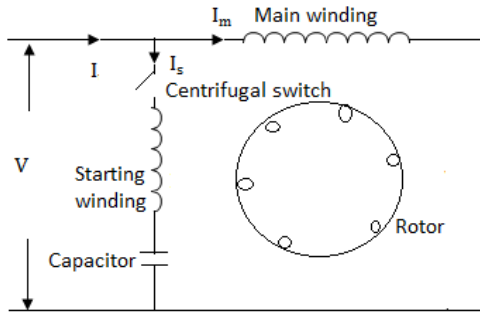


Fig. 10.4 (a)

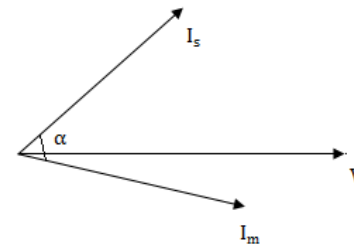


Fig. 10.4 (b)

Application: The application of the split phase induction motor is follow.

- (1) Pumps (2) Compressor (3) Air conditioner (4) Conveyors

10.10.3 **Capacitor start capacitor run motor:** In capacitor start capacitor run motor is shown in fig. 10.5.

This motor is identical to a capacitor start motor except that starting winding is not opened after starting so that both winding remains connected to the supply at starting as well as running. A single capacitor C is used for both running as well as starting. This design eliminates the need of centrifugal switch and improves the efficiency.

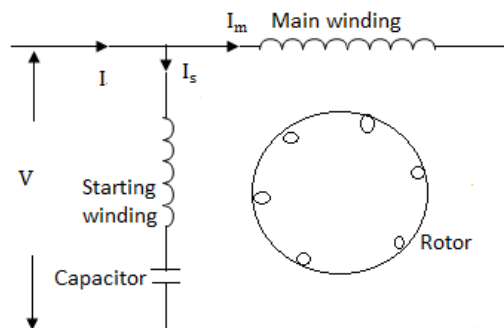


Fig. 10.5

Application: The application of the capacitor start capacitor run induction motor is follow.

- (1) Hospital (2) Air compressor (3) Refrigeration

10.10.4 **Shaded pole motor:**

Construction: The construction of shaded pole induction motor is shown in fig. 10.6.

- (1) Its stator consist the salient pole and each pole slotted on one side.
- (2) A single turn copper ring is fitted on the smaller part of the slotted pole.
- (3) This part of the pole is called shaded pole and ring is called shading coil.
- (4) The shading coil and main coil are separate from each other.

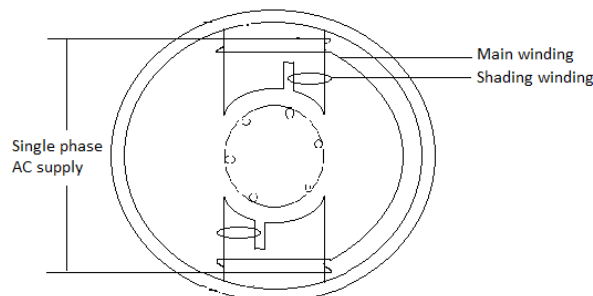


Fig. 10.6

Working: The working of the shaded pole induction motor is follow.

- (1) The main winding is connected to the AC supply, so an alternating flux is setup.
- (2) This alternating flux link with the shading coil and induce emf in them.
- (3) The shading coil produces a flux which opposes the flux of the main winding.
- (4) The flux in the shaded portion of the pole lags the flux in the unshaded portion.
- (5) This result the rotating field moving from the unshaded portion to shaded portion.
- (6) The rotor will rotate from unshaded portion to shaded portion.

Application: The application of the shaded pole induction motor is follow.

- (1) Small fans (2) Toys (3) Hair dryers (4) Electric clock

10.11 NUMERICAL ON SLIP OF 3 PHASE INDUCTION MOTOR

Formula used for numerical on slip

$$\text{Synchronous speed } N_s = \frac{120f}{P}$$

$$\text{Percentage slip } s \% = \frac{N_s - N_r}{N_s} \times 100$$

$$\text{Rotor current frequency } f_2 = sf$$

Where

f = Supply frequency,

N_r = Rotor speed,

P = Number of poles,

s = slip,

N_s = Synchronous speed,

f_2 = Frequency of the rotor current

Example 10.1 A 3 phase 4-pole, 50 Hz induction motor runs at 1460 rpm. Determine (1) Synchronous speed (2) percentage slip (3) frequency of the rotor current

Solution: Given P = 4, f = 50 Hz, N_r = 1460 rpm

- (1) Synchronous speed

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

- (2) Percentage slip

$$s \% = \frac{N_s - N_r}{N_s} \times 100 = \frac{1500 - 1460}{1500} \times 100 = 2.66\% \text{ Ans.}$$

- (3) Frequency of the rotor current

$$f_2 = sf = 0.0266 \times 50 = 1.33 \text{ Hz Ans.}$$

Example 10.2 A 3 phase 2-pole induction motor is running with 4% slip. The supply frequency is 50 Hz. Find out the speed of the induction motor.

Solution: Given P = 2, s = 4% = 0.04, f = 50 Hz

Speed of the induction motor (N_r)

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

$$s \% = \frac{N_s - N_r}{N_s} \times 100 \Rightarrow 4\% = \frac{3000 - N_r}{3000} \times 100$$

$$N_r = 3000 - 3000 \times 0.04 = 3000 - 120 = 2880 \text{ rpm Ans.}$$

Example 10.3 A 3 phase, 50 Hz, induction motor has a full load speed of 1440 rpm. Calculate the number of poles and frequency of rotor induced emf.

Solution: Given $f = 50$ Hz, $N_r = 1440$ rpm

The synchronous speed should be nearer to the full load speed so consider $N_r = N_s$

$$N_s = \frac{120f}{P} \Rightarrow P = \frac{120f}{N_s} = \frac{120 \times 50}{1440} = 4.16$$

The number of pole should be in even number, so

$$P = 4 \text{ Ans.}$$

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

$$s \% = \frac{N_s - N_r}{N_s} \times 100 = \frac{1500 - 1440}{1500} \times 100 = 4\%$$

Frequency of the rotor current $f_2 = sf = 0.04 \times 50 = 2$ Hz **Ans.**

Example 10.4 A 3 phase, 6-pole induction motor is supplied from 3 phase, 50 Hz AC supply. Find (1)The synchronous speed. (2) The rotor speed when slip is 6%. (3) The rotor frequency when rotor runs at 600 rpm.

Solution: Given $P = 6$, $f = 50$ Hz

(1) The synchronous speed. $N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000$ rpm **Ans.**

(2) The rotor speed when slip is 6%

$$s \% = \frac{N_s - N_r}{N_s} \times 100 \Rightarrow 6\% = \frac{1000 - N_r}{1000} \times 100$$

$$N_r = 1000 - 1000 \times 0.06 = 1000 - 60 = 940 \text{ rpm Ans.}$$

(3) The rotor frequency when rotor runs at 600 rpm.

$$s \% = \frac{N_s - N_r}{N_s} \times 100 = \frac{1000 - 600}{1000} \times 100 = 40\%$$

Rotor Frequency $f_2 = sf = 0.4 \times 50 = 20$ Hz **Ans.**

Example 10.5 A-8 pole, 3 \emptyset alternator is coupled to an engine running at 750 rpm. It supplied a 3 \emptyset induction motor having a full load speed of 2950 rpm. Find % slip, frequency of rotor current and number of poles of the motor.

Solution: Given For alternator $P = 8$ pole, $N = 750$

Supply frequency from alternator

$$f = \frac{N \times P}{120} = \frac{750 \times 8}{120} = 50 \text{ Hz}$$

For induction motor Given $N_r = 2950 \text{ rpm}$.

The synchronous speed should be nearer to the full load speed so consider $N_r = N_s$

$$N_s = \frac{120f}{P} \Rightarrow P = \frac{120f}{N_s} = \frac{120 \times 50}{2950} = 2.03$$

The number of pole should be in even number, so $P = 2 \text{ Ans.}$

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm}$$

$$s \% = \frac{N_s - N_r}{N_s} \times 100 = \frac{3000 - 2950}{3000} \times 100 = 1.67 \% \text{ Ans.}$$

Frequency of the rotor current $f_2 = sf = 0.0167 \times 50 = 0.835 \text{ Hz Ans.}$

Exaple 10.6 A 3 ϕ , 50 Hz induction motor has 8 poles and operates with a slip of 10 % at a certain load. Determine, (i) The speed of the rotor w.r.t. the stator. (ii) The frequency of the rotor current. (iii) The speed of the rotor magnetic field w.r.t rotor (iv) The speed of the rotor magnetic field w.r.t stator (v) The speed of the rotor magnetic field w.r.t. the stator magnetic field. **[Ans. 690 rpm, (ii) 4Hz, (iii) 60 rpm, (iv) 750 rpm, (v) zero]**

Solution: Given $f = 50 \text{ Hz}$, $P = 8 \text{ pole}$, $s = 10 \%$

$$\text{Synchronous speed } N_s = \frac{120f}{P} = \frac{120 \times 50}{8} = 750 \text{ rpm.}$$

(i) The speed of the rotor w.r.t. the stator (N_r).

$$s \% = \frac{N_s - N_r}{N_s} \times 100 \Rightarrow 10 \% = \frac{750 - N_r}{750} \times 100$$

$$N_r = 750 - 750 \times 0.1 = 750 - 75 = 675 \text{ rpm Ans.}$$

(ii) The frequency of the rotor current.

$$f_2 = sf = 0.1 \times 50 = 5 \text{ Hz Ans.}$$

(iii) The speed of the rotor magnetic field w.r.t rotor

$$= \frac{120f_2}{P} = \frac{120 \times 5}{8} = 75 \text{ rpm. Ans.}$$

(iv) The speed of the rotor magnetic field w.r.t stator $N_s = 750 \text{ rpm. Ans.}$

(v) The speed of the rotor magnetic field w.r.t. the stator magnetic field is zero. **Ans.**