Unit-IV

Three Phase Induction motors: Three-phase induction motors. Principle of operation, construction, types. Rotating magnetic field, significance of torque-slip characteristic.

Single Phase Induction Motor: Single-phase induction motor. Construction, Principle of operation, Types of single-phase induction motors.

THREE PHASE INDUCTION MOTORS

The induction machine was invented by NIKOLA TESLA in 1888. Right from its inception its ease of manufacture and its robustness have made it a very strong candidate for electromechanical energy conversion. It is available from fractional horsepower ratings to megawatt levels. It finds very wide usage in all various application areas. The induction machine is an AC electromechanical energy conversion device. The machine interfaces with the external world through two connections (ports) one mechanical and one electrical. The mechanical port is in the form of a rotating shaft and the electrical port is in the form of terminals where AC supply is connected. There are machines available to operate from three phase or single phase electrical input.

CONSTRUCTION AND TYPES OF THREE PHASE INDUCTION MOTORS

A 3 phase induction motor consists of two major parts:

- A stator
- A rotor

Stator of 3 Phase Induction Motor

The **stator** of three phase induction motor is made up of numbers of slots to construct a 3 phase winding circuit which is connected with 3 phase AC source. The three-phase winding are arranged in such a manner in the slots that they produce one rotating magnetic field when the three-phase AC supply source is connected. The stator is made up of various stampings with slots to carry three-phase windings. It is wound for a distinct number of poles. The windings are geometrically divided 120 degrees separated. The Figure below represents the stator of three phase induction motor.

Rotor of 3 Phase Induction Motor

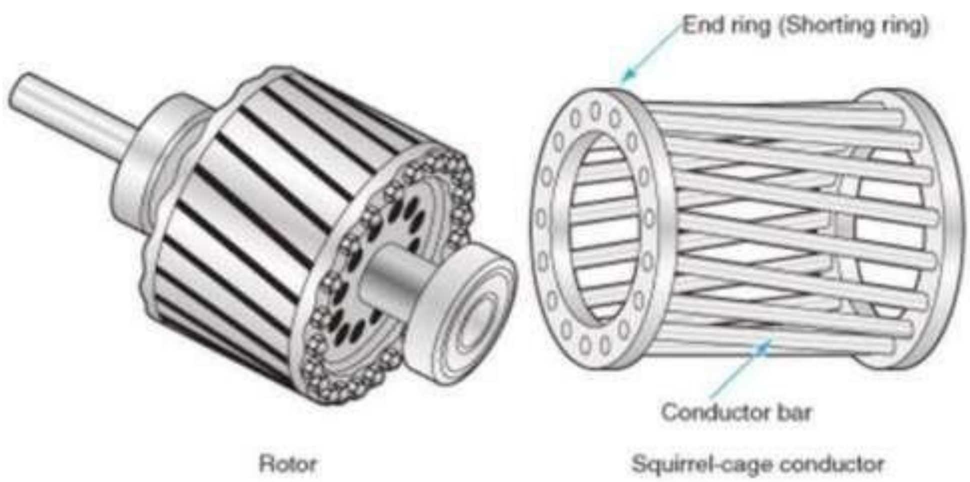
The rotor is the rotating part of the electromagnetic circuit. The rotor of three phase induction motor consists of a cylindrical laminated core with parallel slots that can carry conductors. The conductors are heavy copper or aluminum bars fitted in each slot and short-circuited by the end rings. The slots are not exactly made parallel to the axis of the shaft but are slotted a little skewed because this arrangement reduces magnetic humming noise and can avoid stalling of the motor.

Two types of rotors are used in Induction motors: **Squirrel cage rotor and Wound rotor**. No DC field current is required to run the machine. Rotor voltage is induced in the rotor windings rather than being physically connected by wires.

An induction motor has the same physical stator as a synchronous machine with an alternate rotor development. Induction motor might be worked as either motors or generator. On the other hand, they are fundamentally used as induction motors.

Squirrel cage motors are widely used due to their rugged construction and simple design.. In this motor, the rotor includes a cylindrical core that can be laminated & includes some slots on the external periphery. These slots are not comparable & they are twisted by some angles.

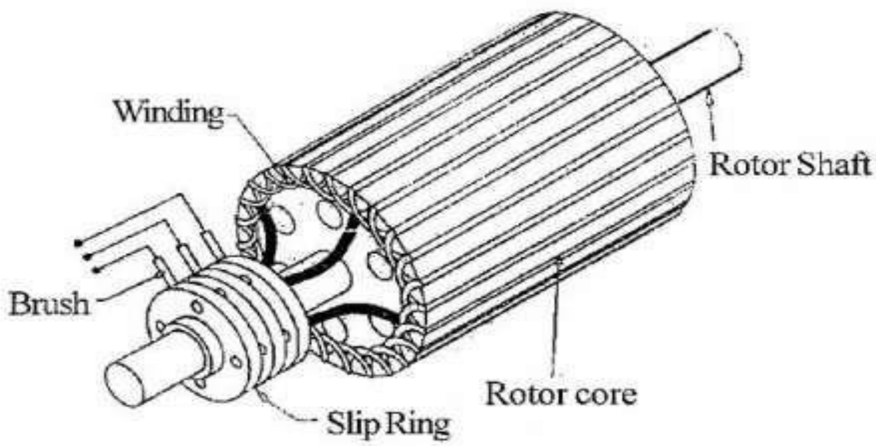
These slots assist to stop magnetic locking among the teeth of the stator & rotor so that smooth operation can be achieved and humming noise can be reduced. These motors include rotors of bars in place of the rotor winding where these bars are fabricated with brass, aluminum otherwise copper. In this type of motor, the winding of the rotor includes an aluminum bar otherwise uninsulated copper fixed into semi-closed rotor slots. At both ends of this motor, these conductors are short-circuited through similar material's end ring. As a result, this type of rotor is similar to a squirrel cage, so this is known as a squirrel cage induction motor.



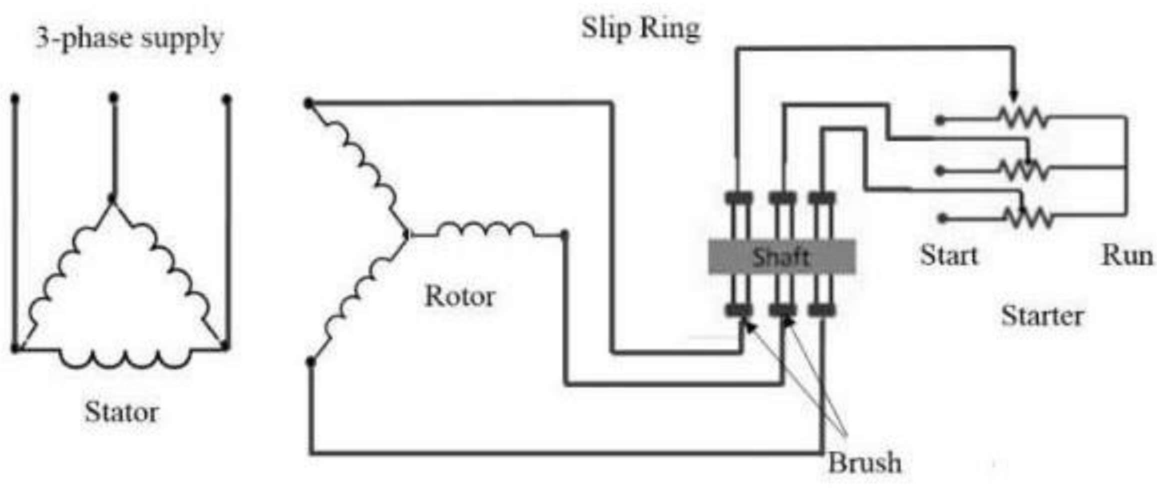
SLIP RING INDUCTION MOTOR

The slip-ring induction motor is also called a wound rotor motor. In this motor, the rotor includes a laminated cylindrical core. Similar to the squirrel cage, there are some slots on the outer periphery. The rotor winding is placed inside the slots.

In the wound rotor, the insulated windings are wound on top of the rotor similarly like on the stator. The winding of this rotor can be distributed uniformly & usually connected in the STAR model. The three terminals of this STAR connection can be taken out throughout the slip ring. So this is the reason to call this motor a slip ring induction motor. Slip ring motors require external resistors to have high starting torque, low initial current and improved power factor. The rotor windings consist of more number of windings, higher induced voltage, and less current compared to the squirrel-cage rotor. The windings are connected to external resistance through slip rings, which helps to control the torque/speed of a motor. The rotor of this type of motor is wound type. It comprises of a cylindrical laminated steel core and a semi-closed groove at the outer boundary to accommodate a 3-phase insulated winding circuit.



Slip Ring in Induction Motor



Slip Ring Induction Motor Connection Diagram

The rotor is wound to match the number of poles on the stator. The three terminals of a rotor and three start terminals connecting through slip rings are connected to a shaft. The aim of the shaft is to transmit mechanical power.

Induction motors are used in industrial and domestic appliances because these are rugged in construction requiring hardly any maintenance, that they are comparatively cheap, and require supply only to the stator. The load is connected to the shaft.

Advantages and Disadvantages of Slip Ring Induction Motor

The advantages are

- High and excellent starting torque to support high inertia loads.
- It has a low starting current due to external resistance
- Can take full load current that is 6 to 7 times higher

The disadvantages are

- Includes higher maintenance costs due to brushes and slip rings compared to squirrel cage motor
- Intricate construction
- High copper loss
- Low efficiency and low power factor
- Expensive than 3 phase squirrel cage induction motor

Applications

Some of the **applications of slip ring induction motor** are

- These motors are used where higher torque and low starting current are required.
- Used in applications like elevators, compressors, cranes, conveyors, hoists

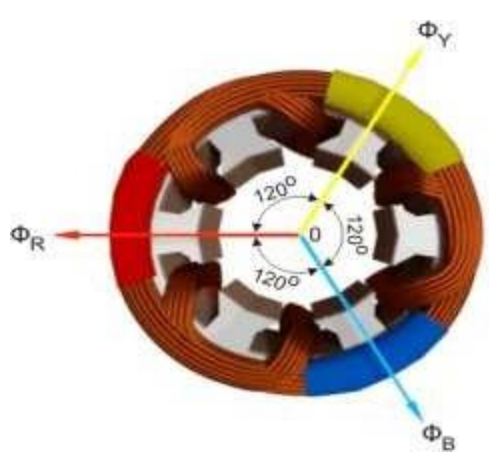
Comparison between Squirrel cage and Slip Ring Induction motor

Slip Ring Motor	Squirrel Cage Motor
It has a rotor of wound type	Its rotor is of squirrel cage type
Rotor has cylindrical core has parallel slots, in which each slot has a bar	Slots are not parallel to each other
Construction is complicated because of slip rings and brushes	Construction is simple
External resistance circuit is connected with a motor	No external resistance circuit as bars of the rotor is completely slotted
Starting torque is high	Torque is low
Efficiency is low	Efficiency is high

CONCEPT OF ROTATING MAGNETIC FIELD

When a three-phase supply is applied to a three-phase distributed winding of a rotating machine, a **rotating magnetic field** is produced which rotates in synchronous speed.

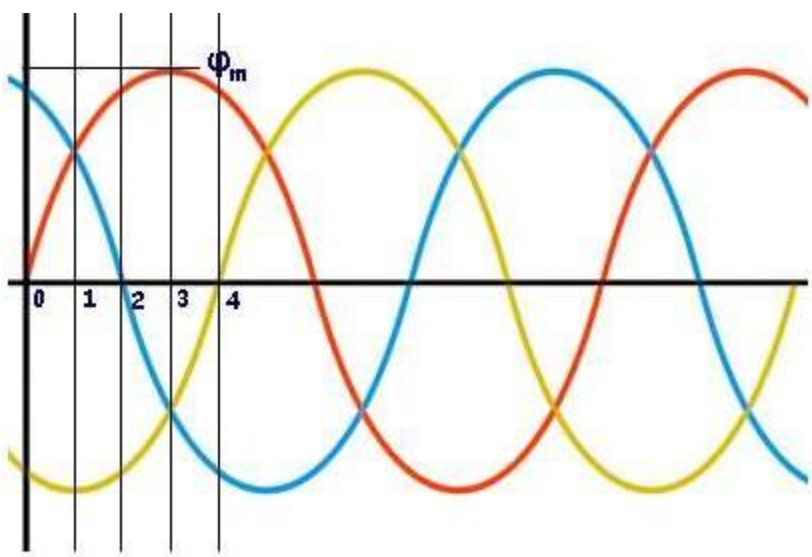
First consider one stator of an electric motor where three-phase winding is physically distributed in the stator core in such a manner that winding of each phase is separated from other by 120o in space.



Although the vector sum of three currents in a balanced three-phase system is zero at any instant, but the resultant of the magnetic fields produced by the currents is not zero rather it will have a constant non-zero value rotating in space in respect to time. The magnetic flux produced by the current in each phase can be represented by the equations given below. This is a similar representation of current is a three-phase system as the flux is cophasial with the current.

$$\phi_R = \phi_m \sin(\omega t)$$
$$\phi_Y = \phi_m \sin(\omega t - 120^o)$$
$$\phi_B = \phi_m \sin(\omega t - 240^o)$$

Where, φ_R, φ_Y and φ_B are the instantaneous flux of corresponding Red, Yellow and Blue phase winding, φ_m amplitude of the flux wave. The flux wave in the space can be represented as shown below.



Now, on the above graphical representation of flux waves, we will first consider the point 0.

Here, the value of φ_R is

$$\phi_R = \phi_m \sin(0) = 0$$

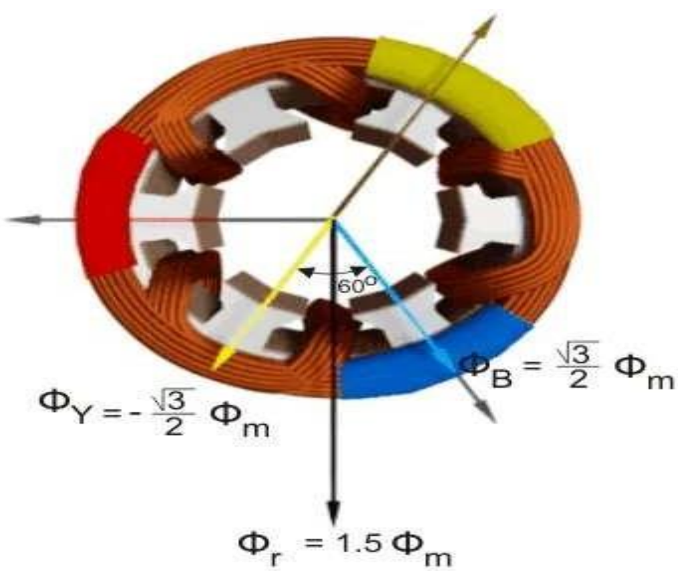
The value of φ_Y is

$$\phi_Y = \phi_m \sin(0 - 120^o) = \phi_m \sin(-120^o) = -\frac{\sqrt{3}}{2}\phi_m$$

The value of φ_B is

$$\phi_B = \phi_m \sin(0 - 240^o) = \phi_m \sin(-240^o) = \frac{\sqrt{3}}{2}\phi_m$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below.



Now, on the above graphical representation of flux waves, we will consider the point 1, where $\omega t = \pi / 6$ or 30^o.

Here, the value of φ_R is

$$\phi_R = \phi_m \sin(30^0) = \frac{1}{2}\phi_m$$

The value of ϕ_Y is

$$\phi_Y = \phi_m \sin(30^o - 120^o) = \phi_m \sin(-90^o) = -\phi_m$$

The value of ϕ_B is

$$\phi_B = \phi_m \sin(30^o - 240^o) = \phi_m \sin(-210^o) = \frac{1}{2}\phi_m$$

The resultant of these fluxes at that instant (φr) is 1.5φm which is shown in the figure below. it is clear that the resultant flux vector is rotated 30o further clockwise without changing its value.

Now, on the graphical representation of flux waves, we will consider the point 2, where ωt = π / 3 or 60 deg.

Here, the value of ϕ_R is

$$\phi_R = \phi_m \sin(60^o) = \frac{\sqrt{3}}{2}\phi_m$$

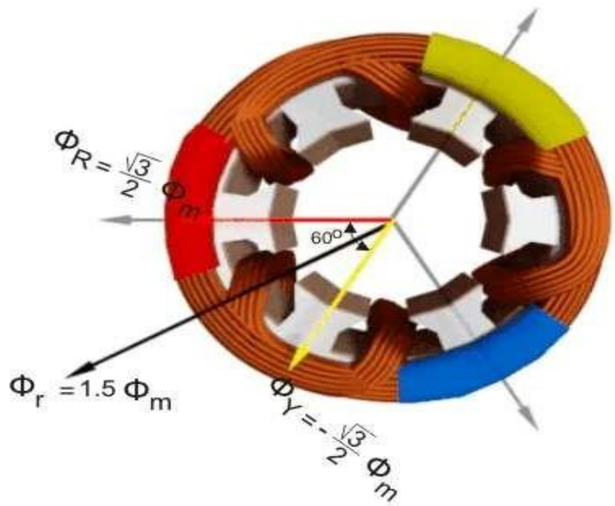
The value of ϕ_Y is

$$\phi_Y = \phi_m \sin(60^o - 120^0) = \phi_m \sin(-60^o) = -\frac{\sqrt{3}}{2}\phi_m$$

The value of ϕ_B is

$$\phi_B = \phi_m \sin(60^o - 240^0) = \phi_m \sin(-180) = 0$$

The resultant of these fluxes at that instant (φr) is 1.5φm which is shown in the figure below. Here it is clear that the resultant flux vector is rotated 30° further clockwise without changing its value.



Now, on the graphical representation of flux waves, we will consider the point 3, where ωt = π / 2 or 90o.

Here, the value of ϕ_R is

$$\phi_R = \phi_m \sin(90^o) = \phi_m$$

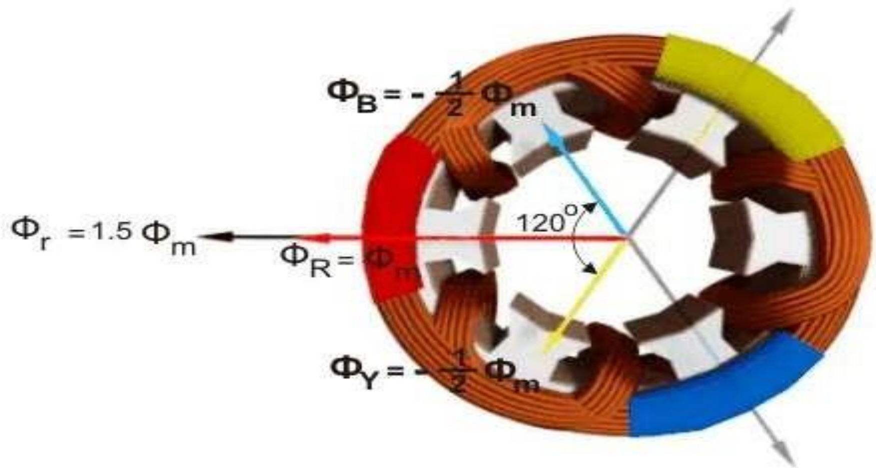
The value of ϕ_Y is

$$\phi_Y = \phi_m \sin(90^o - 120^o) = \phi_m \sin(-30^o) = -\frac{1}{2}\phi_m$$

The value of ϕ_B is

$$\phi_B = \phi_m \sin(90^o - 240^o) = \phi_m \sin(-150^o) = -\frac{1}{2}\phi_m$$

The resultant of these fluxes at that instant (φ_r) is $1.5\varphi_m$ which is shown in the figure below. Here it is clear that the resultant flux vector is rotated 30^o further clockwise without changing its value.



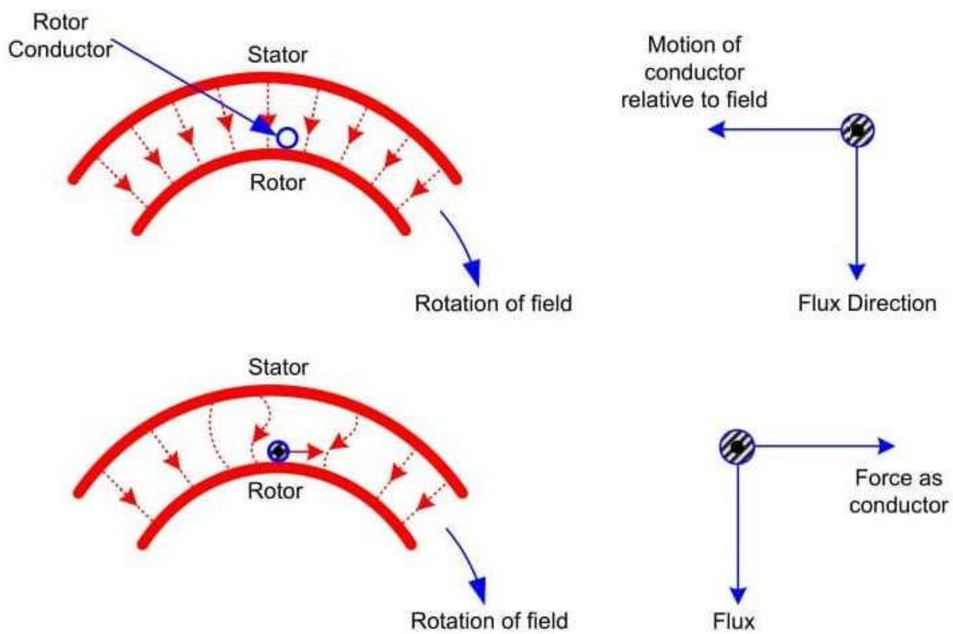
It can be proved that the due to balanced supply applied to the three phase stator winding a rotating or revolving magnetic fields is established in the space.

PRINCIPLE OF OPERATION OF THREE PHASE INDUCTION MOTOR:

The most commonly used AC motor which is also called asynchronous motor because this motor works at less speed as compared to synchronous speed. Here, synchronous speed is nothing but the rotary magnetic field's speed within the stator.

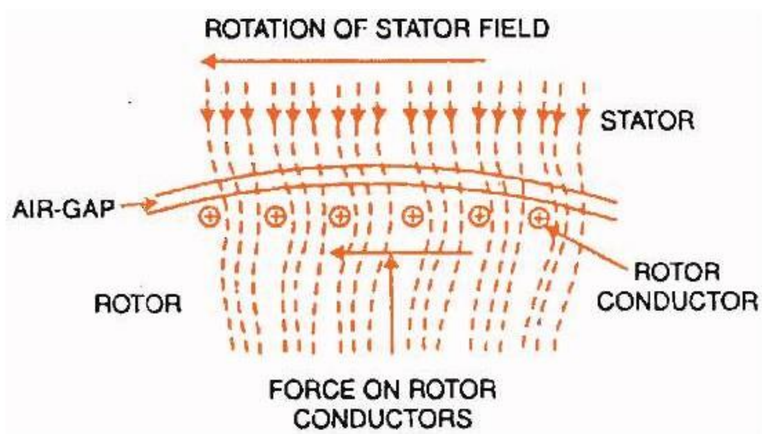
The induction motor works on the principle of induction where an electromagnetic field is induced into the rotor when the rotating magnetic field of the stator cuts the stationary rotor. Induction machines are by far the most common type of motor used in industrial, commercial, or residential settings.

Consider a portion of the three-phase induction motor as shown in the figure.



The working of the three-phase induction motor is based on the principle of electromagnetic induction.

When three-phase stator winding of an induction motor is energized from a 3 phase supply, a **rotating magnetic field** is set up which rotates around the stator at synchronous speed (N_s).



A portion of rotating magnetic field in a three-phase induction motor

Synchronous Speed,

$$N_s = 120\ f/P$$

Where,
f = frequency
P = Number of Poles

This rotating field passes through the air gap and cuts the rotor conductors, which are stationary. An EMF gets induced in every rotor conductor due to the relative speed between the rotating magnetic flux and the stationary rotor. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.

The current-carrying rotor conductors are placed in the magnetic field produced by the stator. Consequently, a **mechanical force** acts on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a **torque** which tends to move the rotor in the same direction as the rotating field.

The fact that the rotor is urged to follow the stator field (i.e., rotor moves in the direction of stator field) can be explained by Lenz's law.

According to Lenz's law, the direction of rotor currents will be such that they tend to oppose the cause of producing them. Now, the cause producing the rotor currents is the relative speed between the rotating field and thestationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of the stator field and tries to catch it. Hence three-phase induction motor starts running.

SLIP AND ITS SIGNIFICANCE IN INDUCTION MOTOR

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 stator 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 in a three-phase induction motor**.

Slip is usually expressed as a percentage of synchronous speed i.e.,

$$\textbf{Slip, } s = (N_s - N)/N_s \times 100\ \%$$

The quantity N s – N is sometimes called **slip speed**.

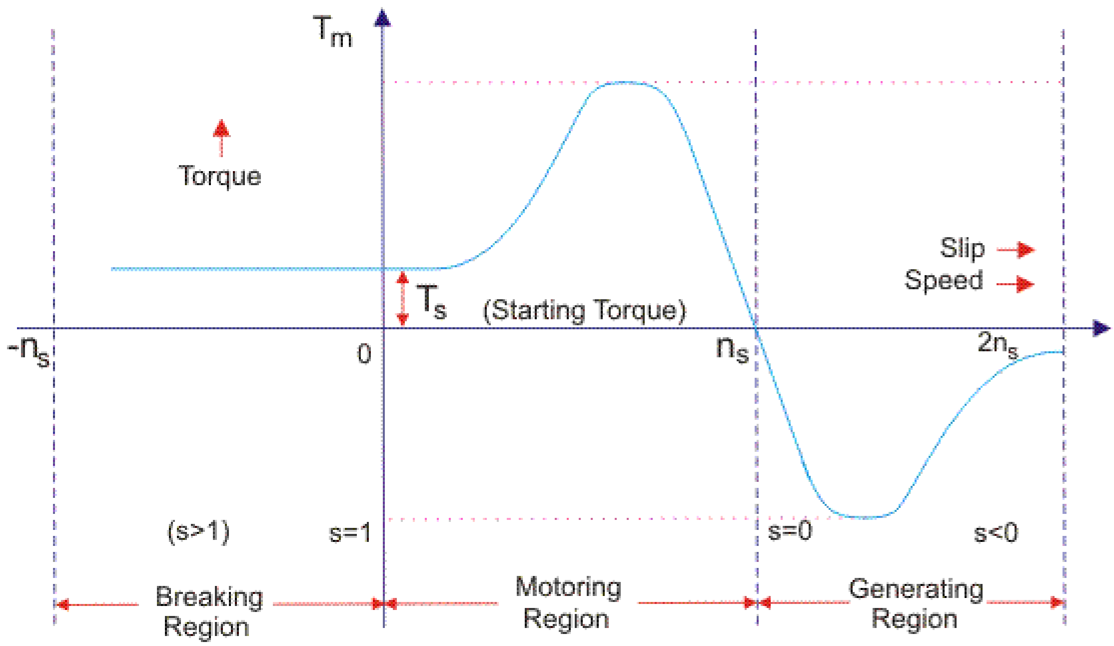
When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.

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**.

TORQUE SLIP CHARACTERISTICS OF THREE PHASE INDUCTION MOTOR

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip. The slip is defined as the ratio of difference of synchronous speed and actual rotor speed to the synchronous speed of the machine. The variation of slip can be obtained with the variation of speed that is when speed varies the slip will also vary and the torque corresponding to that speed will also vary.

The torque slip curve has three modes of operation as shown below.



Torque Slip Curve for Three Phase Induction Motor

Motoring Mode:

In this mode of operation, supply is given to the stator sides and the motor always rotates below the synchronous speed. The induction motor torque varies from zero to full load torque as the slip varies. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip.

That is, more is the slip, more will be the torque produced and vice-versa. The linear relationship simplifies the calculation of motor parameter to great extent.

Generating Mode:

In this mode of operation induction motor runs above the synchronous speed and it should be driven by a prime mover. The stator winding is connected to a three phase supply in which it supplies electrical energy. Actually, in this case, the torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy. Induction motor is not much used as generator because it requires reactive power for its operation.

That is, reactive power should be supplied from outside and if it runs below the synchronous speed by any means, it consumes electrical energy rather than giving it at the output. So, as far as possible, induction generators are generally avoided.

Braking Mode:

In the Braking mode, the two leads or the polarity of the supply voltage is changed so that the motor starts to rotate in the reverse direction and as a result the motor stops. This method of braking is known as plugging. This method is used when it is required to stop the motor within a very short period of time. The kinetic energy stored in the revolving load is dissipated as heat. Also, motor is still receiving power from the stator which is also dissipated as heat. So as a result of which motor develops enormous heat energy. For this stator is disconnected from the supply before motor enters the braking mode.

If load which the motor drives accelerates the motor in the same direction as the motor is rotating, the speed of the motor may increase more than synchronous speed. In this case, it acts as an induction generator which supplies electrical energy to the mains which tends to slow down the motor to its synchronous speed, in this case the motor stops. This type of breaking principle is called dynamic or regenerative breaking.

SINGLE PHASE MOTORS:

There are two basic reasons for the use of single-phase motors rather than 3-phase motors.

1. For reason of economy, most houses, offices and also rural areas are supplied with single phase a.c, as power requirements of individual load items are rather small.
2. The economics of the motor and its branch circuit.
   - Fixed loads requiring not more than 0.5KW can generally be served most economically with single phase power and a single phase motor.
   - Single phase motors are simple in construction, reliable, easy to repair and comparatively cheaper in cost and therefore, find wide use in fans, refrigerators, vacuum cleaners, washing machines, other kitchen equipment, tools, blowers, centrifugal pumps, small farming appliances etc.

Because of above reasons motors of comparatively small ratings (mostly in fractional KW ratings) are manufactured in large number to operate on single phase ac at standard frequencies. An indication of the number of such motors can be had from the fact that the sum of total of all fractional kilowatt motors in use today far exceeds the total of integral kilowatt motors of all types.

TYPES OF SINGLE-PHASE MOTOR:

The Single phase motors may be of the following types:

1. **Single-phase Induction Motors:**
   - A. Split-phase motors
     - (i) Resistance-start motor
     - (ii) Capacitor-start motor
     - (iii) Permanent-split (single-value) capacitor motor
     - (iv) Two-value capacitor motor.
   - B. Shaded-pole induction motor.

C. Reluctance-start induction motor.
D. Repulsion-start induction motor.

2. Commutator-Type, Single-Phase Motors:

A. Repulsion motor.
B. Repulsion-induction motor.
C. A.C series motor.
D. Universal motor.

3. Single-phase Synchronous Motors:

A. Reluctance motor.
B. Hysteresis motor.
C. Sub-synchronous motor.

SINGLE-PHASE INDUCTION MOTORS

Applications:

- Single phase induction motors are in very wide use in industry especially in fractional horse-power field.

  They are extensively used for electrical drive for low power constant speed apparatus such as machine tools, domestic apparatus and agricultural machinery in circumstances where a three-phase supply is not readily available.
- Single phase induction motors sizes vary from 1/400 kw to 1/25 kw are used in toys, hair dryers, vending machines etc.
- Universal motor is widely used in portable tools, vacuum cleaners& kitchen equipment.

Though these machines are useful for small outputs, they are not used for large powers asthey suffer from many disadvantages and are never used in cases where three-phase machinescan be adopted.

The main disadvantages of single-phase induction motors are:

1. Their output is only 50% of the three-phase motor, for a given frame size and temperature rise.

2. They have lower power factor.
3. Lower efficiency.
4. These motors do not have inherent starting torque.
5. More expensive than three-phase motors of the same output.
6. Low overload capacity.

CONSTRUCTION OF SINGLE PHASE INDUCTION MOTOR:

Single phase induction motor is very simple and robust in construction. The stator carries a distributed winding in the slots cut around the inner periphery. The stator conductors have low resistance and they are winding called Starting winding is also mounted on the stator. This winding has high resistance and its embedded deep inside the stator slots, so that they have considerable inductance. The rotor is invariably of the squirrel cage type. In practice, in order to convert temporarily the single phase motor into two-phase motor, auxiliary conductors are placed in the upper layers of stator slots. The auxiliary winding has a centrifugal switch in series with it. The function of the switch is to cut off the starting winding, when the rotor has accelerated to about 75% of its rated speed. In capacitor-start motors, an electrolytic capacitor of suitable capacitance value is also incorporated in the starting winding circuit.

The main stator winding and auxiliary (or starting) winding are joined in parallel, and there is an arrangement by which the polarity of only the starting winding can be reversed. This is necessary for changing the direction of rotation of the rotor.

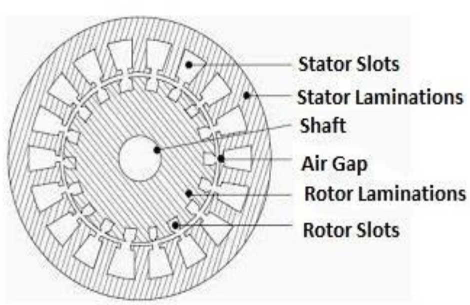


Fig: 4.1

A 1-phase induction motor is similar to a 3-phase squirrel cage induction motor in physical appearance. The rotor is same as that employed in 3-phase squirrel cage induction motor. There is uniform air gap between stator and rotor but no electrical connection between them.

Although single phase induction motor is more simple in construction and is cheaper than a 3-phase induction motor of the same frame size, it is less efficient and it operates at lower power factor.

WORKING OF SINGLE-PHASE INDUCTION MOTOR:

A single phase induction motor is inherently not self-staring can be shown easily.

Consider a single phase induction motor whose rotor is at rest. Let a single phase a.c. source be connected to the stator winding (it is assumed that there is no starting winding). Let the stator be wound for two poles.

When power supply for the stator is switched on, an alternating current flows through the stator winding. This sets up an alternating flux. This flux crosses the air gap and links with the rotor conductors. By electromagnetic induction e.m.f.'s are induced in the rotor conductors. Since the rotor forms a closed circuit, currents are induced in the rotor bars. Due to interaction between the rotor induced currents and the stator flux, a torque is produced. It is readily seen that if all rotor conductors in the upper half come under a stator N pole, all rotor conductors in the lower half come under a stator S pole. Hence the upper half of the rotor is subjected to a torque which tends to rotate it in one direction and the lower half of the rotor is acted upon by an equal torque which tends to rotate it in the opposite direction. The two equal and opposite torques cancel out, with the result that the net driving torque is zero. Hence the rotor remains stationary. Thus the single phase motor fails to develop starting torque.

This argument holds good irrespective of the number of stator poles and the polarity of the stator winding. The net torque acting on the rotor at standstill is zero.

If, however, the rotor is in motion in any direction when supply for the stator is switched on, it can be shown that the rotor develops more torque in that direction. The net torque then, would have non-zero value, and under its impact the rotor would speed up in its direction.

The analysis of the single phase motor can be made on the basis of two theories:

i. Double revolving field theory, and
ii. Cross field theory.

DOUBLE REVOLVING FIELD THEORY:

This theory makes use of the idea that an alternating uni-axial quantity can be represented by two oppositely-rotating vectors of half magnitude. Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously in opposite direction.

As shown in figure:4.2 (a) let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each equal to $\phi_m/2$ revolving in anti-clockwise and clockwise directions respectively.

After some time, when A and B would have rotated through angle +Θ and – Θ, as in figure: 4.2(b), the resultant flux would be

$$= 2*\frac{\phi_m}{2}\cos\frac{2\theta}{2} = \phi_m \cos\theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositely-directed as shown in figure: 4.2(c) so that the resultant flux would be zero.

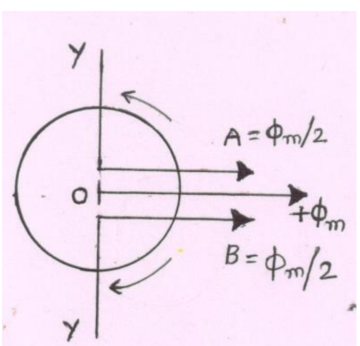


Fig: 4.2(a)

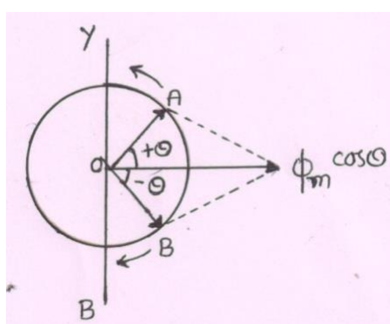


Fig: 4.2(b)

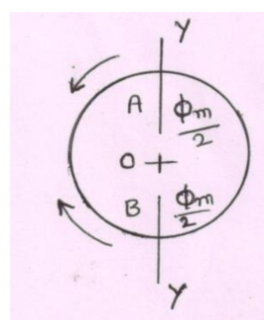


Fig: 4.2(c)

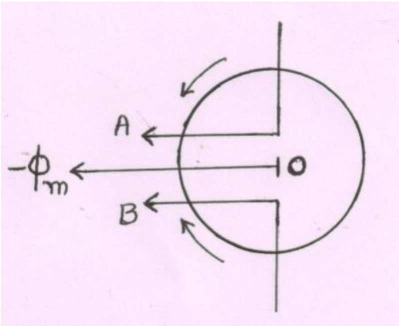


Fig: 4.2(d)

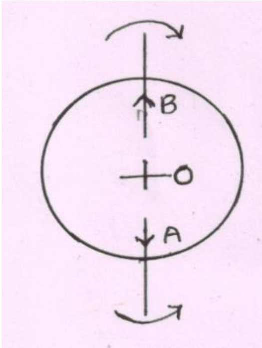


Fig: 4.2(e)

After half a cycle, fluxes A and B will have a resultant of $-2*\frac{\phi_m}{2} = -\phi_m$. After three quarters of a cycle, again the resultant is zero, as shown in figure: 4.2(e) and so on. If we plot thevalues of resultant flux against Θ between limits $\Theta=0^0$ to $\Theta=360^0$, then a curve similar to theone shown in figure: 4.3 is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions.

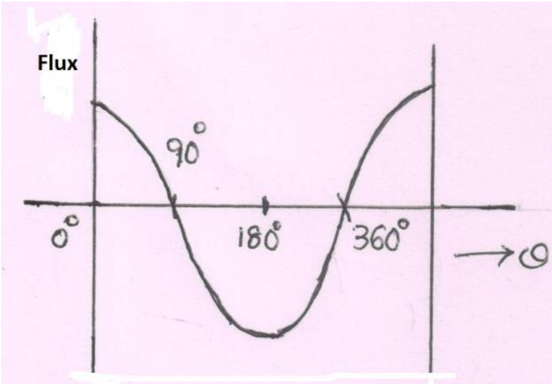


Fig: 4.3

It may be noted that if the slip of the rotor is S with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2-S).

Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an e.m.f. and this produces its own torque. Obviously, the two torques (called forward and backward torques) are oppositely-directed, so that the net or resultant torques is equal to their difference as shown in fig: 4.4

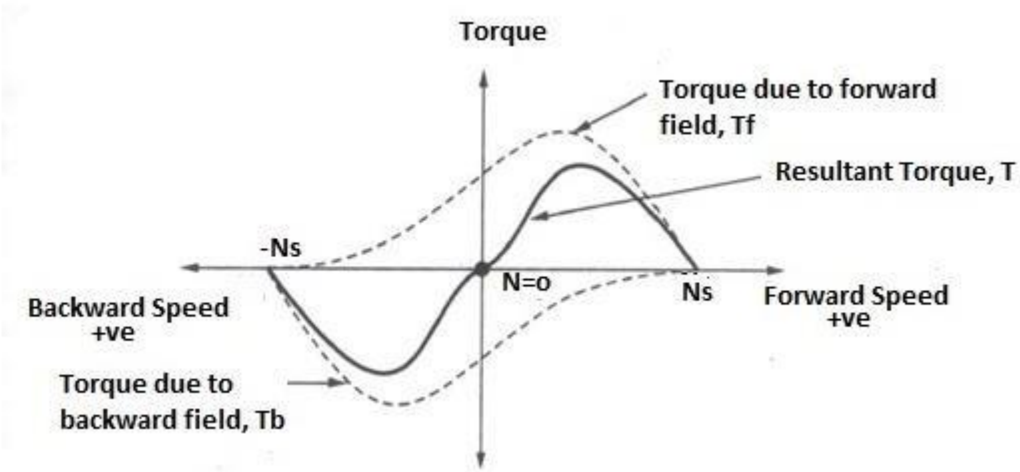


Fig: 4.4 Torque-Speed characteristics

Fig: 4.4 shows both torques and the resultant torque for slips between zero and +2. At standstill, S=1 and (2-S) =1. Hence, T_f and T_b are numerically equal but, being oppositely directed, produce no resultant torque. That explains why there is no starting torque in a single-phase induction motor.

However, if the rotor is started somehow, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

Problems on Induction Motors	
Q1	A 3 phase, 4 pole, 440 V, 50 Hz induction motor runs with a slip of 4%. Find the rotor speed and frequency of the rotor current. $N_S = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1{,}500$ r.p.m. $S = \frac{N_s - N}{N_s}$ i.e. $0.04 = \frac{1{,}500 - N}{1{,}500}$ $\therefore\ N = 1{,}440$ r.p.m. $f' = S\,f = 0.04 \times 50 = 2$ Hz = frequency of rotor current
Q2	The frequency of the e.m.f. in the stator of a 4 pole induction motor is 50 Hz and that in the rotor is 1½ HZ. What is the slip and at what speed the motor is running? $f' = S\,f$ i.e. $\frac{3}{2} = S \times 50$, $\therefore\ S = 0.03$ $N_S = \frac{120\,f}{P} = \frac{120 \times 50}{4} = 1{,}500$ r.p.m. $S = \frac{N_s - N}{N_s}$ i.e. $0.03 = \frac{1{,}500 - N}{1{,}500}$ $\therefore\ N = 1455$ r.p.m.
Q3	A 6 pole induction motor is connected to a 50 Hz supply. It is running at a speed of 970 r.p.m. Find the synchronous speed and the slip. $N_S = \frac{120\,f}{P} = \frac{120 \times 50}{6} = 1{,}000$ r.p.m. $S = \frac{N_s - N}{N_s} = \frac{1{,}000 - 970}{1{,}000} = 0.03$

Q4	**A 10 pole induction motor is supplied by a 6 pole alternator, which is driven at 1200 r.p.m. If the motor runs with a slip of 3%, what is its speed?** *For alternator:* $N = \frac{120f}{P}$ i.e. $1200 = \frac{120f}{6}$, $\therefore f = 60$ Hz *For induction motor:* $N_S = \frac{120f}{P} = \frac{120 \times 60}{10} = 720$ r.p.m. $S = \frac{N_s - N}{N_s}$ i.e. $0.03 = \frac{720 - N}{720}$ $\therefore N = 698.4$ r.p.m.
Q5	**A 4 pole, 50 Hz induction motor has a slip of 1 % at no load. When operated at full load, the slip is 2.5%. Find the change in speed from no load to full load.** *On no load:* $N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1{,}500$ r.p.m. $S = \frac{N_S - N}{N_S}$ i.e. $0.01 = \frac{1{,}500 - N_0}{1{,}500}$ $\therefore N_0 =$ No load speed $= 1{,}485$ r.p.m. *On full load:* $S = \frac{N_S - N}{N_S}$ i.e. $0.025 = \frac{1{,}500 - N}{1{,}500}$ $\therefore N =$ Full load speed $= 1{,}462.5$ r.p.m. $\therefore$ Change in speed $= N_0 - N = 1{,}485 - 1{,}462.5 = 22.5$ r.p.m.

Q6	**A 12 pole, 3 phase alternator is coupled to an engine running at 500 r.p.m. It supplies an induction motor which has a full load speed of 1,440 r.p.m. Find the percentage slip and the number of poles of the motor.** $f = \frac{PN}{120} = \frac{12 \times 500}{120} = 50$ Hz (from alternator data) N_S for induction motor is assumed to be 1,500 r.p.m. as the actual speed is 1,440 r.p.m. $N_S = \frac{120 f}{P}$ i.e. $1{,}500 = \frac{120 \times 50}{P}$, $\therefore P = 4$ $\% \text{ slip} = \frac{N_s - N}{N_s} \times 100 = \frac{1{,}500 - 1{,}440}{1{,}500} \times 100 = 4\%$
Q7	**A 12 pole, 3 phase, 50 Hz alternator is driven by a 440 V, 3 phase 6 pole induction motor running at a slip of 3%. Find the frequency of the e.m.f. generated by the alternator** *For induction motor:* $N_S = \frac{120 f}{P} = \frac{120 \times 50}{6} = 1{,}000$ r.p.m. $N = N_S (1 - S) = 1000 (1 - 0.03) = 970$ r.p.m. The alternator is driven by induction motor. Hence, the speed of the alternator is 970 r.p.m. *For alternator :* $f = \frac{PN}{120} = \frac{12 \times 970}{120} = 97$ Hz
Q8	**A 3 phase, 4 pole, 400V, 50 Hz induction motor runs with a slip of 4%. Find the rotor speed and frequency.** $N_S = \frac{120 f}{P} = \frac{120 \times 50}{4} = 1{,}500$ r.p.m. $S = \frac{N_s - N}{N_s}$ i.e. $0.04 = \frac{1{,}500 - N}{1{,}500}$ $\therefore N = 1{,}440$ r.p.m. $f' = S f = 0.04 \times 50 = 2$ Hz

Q9	**A 3 phase induction motor has 6 poles and runs at 960 r.p.m. on full load. It is supplied from an alternator having 4 poles and running at 1,500 r.p.m. Calculate the full load slip and the frequency of the rotor currents of the induction motor.** $f = \frac{PN}{120} = \frac{4 \times 1500}{120} = 50$ Hz (from alternator data) *For induction motor :* $N_S = \frac{120 f}{P} = \frac{120 \times 50}{6} = 1,000$ r.p.m $S = \frac{N_s - N}{N_s} = \frac{1,000 - 960}{1,000} = 0.04$ or 4% $f' = S f = 0.04 \times 50 = 2$ Hz
	Exercise Problems
	:1 A 4 pole, 3 phase, 50 Hz induction motor is running on no load with a slip of 3%. Calculate the speed of the induction motor. **(1,455 r.p.m.)** 2 The rotor current of three phase, 4 pole, 50 Hz induction motor has a frequency of 2 Hz at full load. Calculate the slip and speed at full load. **(0.04, 1,440 r.p.m.)** .3 A 3 phase, 8 pole, 60 Hz induction motor has a rotor e.m.f. of 10 V induced in the rotor winding, at standstill. Calculate the voltage and frequency induced in the rotor winding when it rotates at 864 r.p.m. **(0.4 V, 2.4 Hz)** .4 An 8 pole induction motor is supplied by a 4 pole alternator running at 1,500 r.p.m. If the motor runs with a slip of 4%, what is its speed? **(1,440 r.p.m.)** .5 An 8 pole, 50 Hz induction motor has a slip of 2% on no load. On full load, the slip is 5%. Find the change in speed from no load to full load. **(22.5 r.p.m.)** .6 An 8 pole, three phase alternator is coupled to an engine running at 750 r.p.m. and supplies a three phase induction motor having a full load speed of 1,440 r.p.m. The frequency of the rotor current is 2 Hz. Find the percentage slip and the number of poles of the motor. **(4%, 4)** 7 A 4 pole, three phase induction motor runs at 1,470 r.p.m., when connected to a 50 Hz supply. Find the percentage slip and the frequency of the rotor currents. **(2%, 1 Hz)** 8 An 8 pole, three phase induction motor is supplied at 50 Hz and the frequency of the e.m.f. induced in the rotor is 2 Hz. Find the slip and speed of the motor. **(0.04, 720 r.p.m.)**