Module
8
Three-phase Induction Motor

Lesson 30

Construction and Principle of Operation of IM

In the previous, i.e. first, lesson of this module, the formation of rotating magnetic field in the air gap of an induction motor (IM), has been described, when the three-phase balanced winding of the stator is supplied with three-phase balanced voltage. The construction of the stator and two types of rotor − squirrel cage and wound (slip-ring) one, used for three-phase Induction motor will be presented. Also described is the principle of operation, i.e. how the torque is produced.

Keywords: Three-phase induction motor, cage and wound (slip-ring) rotor, synchronous and rotor speed, slip, induced voltages in stator winding and rotor bar/winding.

After going through this lesson, the students will be able to answer the following questions:

1. How would you identify the two types (cage and wound, or slip-ring) of rotors in three-phase induction motor?
2. What are the merits and demerits of the two types (cage and wound, or slip-ring) of rotors in IM?
3. How is the torque produced in the rotor of the three-phase induction motor?
4. How does the rotor speed differ from synchronous speed? Also what is meant by the term 'slip'?

Construction of Three-phase Induction Motor

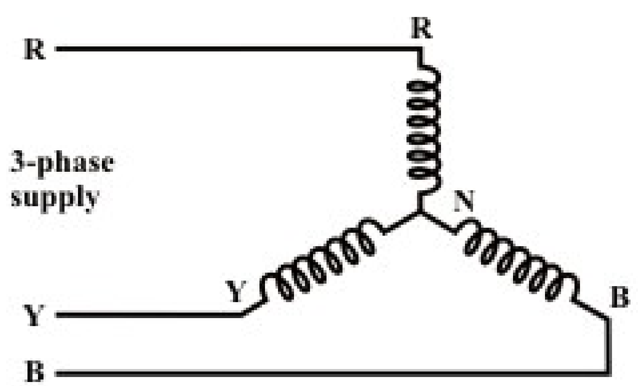

Fig. 30.1: Schematic diagram of the stator windings in a three-phase induction motor.

This is a rotating machine, unlike the transformer, described in the previous module, which is a static machine. Both the machines operate on ac supply. This machine mainly works as a motor, but it can also be run as a generator, which is not much used. Like all rotating machines, it consists of two parts − stator and rotor. In the stator (Fig. 30.1), the winding used is a balanced three-phase one, which means that the number of turns in each phase, connected in star/delta, is equal. The windings of the three phases are placed 120° (electrical) apart, the mechanical angle between the adjacent phases being $[(2\times 120°)/p]$, where p is no. of poles. For a 4-pole (p = 4) stator, the mechanical angle between the winding of the adjacent phases, is $[(2\times120°)/4]=120°/2=60°$, as shown in Fig. 29.4. The conductors, mostly multi-turn, are placed in the slots, which may be closed, or semi-closed, to keep the leakage inductance low. The start and return parts of the winding are placed nearly $180°$, or $(180°-\beta)$ apart. The angle of short chording (β) is nearly equal to $30°$, or close to that value. The short chording results in reducing the amount of copper used for the winding, as the length of the conductor needed for overhang part is reduced. There are also other advantages. The section of the stampings used for both stator and rotor, is shown in Fig. 30.2. The core is needed below the teeth to reduce the reluctance of the magnetic path, which carries the flux in the motor (machine). The stator is kept normally inside a support.

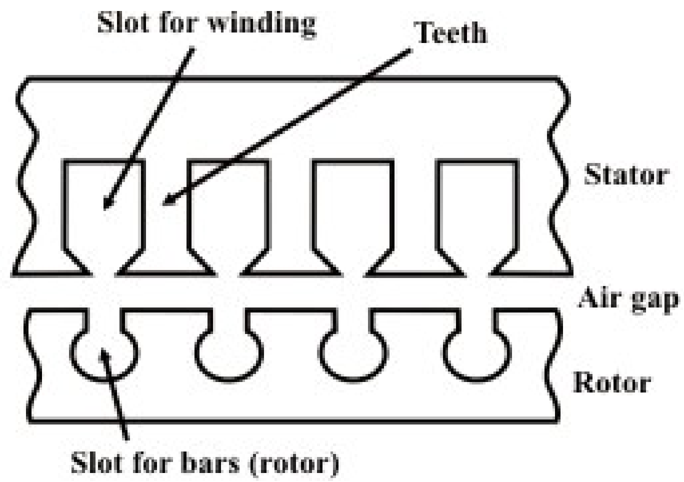

Fig. 30.2: Section for stamping of stator and rotor in IM (not to scale).

There are two types of rotor used in IM, viz. squirrel cage and wound (slip-ring) one. The cage rotor (Fig. 30.3a) is mainly used, as it is cheap, rugged and needs little or no maintainance. It consists of copper bars placed in the slots of the rotor, short circuited at the two ends by end rings, brazed with the bars. This type of rotor is equivalent to a wound (slip-ring) one, with the advantage that this may be used for the stator with different no. of poles. The currents in the bars of a cage rotor, inserted inside the stator, follow the pattern of currents in the stator winding, when the motor (IM) develops torque, such that no. of poles in the rotor is same as that in the stator. If the stator winding of IM is changed, with no. of poles for the new one being different from the earlier one, the cage rotor used need not be changed, thus, can be same, as the current pattern in the rotor bars changes. But the no. of poles in the rotor due to the above currents in the bars is same as no. of poles in the new stator winding. The only problem here is that the equivalent resistance of the rotor is constant. So, at the design stage, the value is so chosen, so as to obtain a certain value of the starting torque, and also the slip at full load torque is kept within limits as needed.

The other type of rotor, i.e., a wound rotor (slip ring) used has a balanced three-phase winding (Fig. 30.3b), being same as the stator winding, but no. of turns used depends on the voltage in the rotor. The three ends of the winding are brought at the three slip-rings, at which points external resistance can be inserted to increase the starting torque requirement. Other three ends are shorted inside. The motor with additional starting resistance is costlier, as this type of rotor is itself costlier than the cage rotor of same power rating, and additional cost of the starting resistance is incurred to increase the starting torque as required. But the slip at full load torque is lower than that of a cage rotor with identical rating, when no additional resistance is used, with direct short-circuiting at the three slip-ring terminals. In both types of rotor, below the teeth, in which bars of a cage rotor, or the conductors of the rotor winding, are placed, lies the iron core, which carries the flux as is the case of the core in the stator. The shaft of the rotor passes below the rotor core. For large diameter of the rotor, a spider is used between the rotor core and the shaft. For a wound (slip-ring) rotor, the rotor winding must be designed for same no. of poles as used for the stator winding. If the no. of poles in the rotor winding is different from no. of poles in the stator winding, no torque will be developed in the motor. It may be noted that this was not the case with cage rotor, as explained earlier.

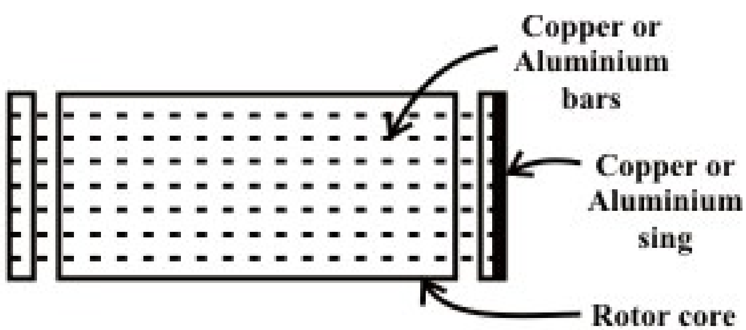

Fig. 30.3(a): Squirrel cage rotor of induction motor

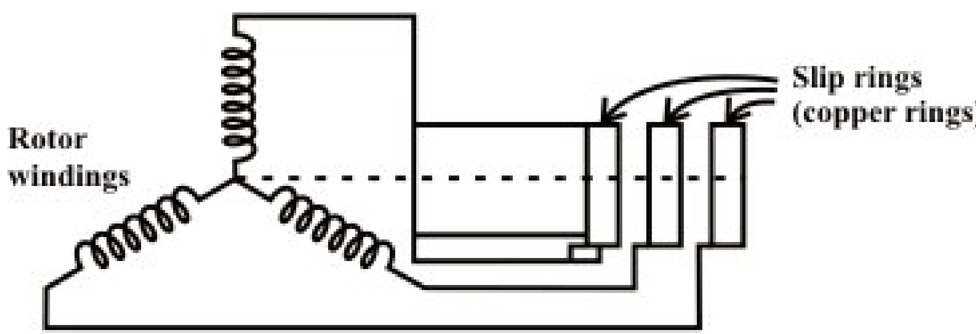

Fig. 30.3(b): Wound rotor (slip ring) of induction motor

The wound rotor (slip ring) shown in Fig. 30.3 (b) is shown as star-connected, whereas the rotor windings can also be connected in delta, which can be converted into its equivalent star configuration. This shows that the rotor need not always be connected in star as shown. The No. of rotor turns changes, as the delta-connected rotor is converted into star-connected equivalent. This point may be kept in mind, while deriving the equivalent circuit as shown in the next lesson (#31), if the additional resistance (being in star) is connected through the slip rings, in series with the rotor winding

Principle of Operation

The balanced three-phase winding of the stator is supplied with a balanced three-phase voltage. As shown in the previous lesson (#29), the current in the stator winding produces a rotating magnetic field, the magnitude of which remains constant. The axis of the magnetic field rotates at a synchronous speed ($n_s = (2 \cdot f)/p$), a function of the supply frequency (f), and number of poles (p) in the stator winding. The magnetic flux lines in the air gap cut both stator and rotor (being stationary, as the motor speed is zero) conductors at the same speed. The emfs in both stator and rotor conductors are induced at the same frequency, i.e. line or supply frequency, with No. of poles for both stator and rotor windings (assuming wound one) being same. The stator conductors are always stationary, with the frequency in the stator winding being same as line frequency. As the rotor winding is short-circuited at the slip-rings, current flows in the rotor windings. The electromagnetic torque in the motor is in the same direction as that of the rotating magnetic field, due to the interaction between the rotating flux produced in the air gap by the current in the stator winding, and the current in the rotor winding. This is as per Lenz's law, as the developed torque is in such direction that it will oppose the cause, which results in the current flowing in the rotor winding. This is irrespective of the rotor type used − cage or wound one, with the cage rotor, with the bars short-circuited by two end-rings, is considered equivalent to a wound one The current in the rotor bars interacts with the air-gap flux to develop the torque, irrespective of the no. of poles for which the winding in the stator is designed. Thus, the cage rotor may be termed as universal one. The induced emf and the current in the rotor are due to the relative velocity between the rotor conductors and the rotating flux in the air-gap, which is maximum, when the rotor is stationary ($n_r = 0.0$). As the rotor starts rotating in the same direction, as that of the rotating magnetic field due to production of the torque as stated earlier, the relative velocity decreases, along with lower values of induced emf and current in the rotor. If the rotor speed is equal that of the rotating magnetic field, which is termed as synchronous speed, and also in the same direction, the relative velocity is <u>zero</u>, which causes both the induced emf and current in the rotor to be reduced to zero. Under this condition, torque will <u>not</u> be produced. So, for production of positive (motoring) torque, the rotor speed must always be lower than the synchronous speed. The rotor speed is never equal to the synchronous speed in an IM. The rotor speed is determined by the mechanical load on the shaft and the total rotor losses, mainly comprising of copper loss.

The difference between the synchronous speed and rotor speed, expressed as a ratio of the synchronous speed, is termed as 'slip' in an IM. So, slip (s) in pu is

$$s = \frac{n_s - n_r}{n_s} = 1 - \frac{n_r}{n_s} \qquad \text{or,} \quad n_r = (1-s) \cdot n_s$$

where, n_s and n_r are synchronous and rotor speeds in rev/s.

In terms of $N_s = 60 \times n_s$ and $N_r = 60 \times n_r$, both in rev/min (rpm), slip is

$$s = (N_s - N_r)/N_s$$

If the slip is expressed in %, then $s = [(N_s - N_r)/N_s] \times 100$

Normally, for torques varying from no-load (≈ zero) to full load value, the slip is proportional to torque. The slip at full load is 4-5% (0.04-0.05).

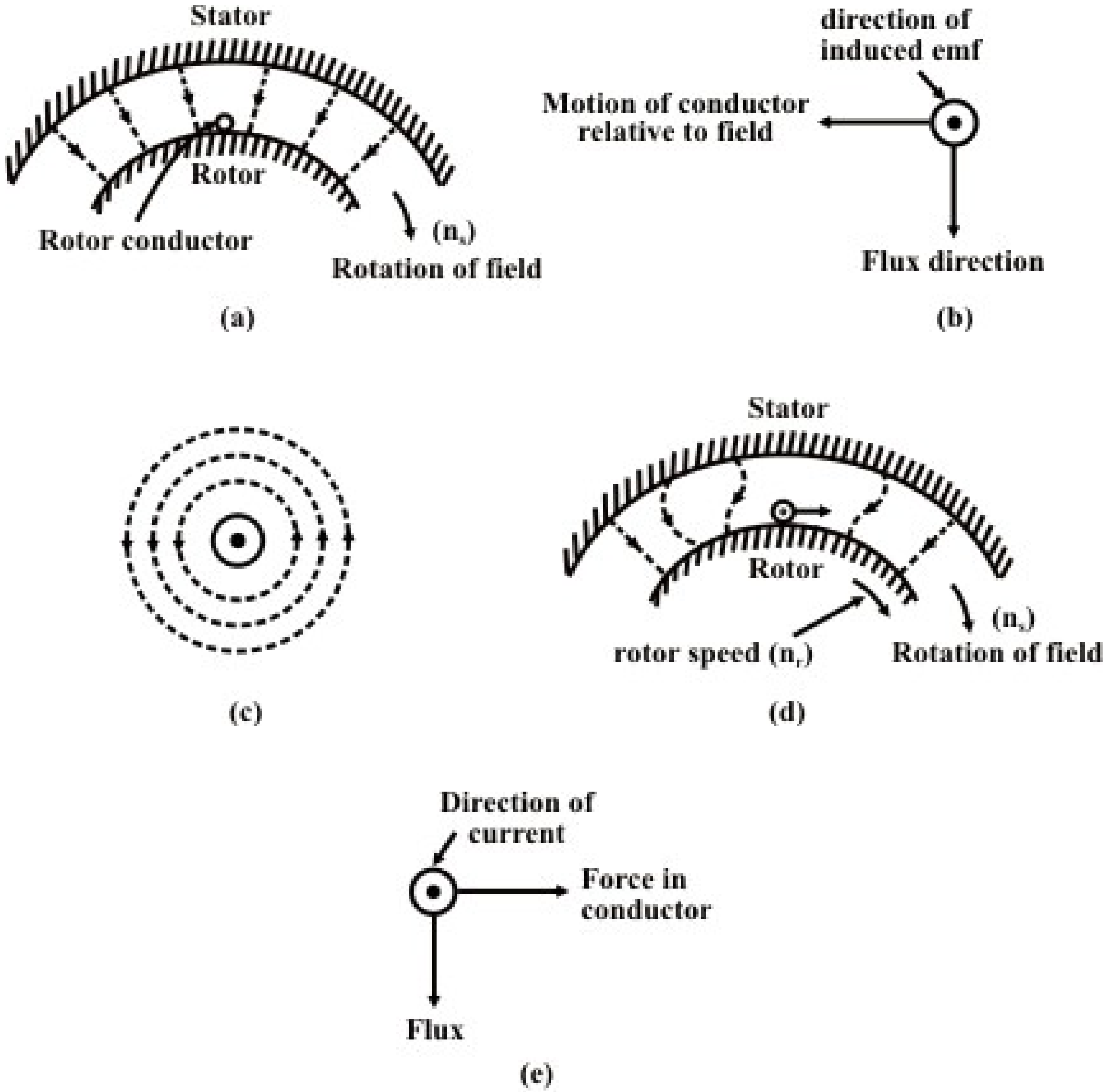

Fig. 30.4: Production of torque

An alternative explanation for the production of torque in a three-phase induction motor is given here, using two rules (right hand and left hand) of Fleming. The stator and rotor, along with air-gap, is shown in Fig. 30.4a. Both stator and rotor is shown there as surfaces, but without the slots as given in Fig, 30.2. Also shown is the path of the flux in the air gap. This is for a section, which is under North pole, as the flux lines move from stator to rotor. The rotor conductor shown in the figure is at rest, i.e., zero speed (stand-still). The rotating magnetic field moves past the conductor at synchronous speed in the clockwise direction. Thus, there is relative movement between the flux and the rotor conductor. Now, if the magnetic field, which is rotating, is assumed to be at standstill as shown in Fig. 30.4b, the conductor will move in the direction shown. So, an emf is induced in the rotor conductor as per Faraday's law, due to change in flux linkage. The direction of the induced emf as shown in the figure can be determined using Fleming's right hand rule.

As described earlier, the rotor bars in the cage rotor are short circuited via end rings. Similarly, in the wound rotor, the rotor windings are normally short-circuited externally via the slip rings. In both cases, as emf is induced in the rotor conductor (bar), current flows there, as it is short circuited. The flux in the air gap, due to the current in the rotor conductor is shown in Fig. 30.4c. The flux pattern in the air gap, due to the magnetic fields produced by the stator windings and the current carrying rotor conductor, is shown in Fig. 304d. The flux lines bend as shown there. The property of the flux lines is to travel via shortest path as shown in Fig. 30.4a. If the flux lines try to move to form straight line, then the rotor conductor has to move in the direction of the rotating magnetic field, but not at the same speed, as explained earlier. The current carrying rotor conductor and the direction of flux are shown in Fig. 30.4e. It is known that force is produced on the conductor carrying current, when it is placed in a magnetic field. The direction of the force on the rotor conductor is obtained by using Fleming's left hand rule, being same as that of the rotating magnetic field. Thus, the rotor experiences a motoring torque in the same direction as that of the rotating magnetic field. This briefly describes how torque is produced in a three-phase induction motor.

The frequency of the induced emf and current in the rotor

As given earlier, both the induced emf and the current in the rotor are due to the relative velocity between the rotor conductors and the rotating flux in the air-gap, the speed of which is the synchronous speed ($N_s = (120 \times f)/p$). The rotor speed is

$$N_r = (1 - s) \cdot N_s$$

The frequency of the induced emf and current in the rotor is

$$f_r = p \cdot (n_s - n_r) = s \cdot (p \cdot n_s) = s \cdot f$$

For normal values of slip, the above frequency is small. Taking an example, with full load slip as 4% (0.04), and supply (line) frequency as 50 Hz, the frequency (Hz) of the rotor induced emf and current, is $f_r = 0.04 \times 50.0 = 2.0$, which is very small, whereas the frequency (f) of the stator induced emf and current is 50 Hz, i.e. line frequency. At standstill, i.e. rotor stationary ($n_r = 0.0$), the rotor frequency is same as line frequency, as shown earlier, with slip [s = 1.0 (100%)]. The reader is requested to read the next lesson (#31), where some additional points are included in this matter. Also to note that the problems are given there (#31).

In this lesson – the second one of this module, the construction of a three-phase Induction Motor has been presented in brief. Two types of rotor – squirrel cage and wound (slip-ring) ones, along with the stator part, are described. Then, the production of torque in IM, when the balanced stator winding is fed from balanced three-phase voltage, with the balanced rotor winding in a wound one being short-circuited, is taken up. In the next lesson, the equivalent circuit per phase of IM will be derived first. Then, the complete power flow diagram is presented.