5 Polyphase Induction Machines

5.1 INTRODUCTION TO POLYPHASE INDUCTION MACHINES

An *induction motor* is one in which alternating current is supplied to the stator directly and to the rotor by induction or transformer action from the stator. As in the synchronous machine, the stator winding is of the type discussed in Section 4. When excited from a balanced polyphase source, it will produce a magnetic field in the air gap rotating at synchronous speed $n_S=60f/p$ as determined by the number of stator poles and the applied stator frequency.

The rotor of a polyphase induction machine may be one of two types. A *wound rotor* is built with a polyphase winding similar to, and wound with the same number of poles as, the stator. The terminals of the rotor winding are connected to insulated slip rings mounted on the shaft. Carbon brushes bearing on these rings make the rotor terminals available external to the motor, Wound-rotor induction machines are relatively uncommon, being found only in a limited number of specialized applications.

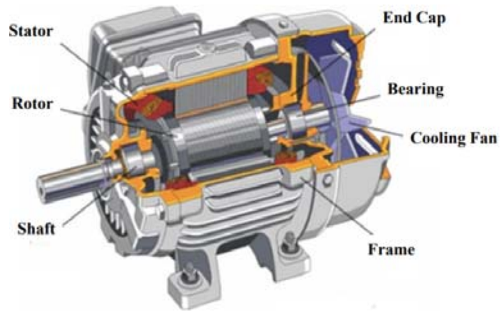

Figure 1 Cutaway view of a three-phase squirrel-cage motor. The rotor cutaway shows the squirrel-cage laminations.

On the other hand, the polyphase induction motor shown in cutaway in Fig. 1 has a *squirrel-cage rotor* with a winding consisting of conducting bars embedded in slots in the rotor iron and short-circuited at each end by conducting end rings. The extreme simplicity and ruggedness of the squirrel-cage construction are outstanding advantages of this type of induction motor and make it by far the most commons used type of motor in sizes ranging from fractional horsepower on up. Figure 2a shows the rotor of a small squirrel-cage motor while Fig. 2b shows the squirrel cage itself after the rotor laminations have been chemically etched away.

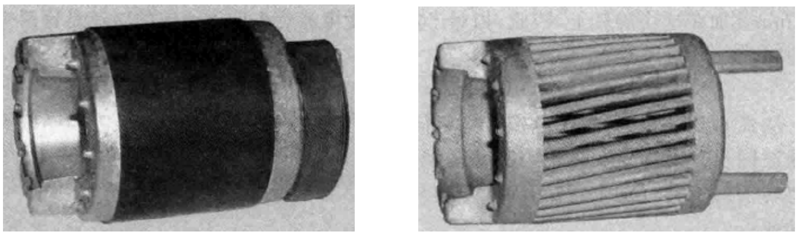

Figure 2 (a) The rotor of a small squirrel-cage motor. (b) The squirrel-cage structure after the rotor laminations have been chemically etched away.

Let us assume that the rotor is turning at the steady speed of n r/min in the same direction as the rotating stator field. Let the synchronous speed of the stator field be n_S r/min as given by $n_S=60f/p$. The difference between synchronous speed and the rotor speed is commonly referred to as the slip of the rotor; in this case the rotor slip is n_S-n, as measured in r/min. Slip is most commonly defined as a fraction of synchronous speed as

$$s=(n_S-n)/n_S \tag{1}$$

In is this definition of slip which is used in the equations which characterize the performance of induction machines as developed in this chapter. Finally, slip is often expressed in percent, simply equal to 100 percent times the fractional slip of Eq.1; e.g. a motor operating with a slip of s = 0.025 would be said to be operating at a slip of 2.5 percent.

The rotor speed in r/min can be expressed in terms of the slip and the synchronous speed as

$$n=(1-s)n_s \tag{2}$$

Similarly, the mechanical angular velocity Ω can be expressed in terms of the synchronous angular velocity Ω_s and the slip as

$$\Omega=(1-s)\ \Omega_s \tag{3}$$

The relative motion of the stator flux and the rotor conductors induces voltages of frequency f_2

$$f_2=sf_1 \tag{4}$$

referred to as the slip frequency, in the rotor. Thus, *the electrical behavior of an induction machine is similar to that of a transformer* but with the additional feature of frequency transformation produced by the relative motion of the stator and rotor windings. In fact, a wound-rotor induction machine can be used as a frequency changer.

The rotor terminals of an induction motor are short circuited; by construction in the case of a squirrel-cage motor and externally in the case of a wound-rotor motor. Slip-frequency voltages are induced in the rotor windings by the rotating air gap flux. The rotor currents are then determined by the magnitudes of the induced voltages and the slip-frequency rotor impedance. At starting, the rotor is stationary (n = 0), the slip is unity (s = 1), and the rotor frequency equals the stator frequency f_1. The field produced by the rotor currents therefore revolves at the same speed as the stator field, and a starting torque results, tending to turn the rotor in the direction of rotation of the stator-inducing field. If this torque is sufficient to overcome the opposition to rotation created by the shaft load, the motor will come up to its operating speed. The operating speed can never equal the synchronous speed however, since the rotor conductors would then be stationary with respect to the stator field; no current would be induced in them, and hence no torque would be produced.

With the rotor revolving in the same direction of rotation as the stator field, the frequency of the rotor currents will be sf_1 and they will produce a rotating flux wave which will rotate at sn_s r/min *with respect to the rotor* in the forward direction. But superimposed on this rotation is the mechanical rotation of the rotor at n r/min. Thus, with respect to the stator, the speed of the flux wave produced by the rotor currents is the sum of these two speeds and equals

$$sn_s+n=sn_s+n_s\left(1-s\right)=n_s \tag{5}$$

From Eq. 5 we see that the rotor currents produce an air-gap flux wave which rotates at synchronous speed and hence in synchronism with that produced by the stator currents. Because the stator and rotor fields each rotate synchronously, they are stationary with respect to each other and produce a steady torque, thus maintaining rotation of the rotor. Such torque, which exists for any mechanical rotor speed n other than synchronous speed, is called an *asynchronous torque*.

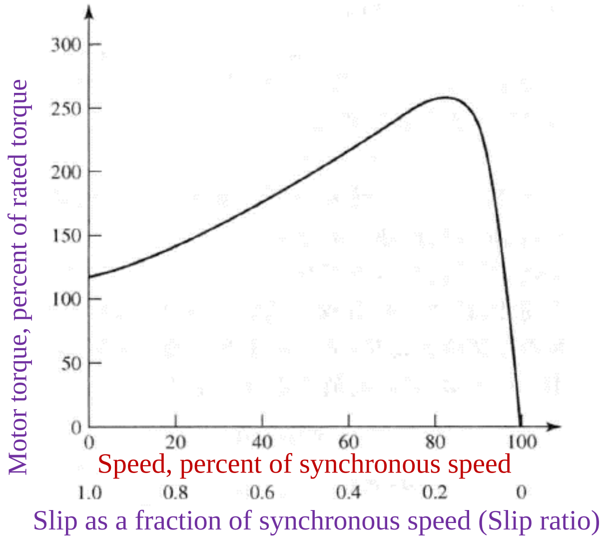

Figure 6.3 Typical induction-motor torque–speed curve for constant-voltage, constant-frequency operation.

Figure 3 shows the form of a typical polyphase squirrel-cage induction motor torque-speed curve. The factors influencing the shape of this curve can be appreciated in terms of the torque equation. Note that the resultant air-gap flux Φ_m in this equation is approximately constant when the stator applied voltage and frequency are constant. Also, recall that the rotor mmf F_2 is proportional to the rotor current I_2. Torque equation can be expressed in the form

$$T_e = K I_2 \sin\delta \qquad (6)$$

where K is a constant and δ is the angle by which the rotor mmf wave lags the resultant air-gap mmf wave.

Under normal running conditions the slip is small: 2 to 10 percent at full load in most squirrel-cage motors. The rotor frequency ($f_2 = sf_1$) therefore is very low; correspondingly on the order of 1 to 5 Hz in 50-Hz motors. For these frequencies, the rotor impedance is largely resistive and hence independent of slip. The rotor-induced voltage, on the other hand, is proportional to slip and lags the resultant air-gap flux by 90^o. Since the rotor windings are short-circuited, the rotor current must be equal to the positive of the voltage induced by the air-gap flux divided by the rotor impedance. Thus, it is very nearly proportional to the slip, and proportional to the rotor voltage. As a result, the rotor-mmf wave lags the resultant air-gap flux by approximately 90 electrical degrees.

Approximate proportionality of rotor current and hence torque with slip is therefore to be expected in the range where the slip is small. As slip increases, the rotor impedance increases because of the increasing contribution of the rotor leakage inductance and the increase of current and torque with slip becomes less than proportional. Also, the rotor current lags farther behind the induced voltage, and the magnitude of sin δ, decreases, further decreasing the resultant torque. A more detailed analysis will show that the torque increases with increasing slip up to a maximum value and then decreases, as shown in Fig.3. The maximum torque, or *breakdown* *torque*, which is typically a factor of two or more larger than the rated motor torque, limits the short-time overload capability of the motor.

We will see that the slip at which the peak torque occurs is proportional to the rotor resistance. For squirrel-cage motors this peak-torque slip is relatively small, much as is shown in Fig. 3. Thus, the squirrel-cage motor is substantially a constant-speed motor having a few percent drop in speed from no load to full load. In the case of a wound-rotor motor, the rotor resistance can be increased by inserting external resistance, hence increasing the slip at peak-torque, and thus decreasing the motor speed for a specified value of torque. Since wound-rotor induction machines are larger, more expensive, and require significantly more maintenance than squirrel-cage machines, this method of speed control is rarely used, and induction machines driven from constant-frequency sources tend to be limited to essentially constant-speed applications. In recent years, the use of solid-state, variable-voltage, variable-frequency drive systems make it possible to readily control the speed of squirrel-cage induction machines and, as a result, they are now widely used in a wide-range of variable-speed applications.

5.2 CURRENTS AND FLUXES IN POLYPHHASE INDUCTION MACHINES

For a coil-wound rotor, the flux-mmf situation can be seen with the aid of Fig, 4. This sketch shows the development of a simple two pole, three phase rotor winding must in a two- pole field. It therefore conforms with the restriction that a wound rotor must have the same number of poles as the stator (although the number of phases need not be the same). The rotor flux -density wave is moving to the right at angular velocity ω_s and at slip angular velocity $s\omega_s$ with respect to the rotor winding, which in turn is rotating to the right at angular velocity (1-s) ω_s. It is shown in Fig.4 in the position of maximum instantaneous voltage in phase a.

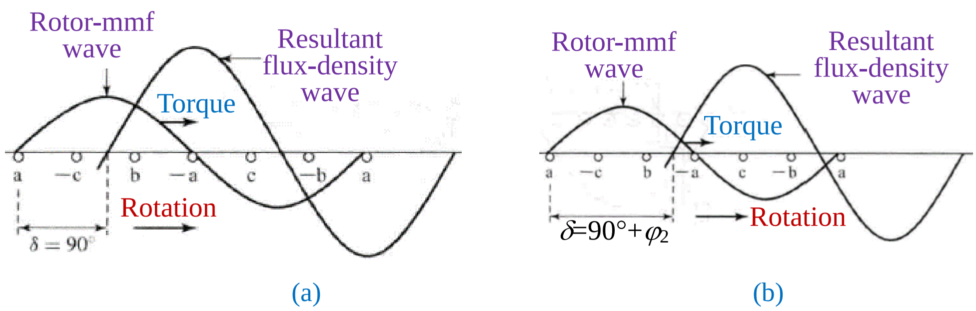

Figure 4 Developed rotor winding of an induction motor with its flux density and mmf waves in their relative positions tor (a) zero and (b) nonzero rotor leakage reactance.

If the rotor leakage reactance, equal to $s\omega_s$ times the rotor leakage inductance, is very small compared with the rotor resistance (which is typically the case at the small slips corresponding to normal operation), the phase-a current will also be a maximum. The rotor-mmf wave will then be centered on phase a; it is so shown in Fig. 4a. The displacement angle, or torque angle, δ, under these conditions is at its optimum value of 90°.

If the rotor leakage reactance is appreciable however, the phase-a current lags the induced voltage by the power-factor angle φ_2 of the rotor leakage impedance. The phase-a current will not be at maximum until a correspondingly later time. The rotor-mmf wave will then not be centered on phase a until the flux wave has traveled φ_2 degrees farther down the gap, as shown in Fig. 4b. The angle δ is now $(90°+\varphi_2)$. In general, therefore, the torque angle of an induction motor is

$$\delta = 90°+\varphi_2 \tag{7}$$

It departs from the optimum value of 90 by the power-factor angle of the rotor leakage impedance at slip frequency. The electromechanical rotor torque is directed toward the right in Fig. 4, or in the direction of the rotating flux wave.

The comparable picture for a squirrel-cage rotor is given in Fig.5. A l6-bar rotor placed in a two-pole field is shown in developed form. To simplify the drawing, only a relatively small number of rotor bars has been chosen and the number is an integral multiple of the number of poles, a choice normally avoided in practice in order to prevent harmful harmonic effects. In Fig. 5a the sinusoidal flux-density wave induces a voltage in each bar which has an instantaneous value indicated by the solid vertical lines.

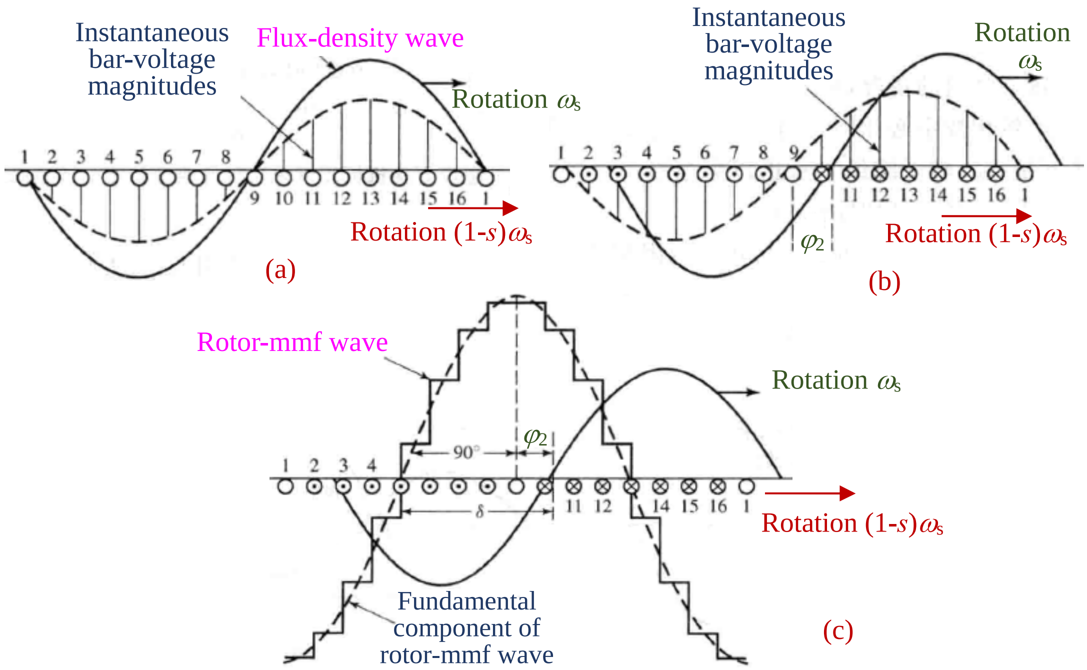

Figure 5 Reactions of a squirrel-cage rotor in a two-pole field.

At a somewhat later instant of time, the bar currents assume the instantaneous values indicated by the solid vertical lines in Fig.5b, the time lag corresponding to the rotor power-factor angle φ_2. In this time interval, the flux-density wave has traveled in its direction of rotation with respect to the rotor through a space angle φ_2 and is then in the position shown in Fig. 5b. The corresponding rotor-mmf wave is shown by the step wave of Fig. 5c. The fundamental component is shown by the dashed sinusoid and the flux density wave by the solid sinusoid. Study of these figures confirms the general principle that the number of rotor poles in a squirrel-cage rotor is determined by the inducing flux wave.