Pearson New International Edition

Electrical Machines, Drives, and Power Systems

Theodore Wildi

Sixth Edition

Pearson New International Edition

Electrical Machines, Drives,
and Power Systems
Theodore Wildi
Sixth Edition

PEARSON

Three-Phase Induction Machines

Introduction

Three-phase induction machines comprise both motors and generators.

Three-phase induction motors are the motors most frequently encountered in industry. They are simple, rugged, low-priced, and easy to maintain. They run at essentially constant speed from zero to full-load. The speed is frequency-dependent and, consequently, these motors are not easily adapted to speed control. However, variable frequency electronic drives are being used more and more to control the speed of commercial induction motors.

In this chapter we cover the basic principles of the 3-phase induction motor and develop the fundamental equations describing its behavior. We then discuss its general construction and the way the windings are made.

Squirrel-cage, wound-rotor, and linear induction motors ranging from a few horsepower to several thousand horsepower permit the reader to see that they all operate on the same basic principles.

In this chapter we will also see that 3-phase induction motors can operate as 3-phase induction generators.

1 Principal components

A 3-phase induction motor (Fig. 1) has two main parts: a stationary stator and a revolving rotor. The rotor is separated from the stator by a small air gap that ranges from 0.4 mm to 4 mm, depending on the power of the motor.

The *stator* (Fig. 2) consists of a steel frame that supports a hollow, cylindrical core made up of stacked laminations. A number of evenly spaced slots, punched out of the internal circumference of the laminations, provide the space for the stator winding.

The *rotor* is also composed of punched laminations. These are carefully stacked to create a series of rotor slots to provide space for the rotor winding. We use two types of rotor windings: (1) conventional 3-phase windings made of insulated wire and (2) squirrel-cage windings. The type of winding gives rise to two main classes of motors: *squirrel-cage induction motors* (also called *cage motors*) and *wound-rotor induction motors.*

A **squirrel-cage rotor** is composed of bare copper bars, slightly longer than the rotor, which are pushed into the slots. The opposite ends are welded to two copper end-rings, so that all the bars are short-circuited together. The entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived. In small and medium-size motors, the bars and end-rings are made of die-cast aluminum, molded to form an integral block (Fig. 3a). Figs.3b and 3c show progressive stages in the manufacture of a squirrel-cage motor.

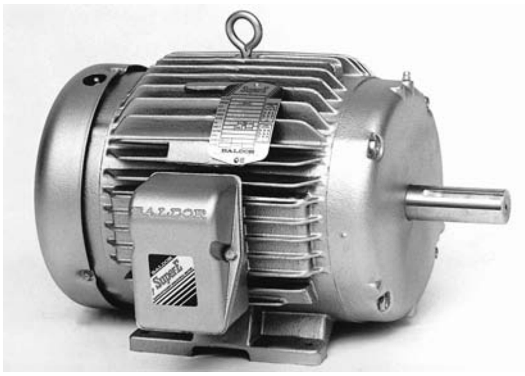

Figure 1
Super-E, premium efficiency induction motor rated 10 hp, 1760 r/min, 460 V, 3-phase, 60 Hz. This totally-enclosed fan-cooled motor has a full-load current of 12.7 A, efficiency of 91.7%, and power factor of 81%. Other characteristics: no-load current: 5 A; locked rotor current: 85 A; locked rotor torque: 2.2 pu; breakdown torque: 3.3 pu; service factor 1.15; total weight: 90 kg; overall length including shaft: 491 mm; overall height: 279 mm.
(Courtesy of Baldor Electric Company)

A **wound rotor** has a 3-phase winding, similar to the one on the stator. The winding is uniformly distributed in the slots and is usually connected in 3-wire wye. The terminals are connected to three slip-rings, which turn with the rotor (Fig. 4). The revolving slip-rings and associated stationary brushes enable us to connect external resistors in series with the rotor winding. The external resistors are mainly used during the start-up period; under normal running conditions, the three brushes are short-circuited.

2 Principle of operation

The operation of a 3-phase induction motor is based upon the application of Faraday's Law and the Lorentz force on a conductor (Sections 2.20, 2.21, and 2.22). The behavior can readily be understood by means of the following example.

Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig. 5a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:

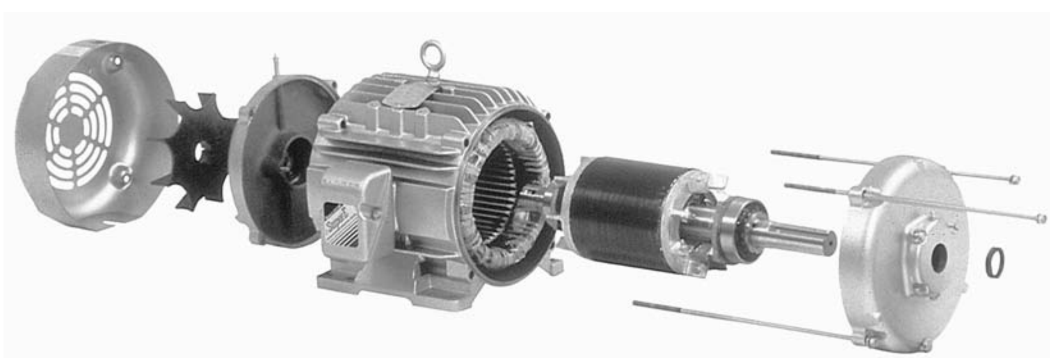

Figure 2
Exploded view of the cage motor of Fig. 1, showing the stator, rotor, end-bells, cooling fan, ball bearings, and terminal box. The fan blows air over the stator frame, which is ribbed to improve heat transfer.
(Courtesy of Baldor Electric Company)

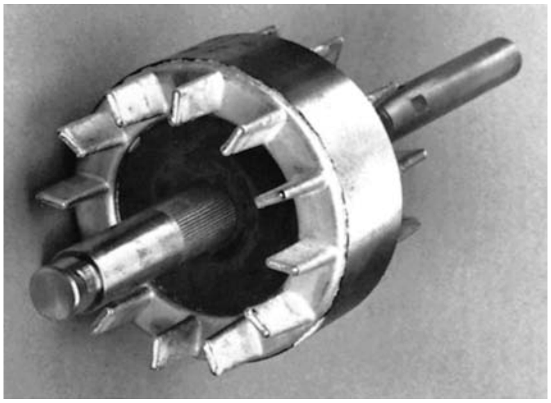

Figure 3a
Die-cast aluminum squirrel-cage rotor with integral cooling fan.
(Courtesy of Lab-Volt)

1. A voltage $E = Blv$ is induced in each conductor while it is being cut by the flux (Faraday's law).
2. The induced voltage immediately produces a current *I,* which flows down the conductor underneath the pole-face, through the end-bars, and back through the other conductors.
3. Because the current-carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).
4. The force always acts in a direction to drag the conductor along with the magnetic field.

If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors will also decrease. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero.

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig. 5b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings, as we will now explain.

3 The rotating field

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig. 6). Coils that are diametrically opposite are connected in series by means of three jumpers that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings, AN, BN, CN, that are mechanically spaced at 120° to each other. The

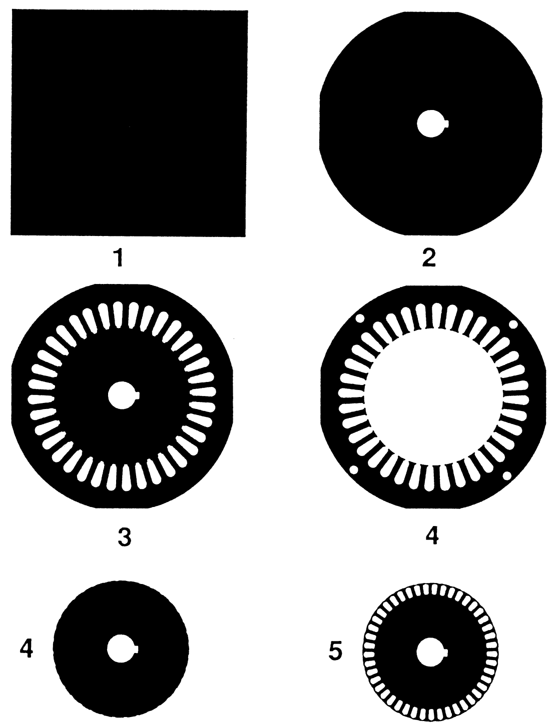

Figure 3b
Progressive steps in the manufacture of stator and rotor laminations. Sheet steel is sheared to size (1), blanked (2), punched (3), blanked (4), and punched (5).
(Courtesy of Lab-Volt)

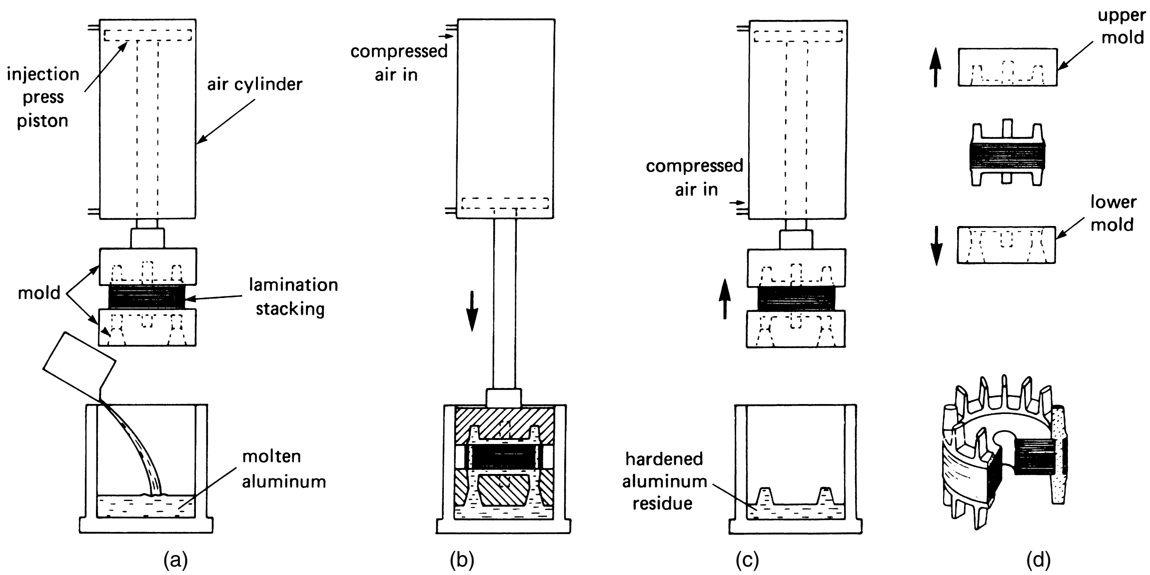

Figure 3c

Progressive steps in the injection molding of a squirrel-cage rotor.

a. Molten aluminum is poured into a cylindrical cavity. The laminated rotor stacking is firmly held between two molds.
b. Compressed air rams the mold assembly into the cavity. Molten aluminum is forced upward through the rotor bar holes and into the upper mold.
c. Compressed air withdraws the mold assembly, now completely filled with hot (but hardened) aluminum.
d. The upper and lower molds are pulled away, revealing the die-cast rotor. The cross-section view shows that the upper and lower end-rings are joined by the rotor bars.

(Courtesy of Lab-Volt)

two coils in each winding produce magnetomotive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line-to-neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

If we connect a 3-phase source to terminals A, B, C, alternating currents I_a, I_b, and I_c will flow in the windings. The currents will have the same value but will be displaced in time by an angle of 120°. These currents produce magnetomotive forces which, in turn, create a magnetic flux. It is this flux we are interested in.

In order to follow the sequence of events, we assume that positive currents (indicated by the arrows) always flow in the windings from line to neutral. Conversely, negative currents flow from neutral to line. Furthermore, to enable us to work with numbers, suppose that the peak current per phase is 10 A. Thus, when $I_a = +7$ A, the two coils of phase A will together produce an mmf of 7 A 10 turns = 70 ampere-turns and a corresponding value of flux. Because the current is positive, the flux is directed vertically upward, according to the right-hand rule.

As time goes by, we can determine the instantaneous value and direction of the current in each winding and thereby establish the successive flux patterns. Thus, referring to Fig. 7 at instant 1, current I_a has a value of +10 A, whereas I_b and I_c both have a value of −5 A. The mmf of phase A is 10 A 10 turns = 100 ampere-turns, while the mmf

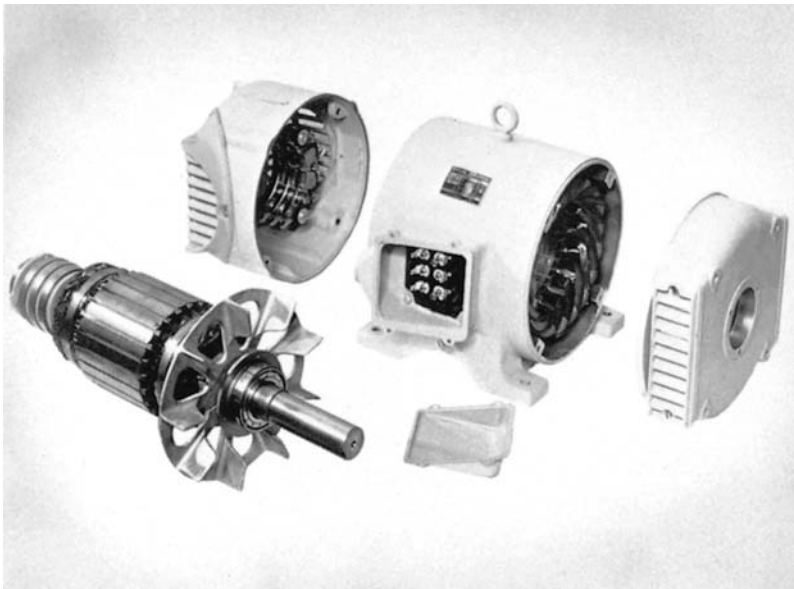

Figure 4a
Exploded view of a 5 hp, 1730 r/min, wound-rotor induction motor.

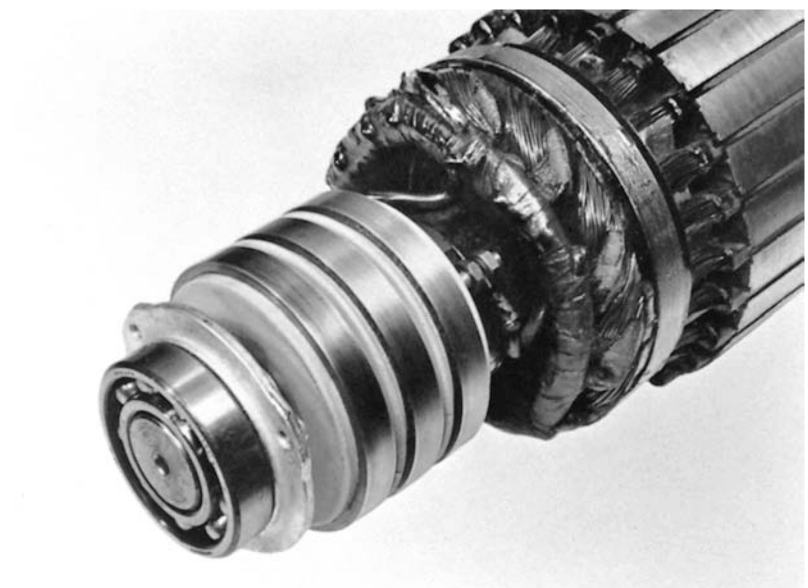

Figure 4b
Close-up of the slip-ring end of the rotor.
(Courtesy of Brook Crompton Parkinson Ltd)

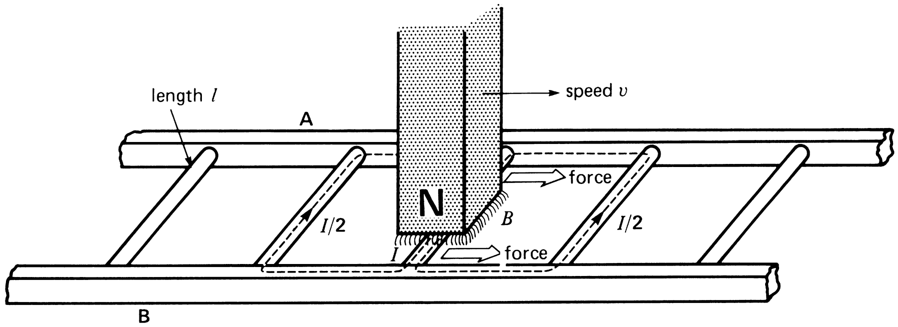

Figure 5a
Moving magnet cutting across a conducting ladder.

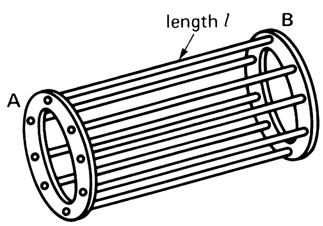

Figure 5b
Ladder bent upon itself to form a squirrel cage.

of phases B and C are each 50 ampere-turns. The direction of the mmf depends upon the instantaneous current flows and, using the right-hand rule, we find that the direction of the resulting magnetic field is as shown in Fig. 8a. Note that as far as the rotor is concerned, the six salient poles together produce a magnetic field having essentially one broad north pole and one broad south pole. This means that the 6-pole stator actually produces a 2-pole field. The combined magnetic field points upward.

At instant 2, one-sixth cycle later, current I_c attains a peak of -10 A, while I_a and I_b both have a value of $+5$ A (Fig. 8b). We discover that the new field has the same shape as before, except that it has moved clockwise by an angle of 60°. In other words, the flux makes 1/6 of a turn between instants 1 and 2.

Proceeding in this way for each of the successive instants 3, 4, 5, 6, and 7, separated by intervals of 1/6

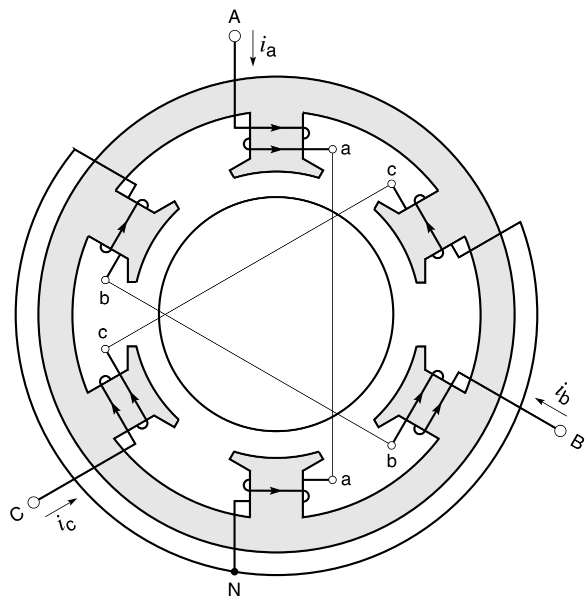

Figure 6
Elementary stator having terminals A, B, C connected to a 3-phase source (not shown). Currents flowing from line to neutral are considered to be positive.

cycle, we find that the magnetic field makes one complete turn during one cycle (see Figs. 8a to 8f).

The rotational speed of the field depends, therefore, upon the duration of one cycle, which in turn depends on the frequency of the source. If the frequency is 60 Hz, the resulting field makes one turn in 1/60 s, that is, 3600 revolutions per minute. On