Chapter 19

Motors

It has been estimated that two-thirds of the electric energy used in the United States goes into motors of one kind or another. Modern houses generally contain 30 to 60 motors for such purposes as fans, furnace control, door openers, pumps, dishwashers, spits, polishers, refrigerators, ovens, dehumidifiers, hair dryers, and on and on. Industrial motor uses are even wider and run from tiny, finger-sized, subfractional-horsepower motors through giants developing thousands of horsepower.

Motors convert electrical power (voltage and current) into shaft torque and rotation.

Motors are divided by power rating into two principal classes: *integral horsepower* (1, 2, 3, 5, 10, etc.) and *fractional horsepower* (motors physically smaller than a standard 1-hp, 1700–1800 rpm machine). Very small motors are sometimes referred to as *subfractional-horsepower* motors.

The objective of this somewhat qualitative introductory chapter is to develop a broad but clear understanding of electric motors in general, their characteristics and operation in circuits. Quantitative analysis and many of the physical details are left for Chapter 20—Rotating Machinery Basics. We start with a typical example of an induction motor and load, and from this look into power in and out, efficiency, general construction, torque-speed characteristics, and some basic circuit considerations. The chapter continues with a discussion of other types of motors, modern variable-speed drives, and ends with some remarks on motor selection and operation.

Motors work by the interaction between electrical currents and magnetic fields.

Readers or instructors may prefer to take up the analysis of Chapter 20 before the external engineering considerations of Chapter 19, and there is no reason that should not be done. It is suggested, however, that those who take that order at least scan the figures and their legends in this chapter first. For most it will be easier to appreciate and use the theory of Chapter 20 after being introduced to the external characteristics and common application practices of motors in this chapter.

19.1 A TYPICAL INDUCTION MOTOR AND LOAD EXAMPLE

Figure 19–1 diagrams a polyphase induction motor driving an industrial fan. Three-phase 440-V power supplies the motor. Power flows from left to right. Most of this electrical power is converted to mechanical power in the motor, which then drives the fan through a rotating shaft. Both motor and fan have losses; neither is 100% efficient.

Three-phase electrical power into the motor can be expressed

$$P_{in} = \sqrt{3}\, VI \cos\theta, \tag{19.1}$$

in watts. Mechanical power out is

$$P_{out} = T\omega_m, \tag{19.2}$$

where if torque T is in newton-meters and if mechanical rotational speed ω_m is in radians per second, power is again in watts. In the United States horsepower is still the most common unit of mechanical power. There are 746 W in 1 hp, so that

$$P_{horsepower} = P_{kilowatts}/0.746. \tag{19.3}$$

EXAMPLE 19.1

The fully loaded 440-V, three-phase motor of Figure 19–1 draws 12.4 A at 86% power factor (pf). Its speed is 1730 rpm and its torque output to the mechanical load is 29.1 lb-ft.

Find: power in, power out in kilowatts and horsepower, and efficiency.

Solution: $P_{in} = \sqrt{3}$ VI cos $\theta = \sqrt{3} \times 440 \times 12.4 \times 0.86 = \underline{8.13 \text{ kW}}$. $T = 29.1 \times 1.356 = 39.5$ N-m. $\omega_m = (1730/60) \times 2\pi = 181.2$ rad/s. Whence $P_{out} = T\omega_m = 39.5 \times 181.2 = \underline{7.15 \text{ kW}}$. $P_{out} = 7.15/0.746 = \underline{9.58 \text{ hp}}$. And eff $= P_{out}/P_{in} = 7.15/8.13 = \underline{88.0\%}$. ■■

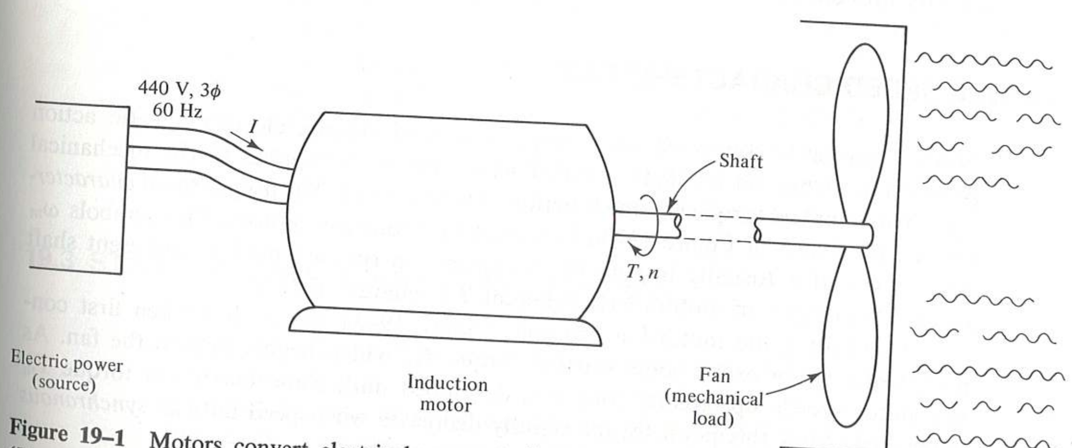

Figure 19–1 Motors convert electrical power ($\sqrt{3}$VI cos θ) into mechanical shaft power ($T\omega_m$). Shaft speed ω_m is in radians per second and should not be confused with electrical radian frequency.

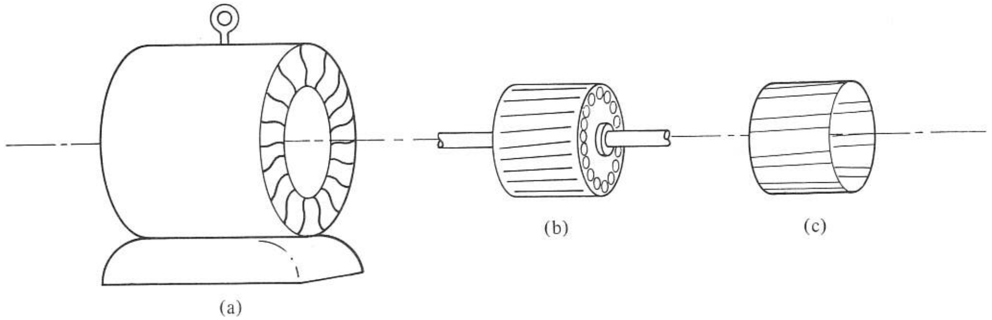

Figure 19–2 Motors have an iron cylindrical fixed part (a), the frame or stator, and an iron rotor (b) that turns inside the stator. Slots inside the stator are wound with electrical conductors. In the squirrel-cage induction motor the electrical rotor portion is a cast aluminum cage (c) which has no external connections.

Figure 19–2 shows the two main parts of motors—a fixed hollow cylinder or frame called the *stator,* and a smaller rotating (usually more or less solid) cylinder called the *rotor.* A rotor revolves inside its stator. (In dc motors the frame is referred to as the *field* and the rotating part as the *armature.*)

Both the stator and rotor are made primarily of magnetic iron to provide a path for flux, similar to the magnetic circuits of the last chapter. For ac machines, electrical conductors are wound in longitudinal slots on the inside surface of the stator. Rotors have various kinds of construction, but almost all have provision for electrical currents in them.

The rotor construction of the common ac machine in Figures 19–1 and 2 is called a *squirrel cage.* Figure 19–2c shows the electrical part of the rotor (the squirrel cage) with the iron stripped away. In this case instead of using conductors wound in slots, the rotor's squirrel-cage electrical conductor system is cast of aluminum directly into slots in the iron.

19.2 TORQUE-SPEED CHARACTERISTICS

When a motor is connected to a proper electrical supply, electromagnetic action produces a torque on its shaft, most of which the shaft supplies to the mechanical load. This supplied torque is some function of motor speed. The *torque-speed characteristic* (T-n) shown in Figure 19–3a is typical for induction motors. The symbols ω_m (in rad/s) and n (usually in rpm but sometimes in rps) are used to represent shaft speed. Other types of motors have different T-n characteristics.

Continuing the motor-fan example, Figure 19–3a shows that when first connected, the motor exerts some starting torque T_s, which begins to turn the fan. As the motor speeds up, greater torque is developed until some maximum torque T_m is reached. After this point torque rapidly decreases with speed until at *synchronous speed* n_s (a term explained below) no torque is produced.

Figure 19–3b shows the torque required to turn the fan load at different speeds—a load T-n diagram—superposed upon the motor's T-n curve. At start (zero speed)

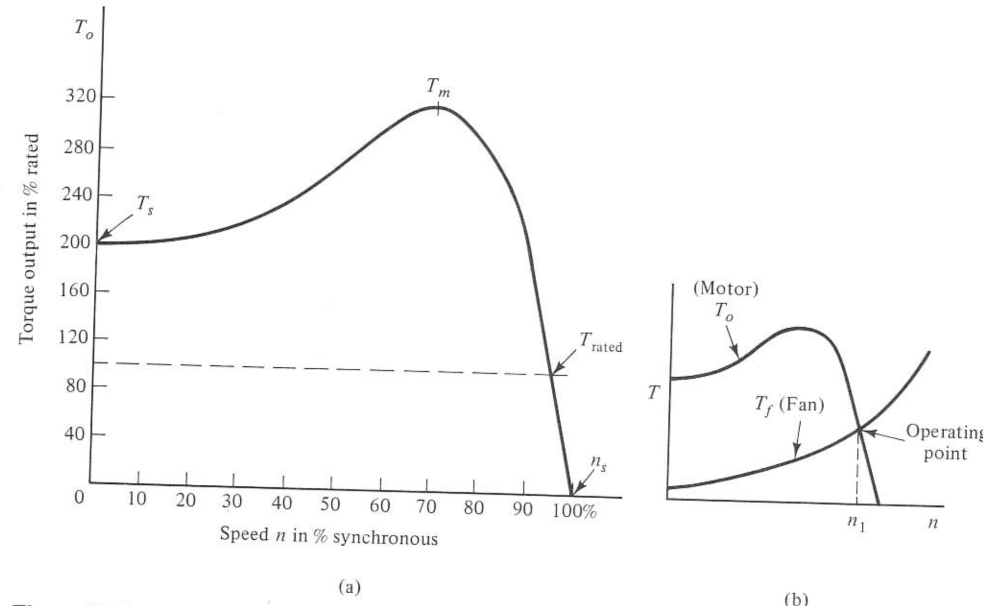

Figure 19–3 An induction motor produces a shaft torque that varies with its speed (a). Similarly the torque required by a mechanical load, (b), varies with speed. If these curves are superposed the speed at which a given motor will drive a given load can be found at their intersection.

very little torque is needed to turn the fan—only enough to overcome bearing friction. As the fan speeds up and starts to move more and more air, the torque required to turn it increases rapidly.

With the two diagrams superposed it will be seen that the extra torque available to accelerate the fan is the difference between motor output torque T_o and the back torque T_f required to move the fan and air. The load will start and begin to speed up because motor starting torque at zero speed is greater than load torque needed. The acceleration could be calculated as $d\omega_m/dt = (T_o - T_f)/J$, where J is the moment of inertia of the entire system. The two curves cross at an *operating point* at speed n_1 as shown. Beyond this point no further acceleration is possible; the motor-load combination will run continuously at that speed. If some transient event should produce a greater speed, the fan would require more torque than the motor is providing and slow the system down. If the speed is below this point, more torque is provided than the fan needs, and the system speeds back up to n_1.

19.3 STARTING AND CONTROLLING MOTORS

Small motors (less than about 1 hp or so) are started by connecting them directly to the line. Motors starting in this way take several times as much current as they do when running at full load. Motors of one common form, if started across the line, draw a starting current of 600% of (full load) running current. Household refrigerator motors are usually about 0.5 hp, but even this small a motor, starting across the line, dims lights in some older

For integral horsepower motors it is usual to limit current by starting at reduced voltage. The controller (or starter) in Figure 19–4 accomplishes this voltage reduction during start and is often simply an autotransformer. Motors are typically started at about half the rated voltage or a little more.

Torque produced by an induction motor at any given speed is roughly proportional to the square of the voltage applied. Thus the curve of Figure 19–3a applies only at rated voltage. A parametric curve of similar shape but at only one-quarter the torques would pretty well represent a half-voltage situation.

Starting torques are an important consideration. Figure 19–5 shows the *T-n* curve for a frictional load, which has a nearly constant torque requirement (conveyors are good examples). When such a load is connected to the induction motor being considered, it is apparent from the curves that although the motor is perfectly capable of driving the load once started, it cannot start it from standstill.

A drop of a few percent in voltage supply will prevent the starting of some motor-load combinations. Under these conditions, loads can be coupled to the motor with clutches which are engaged after the motor reaches operating speed. Or, alternatively, other types of motors or controllers with a better starting characteristic than squirrel-cage induction motors (used directly on 60 Hz) could be applied.

The induction-motor *T-n* curve of Figure 19–3 shows that this type, once started, is a nearly constant-speed machine. Chapter 20 shows that the synchronous speed n_s for 60-Hz supply can have only the values 3600 rpm, 1800, 1200, 900 or any submultiple of 3600 rpm. (For other than 60 Hz, these speeds are proportional to the frequency supplied.) The motors run only a few percent below synchronous.

So it is possible to control induction-motor speed and improve starting by control-

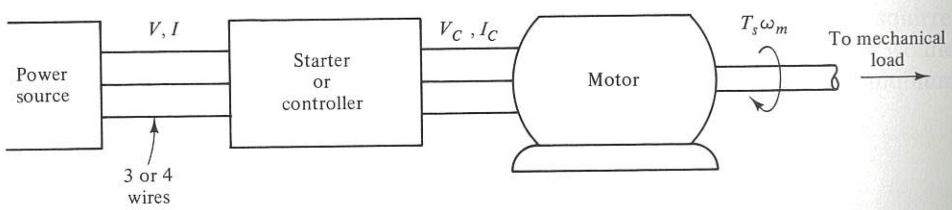

Figure 19–4 For integral horsepower motors a "controller" is interposed between motor and line to provide starting and other control features. In circuit planning the motor and controller are considered as a unit.

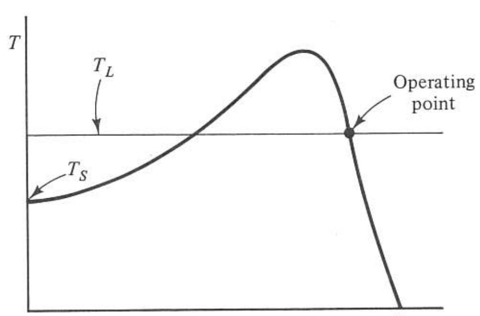

Figure 19–5 Horizontal *T-n* curve marked T_L is typical of frictional loads. Motors with *T-n* characteristic as shown cannot start this load without special provision such as a mechanical clutch.

ling the frequency of power applied to the terminals. Section 19.10 below discusses this procedure under the heading Variable-Frequency Drives.

All but the oldest starters are automatic, requiring the operator to do no more than press a button to start or stop a motor.

19.4 MOTOR CIRCUIT MODELS

For amplifiers and other devices, it was found useful in earlier chapters to develop circuit models to understand and predict their reciprocal effects on the circuit to which they are connected. In the same way, Figure 19–6a is a reasonably good simple motor model which can help in thinking about many problems. Of all applications, this model is least satisfactory for the important induction motor, but it can be modified slightly to provide some general usefulness even for that purpose.

Most motors have two more or less separate circuits—field circuit and armature circuit, as shown in Figure 19–6a. In the dc machine the field is on the stator, the frame, and doesn't rotate. The armature, which in any machine is the heavy-current part, is on the rotor and turns—an unfortunate disadvantage since some kind of heavy-current, rotating connections must be made from frame to rotor. Alternating-current machines are configured in the opposite way, with field on the rotor and a stationary armature on the stator. The induction machine, however, has only one circuit to which power-line electrical connections are made, and that is on the stator.

The armature carries nearly all the supply current drawn. Note that the armature of the machine shown in Figure 19–6 is a Thevenin circuit comprising voltage source, V_g, and impedance represented here by X and R. X can be neglected for steady-state analysis of dc machines, and R can be neglected for much ac machine analysis. While essential, the field circuit has only a few percent of the armature's current or power. It will be seen that the model is a hybrid, showing the mechanical shaft output (shaft speed and torque) emerging directly from the voltage source symbol in the armature electrical circuit. This location is intended to show that most of

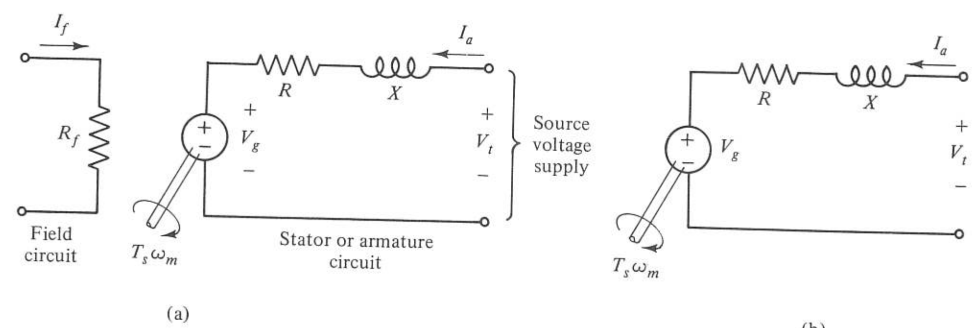

Figure 19–6 Most motors can be approximately modeled as in (a). The circuit shown is one phase and ground of an equivalent-wye diagram. Squirrel-cage induction motors have no field connection (b). V_g is roughly proportional to speed. $V_t - V_g$ drives current through the armature winding. As a heavier mechanical load slows the machine, more current is taken from the line (source), produc

the electrical power going into the "source" V_g is converted to mechanical output power.

The model in Figure 19–6b omits the field circuit but is otherwise the same. It can be used as a crude model for induction motors running near rated speed. This is the motor discussed in the original example. As noted earlier the squirrel-cage rotor has no electrical connection to it, its voltage being induced magnetically by stator currents. Chapter 20 will suggest a more sophisticated circuit model for the induction motor—one based on the transformer. In the meantime Figure 19–6b will be useful to develop a general understanding of induction motors in circuits.

V_t, the line or terminal voltage, and V_g, the back voltage or generated voltage, which opposes the applied voltage V_t, are ac for ac motors and dc for dc motors. Under normal speed and load these two voltages are typically within 10% of each other or closer. For instance, V_t might be 220 V and V_g 200 V. Thus there may be typically only 20 V difference to drive current through the armature circuit impedance. In some ac motors the two voltage magnitudes may be the same, only a phase difference existing to drive current through the stator. Furthermore, V_g is generally proportional to speed, or at least decreases as speed falls off, and for a given voltage, torque is approximately proportional to the product of motor voltage and current.

The important thing that this model tells us is the relation between speed, load, and current drawn. Suppose, for a dc machine such as that shown in Figure 19–6a, rated voltage has been applied to the motor and it is running under approximately full rated load and at a uniform speed. It will be drawing rated current. Now suppose that additional torque is suddenly required by the load. As a simple example the load might be a rock-crushing machine into which a large boulder is suddenly thrown. According to the right-hand side of Figure 19–3a, the motor is providing the rated torque at rated speed. If more torque is required the system will slow down, motor torque will go up (backing up on the curve), and the system will settle at a lower steady-state speed where the motor torque output meets the load requirement.

When the motor slows down, V_g is reduced and more current will flow into the armature circuit from the supply lines since the difference between V_t and V_g is what makes current flow through R and X. And it is this increased current that increases the torque output.

Similarly, if the torque requirement of the load becomes less (rock has been crushed) the motor will be providing more torque than the load needs and the system will speed up until the two torques are again in balance. This increased speed will increase V_g, thus reducing current to reduce torque.

Thus an electric motor, under normal conditions, is a self-regulating device as far as speed and torque and current drawn are concerned. Of course, any motor operates within reasonable limits. For example, if the induction motor is loaded too heavily, the maximum torque point on Figure 19–3a will be passed and the machine will simply stop. The model also shows the possibility of overloading the machine by too much of a torque demand, drawing too much current, and overheating.

The model also suggests the large starting currents. At start (zero speed) V_g is zero. Hence all of V_t is across the R and X of the machine and produces an inordinate current. Numerical examples and problems illustrating these effects are

given in Chapter 20. The loss in R is turned into heat. A motor will overheat if it is started too frequently or if the armature current I_a is too high. There are field and mechanical losses in motors in addition to this armature loss.

Another important but somewhat more subtle point to be appreciated from this model is the dire effect of running motors at reduced voltage for very long. Since torque is proportional to the product of voltage and current, a motor which has too low a voltage will slow down to allow more current. Such a motor can overheat even if the mechanical load is within its rating.

19.5 MAJOR MOTOR TYPES—INDUCTION MOTORS

Induction, synchronous, and *dc* are the principal integral horsepower motor types.

A good deal has already been said about induction motors in the example at the beginning of this chapter where a polyphase induction motor drove a fan. Because of their inexpensive squirrel-cage rotor construction and lack of connections (brushes and slip rings) to the rotating portion of the machine, these motors are the workhorses of industry. They are cheap, rugged, less affected by environment than other types, and easily maintained and rewound. Already the most common motor, they are taking over even more applications with the new variable-frequency drives discussed below in Section 19.10.

Without a variable-frequency supply, the major disadvantage of these motors for some applications is their nearly constant speed. They also have a somewhat limited torque capability on start at reasonable line currents.

Chapter 20 will show in some detail that polyphase currents in the stator windings of most ac motors produce a rotating field which spins around the inside of the stator at *synchronous speed.* The term n_s—Figure 19–3a—the synchronous speed, is defined as the speed at which the stator's rotating field spins. For 60-Hz power supply, two-pole motor fields rotate once for every cycle and therefore have a synchronous speed of 3600 rpm, four-pole (two cycles per revolution) 1800 rpm, six-pole 1200, and so on. Alternating-current synchronous speeds are all submultiples of 3600 rpm for 60 Hz, or of $60f$ for other frequencies. Where p is the number of poles,

$$n_s = 120f/p. \tag{19.4}$$

Induction motors run at full-load speeds slightly below synchronous (by up to about 6%) as suggested in the curve of Figure 19–3a. The amount by which they run below these synchronous speeds is called *slip, S,* and is measured in revolutions per minute or, more often, in percent of synchronous speed,

$$S = (n_s - n)/n_s. \tag{19.5}$$

EXAMPLE 19.2

A four-pole induction motor operates at 4% slip.

Find: the motor speed.

Solution: There are two pole pairs, so $n_s = 3600/2 = 1800$ rpm. Motor speed is 96% of 1800 or 1728 rpm. ■■

EXAMPLE 19.3

Given: A 50-hp, 1150-rpm motor is loaded to 50% of rated torque. (The expression *rated* is often used by engineers for *full load.* The designation of the motor as a "50-hp" machine indicates its rated power output. It is important to recognize that a 50-hp machine may be delivering some other amount of shaft power.)

Find

1. the slip in rpm and in percent;
2. the motor speed in rps and rpm;
3. the largest torque load (in percent of rated) that can be just started if directly coupled to the motor shaft;
4. what is its full-load torque in N-m and in lb-ft?
5. what is the largest torque load it can start in N-m?

Solution

1. n_s is 1200 rpm (nearest synchronous speed just above rated speed). Torque is closely proportional to slip near rated load (see Figure 19–3); for 100% load $S = 50$ rpm, so for 50% torque or load $S = 25$ rpm, or $S = 25/1200 = 2.1\%$.
2. The speed $n = 97.9\% \times 1200$ rpm $= 19.6$ rps or 1175 rpm.
3. According to 19–3a 200% of rated T can be started.
4. $P_{out} = T\omega_m$; so $T = P_{out}/\omega_m = 50 \times 746/(1150 \times 2\pi/60) = 310$ N-m or $310 \times 39.36/12 \times 0.2247 = 228$ lb-ft.
5. $T_s = 200\% \times 310 = 620$ N-m. ■■

The resistance of the armature has a significant effect on starting torque and running slip. Increasing the resistance of the rotor in design increases the starting torque, as shown in the *T-n* curves of Figure 19–7a, an advantage for high-torque starts. But this will also increase the losses and slip. Thus for 60-Hz stators with squirrel-cage rotors, motor speed is already determined when they are designed. There is no very practical way to control it in a given machine. These motors are regarded as almost constant-speed devices. But some motor stators have two sets of windings to produce two possible speeds.

With a given motor almost any nearly constant load speed can be attained by belting or gearing the motor to the load. Such a solution will, however, change the torque available, inversely to the speed transformation. Belting and gearing also have additional mechanical losses, and present cost and maintenance problems.

The great majority of induction motors are of the squirrel-cage type, and this is what is almost always meant by the term *induction motor.* However, in contrast to this squirrel-cage machine, another class of induction motor has a *wound rotor.* Rotor conductors are wound of wire in surface slots. These windings are usually connected in wye and the three terminals brought out through *slip rings* and *brushes* as in Figure 19–7b. Stationary carbon brushes make running contact with rotating slip rings as a means of making electrical connections to the rotating part of the machine. A variable wye-connected resistor is attached to the wye rotor leads. By this means it is possible to change the resistance of the rotor with the effect shown in the *T-n* curves of Figure 19–7a. Up to a point, the higher the resistance the

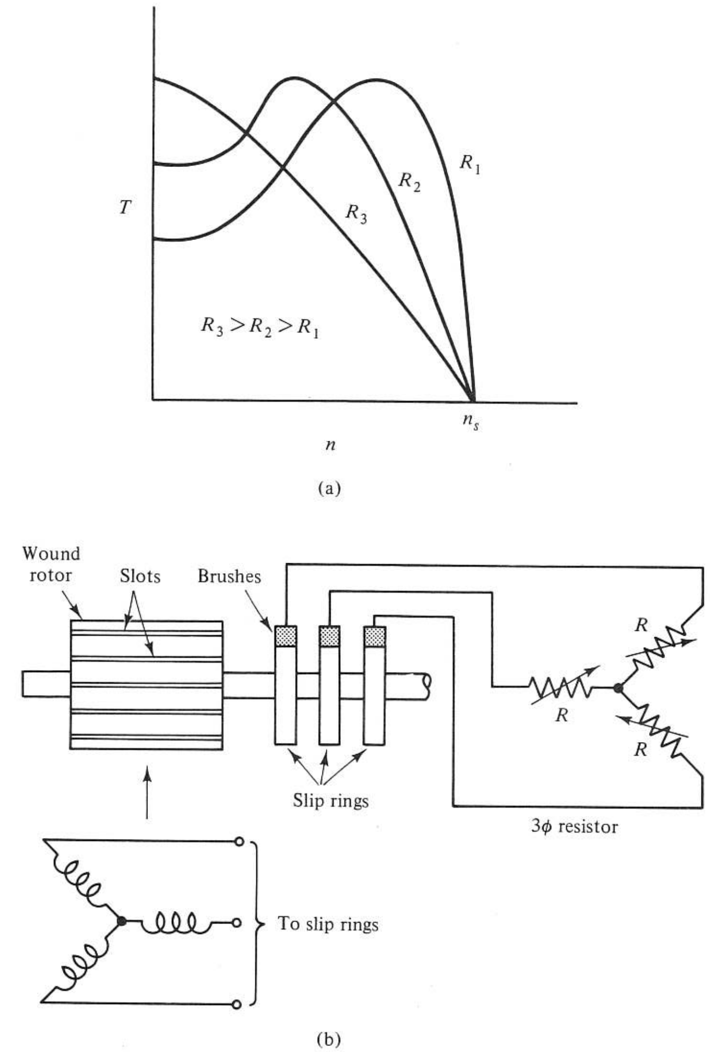

Figure 19–7 Sketch (a) illustrates the effect of greater rotor resistance on *T-n* curves—particularly on starting torque. The wound-rotor motor (b) allows rotor circuit resistance to be varied externally to the machine.

cuts out the resistance for better running efficiency and less speed variation with load. Some limited speed control, at the expense of efficiency, is also possible by this means. Section 19.10 will cover the speed control possibilities for squirrel-cage motors through use of variable-frequency power supply.

A last important characteristic of induction motors to note is their lagging power factor. It is the myriad of induction motors in industry that produce the necessity for power-factor correction procedures discussed in Section 17.11. Well-loaded, moderate-sized motors run at power factors between 80% and 90%, and

19.6 dc MOTORS

Industry has used dc motors for years because of their outstanding speed control capabilities, down to essentially zero revolutions per minute, and because of their good starting and low-speed torque.

Direct-current motors are usually much more expensive than standard induction motors. In contrast to induction machines, the high-current part of the direct-current machine is on the rotor (called the armature in dc machines). In getting from the supply into the armature these high currents must pass through brushes bearing on a *commutator,* a rotating-switch device. Wear on the commutator and brushes adds substantially to maintenance cost and reduces reliability.

Direct-current motors have the further disadvantage that large dc power supplies are generally not available unless especially provided for. In the last few years cheaper and higher-power electronic control equipment has been developed which converts ac to dc right at the motor. Thus small- and moderate-sized motors can be supplied in effect, right from ac mains, eliminating the need for special power supplies. Such an electronic controller can also readily adjust input voltage to the motor.

Shunt motors have the field shunted across (placed in parallel with) the armature as shown in Figure 19–8c. These dc motors provide a family of *T-n* characteristics

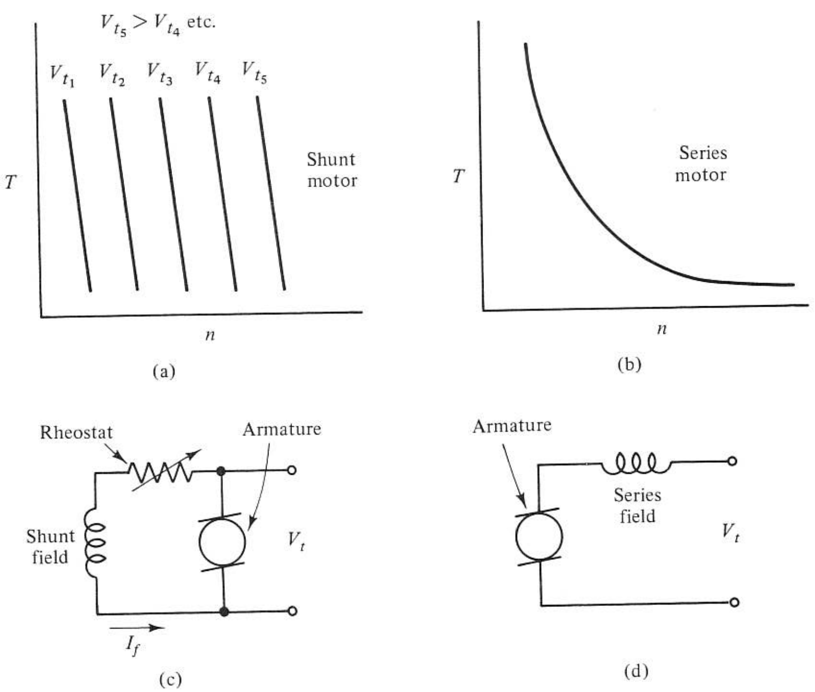

Figure 19–8 (a, c) *T-n* curves of dc shunt motors can be moved horizontally by applying different supply voltages V_t, or to a more limited extent by adjusting field current I_f. The dc series motor, (b, d) is particularly good for electric trains or vehicles.

as shown in 19–8a. Each of the curves is quite like the right side of the induction-motor *T-n* curve of Figure 19–3a. Their parameter is the voltage supplied to the armature, V_t. Varying the field current I_f by means of a rheostat (variable-power resistor) will also have a speed controlling effect over a lesser range of speeds. But field current is small and therefore allows a smooth, cheap, and easy means of control. By varying supply voltage and/or field current the *T-n* curve can be moved horizontally to any speed desired, as shown. This wide speed-control range is the shunt motor's great advantage.

Direct-current shunt motors have one dangerous proclivity that every user should be aware of. If, when a motor is very lightly loaded, the field circuit is accidentally broken or disconnected, the motor tends to run away, going faster and faster until it flies apart. Large shunt machines are always provided with open-field protection.

In the dc *series* motor a few heavy field turns provide the excitation and are connected in series with the armature so that the same current runs through both as in Figure 19–8d. This scheme provides an unusual and very useful *T-n* characteristic (Figure 19–8b)—particularly good for loads that need high torque at low speeds. Typical applications are traction motors in electric railroads or vehicles and also motors for electric drills and hand tools. (See also Section 19.8.) Series motors are also capable of dangerous speeds if unloaded. They are usually coupled directly to their loads permanently. In tools like electric drills gearing losses prevent runaway.

19.7 SYNCHRONOUS MOTORS

These ac motors are designed to run at exactly synchronous speeds, for the United States 3600 rpm, 1800, 1200, and any submultiple of 3600 rpm [see equation (19.4)]. But synchronous motor speed can be adjusted by supplying variable frequency. Large synchronous motors have the same rotating-field stator as the induction motor. But they also require a dc field. There are also various forms of small single-phase, fractional-horsepower machines for such applications as electric clocks, timers, and the like. The theory of Chapter 20 will show that in general any motor can also function as a generator. The large synchronous machine, used as a generator at coal, nuclear, and hydro power plants, is the source of electrical power that sustains civilization today.

Nonsynchronous motor types, when load torque is increased, were shown to develop increased torque by slowing up, thus allowing more current to be drawn from the supply, producing more torque. *T-n* curves developed so far illustrate this point. Synchronous motors, on the other hand, run at a constant speed regardless of load—at least within their torque ratings. How do they react to provide more torque when needed? A truly satisfying answer to this question is postponed to Chapter 20. But for the moment it can be simply said that when a heavier load is applied, the rotor falls back in mechanical phase—usually a few degrees—and continues at synchronous speed.

An interesting analogy would be two bar magnets on opposite sides of a piece of window glass. As one magnet is continuously rotated the other follows, but with a slightly lagging angle. If the following magnet is "loaded" mechanically by putting some viscous material on the glass, or in some other way, the fall-back angle will increase.

An engineer would suspect that there is a limit to possible fall-back angles, which is certainly right. If the motor is torqued too far (that is, too much load torque added to the motor shaft) it will fall out of synchronism, slow up, and eventually stop altogether. For large motors this occurrence is somewhat catastrophic, producing huge fault currents and popping circuit breakers. For small clock motors it is hardly noticed except in the error of the clock.

The synchronous motor produces torque *only* at its synchronous speed. Hence these types cannot start themselves. They are usually provided with starting windings similar to an induction motor to make them self-starting. For starting under these conditions the dc field supply for the rotor is turned off. Like large induction motors they are started at reduced voltages. In some applications their loads can be used to start them.

With these unusual starting requirements and their rotating dc fields with slip rings, large synchronous motors are expensive. They have one redeeming feature, however. Their power factor can be easily controlled simply by adjusting the low-current dc field. This includes the ability to draw large leading currents, making them useful for power factor correction in a manner similar to capacitors. They have often been used where there is a large, constant mechanial load. The power-factor-correcting capability can then be used as an auxiliary advantage and further cost justification. There are still some synchronous motor installations in use in industry where the machine, now called a *synchronous capacitor,* was installed solely for power factor correction before power capacitors became less expensive.

Reluctance motors are small, synchronous, single-phase induction motors that when started run up on the torque-speed curve of Figure 19–3a in the fashion previously described. But their rotors are deeply notched so that there is a rotor iron pole structure to match the rotating field poles of the stator winding. As the motor approaches synchronous speed it has a tendency to jump into synchronism in such a way that its iron rotor poles fall into phase just behind the stator rotating electrical poles generated by stator currents. Thus for light loading the reluctance motor runs synchronously. If slightly overloaded it may slip out of synchronism and run induction at a lower speed. Mechanical timing devices are a major application. Designers using these motors are primarily concerned with obtaining a torque characteristic (usually expressed in inch-ounces) that will be adequate for their mechanical load.

19.8 SINGLE-PHASE AND SMALL MOTORS

Fractional-horsepower and smaller motors are almost exclusively single phase. And there are a few larger single-phase applications where it is uneconomical to provide three-phase power, such as to scattered oil wells or farms.

It is inconvenient in houses and most commercial locations to provide polyphase for small motors. Fortunately, especially designed induction motors will run almost as well on single-phase power as on polyphase once started, as the theory of Chapter 20 will detail. The problem is that it requires polyphase currents to start on induction

motor. Special means must be provided then for single-phase starting. A second-phase stator winding is supplied from the single phase by using capacitance or resistance in series with the supply, to produce a crude out-of-phase component of current.

There are a number of kinds of fractional-horsepower motors (motors smaller than a standard 1700- or 1800-rpm 1-hp motor) that are induction motors, and that differ from each other mostly in how the second (auxiliary) phase is generated and handled. Many have a capacitor (often housed in a small cylindrical case mounted on top) in series with the second winding. Some use a high-resistance auxiliary winding. In some a centrifugal switch disconnects the auxiliary winding when the motor reaches 60% or so of its rated speed. Others leave some or all of the "second phase" current connected. By disconnecting the second winding, it can be made of light wire suitable for intermittent duty only. Typically 400% of rated torque can be realized in this way on start. Starting belt-driven compressors and some other machines can require high torques.

Centrifugal switches in this application are the Achilles heel of reliability. Also capacitors, particularly in high-temperature surroundings, tend to fail before other parts of the motor.

Another common single-phase, fractional-horsepower machine is the *universal motor.* It is essentially a dc series motor with the stator laminated to reduce ac eddy current losses. (The rotor of almost any machine is laminated since the flux in a rotor is alternating as it spins.) The term *universal* refers to its ability to run on ac or dc. It has the disadvantage of requiring a commutator and brushes, with relatively short life between maintenance times. Its great advantages are cheapness and lightness for a given power and torque. And it has the excellent low-speed torque characteristic of series motors. So for such applications as electric hand tools it is ideal—many hand tools are used for such short periods of time that a modest life in hours of use can extend over several years. Weight is important as well as cost in such an application. Any dangerous runaway characteristic is prevented by manufacturing them to be integrally connected to their loads.

Small motors to be used as an integral part of other pieces of equipment—household mixers for example—are produced and sold as "motor parts" consisting of a rotor and the stator shell with windings but no end bells or bearings. The manufacturer designs his appliance to include the motor pieces as integral parts of whatever machine he is manufacturing.

Shaded-pole (induction) motors start without a second winding by providing a shorting turn (copper strap) around part of each iron field pole (at the inside winding face) in the stator (Figure 19–9). The transformer action of this turn changes the phase of the magnetic flux and produces a rotating-field effect which, while inexpensive to build and light in weight, is inefficient. It is suited mostly to either very intermittent use or quite low-power motors.

Torque, for a given voltage, tends to be roughly proportional to current. The smaller the current, the smaller the wire size and the smaller a motor can be constructed. Since power output is $T\omega_m$, motors of a given power tend to be smaller and therefore cheaper the faster they run. Taking advantage of this fact, *gear motors* are electric motors with built-in gear-reduction trains. They are common in fractional-horsepower sizes and frequently provide for right-angle shafting.

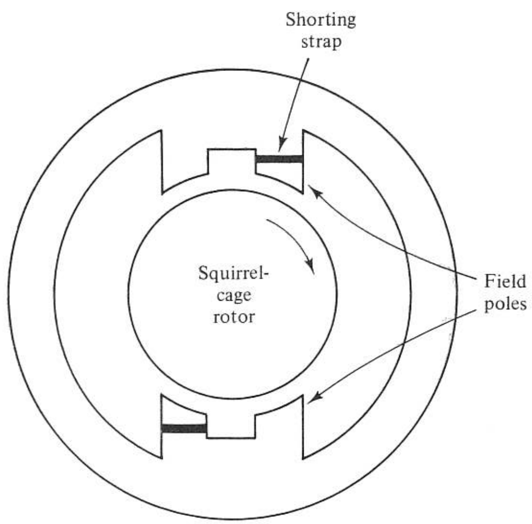

Figure 19–9 In a shaded pole motor parts of the explicit pole structure are surrounded by a *shorting turn,* a copper strap which produces an out-of-phase flux component to make the field crudely rotate.

Stepper motors provide successions of very small incremental turns—typically a degree or two. They are used for precise speed control, or position control for devices such as the heads on computer disk drives. Pulses of power provide the stepping action. They couple easily into computer controlled systems.

19.9 MOTOR STANDARDS

Users of electric motors and designers of products which will incorporate them should be aware of the helpful, detailed standards and wide range of motor classes which have been established by various agencies. This has been contributed to most extensively by NEMA, the National Electrical Manufacturers Association. Their work is intended to promote the public interest as well as the manufacturers' by simplifying communication between user and manufacturer, buyer and seller, and by ensuring that motors can be purchased to recognized performance standards. To this end NEMA has categorized motors into many classes, specifying for example detailed frame sizes with mounting dimensions and shaft heights, starting currents and torques, standard voltages and their tolerances, speed regulation, voltage limitations, and so on—for various types of motors in a wide range of horsepowers.

Many manufacturers produce motors in these standard classes and sizes. It is a good deal more economical, where possible, to design around a standard motor than to specify a special machine of some kind. Continued procurement is also facilitated by this practice.

Another agency, The Underwriters' Laboratory (UL), concerns itself with nonhazardous design and application of motors, issuing approvals for equipment which

passes its tests. These approvals are normally considered to apply to complete devices rather than to the motor alone, although the motor is an important element. See also the material on the National Electrical Code in Chapter 21.

For some applications *explosion-proof* specifications and testing are required. UL is active in this phase of safety also. The U.S. Bureau of Mines has for many years done extensive work in the design, specification, and testing of explosion-proof motors, as part of their work in explosion-proof equipment of all kinds. "Explosion proof" means that an explosion can take place inside a machine without propagating itself to an outside explosive atmosphere. Typical applications are in soft coal mines, flour mills, and environments subject to gasoline or similar fumes and gases.

19.10 VARIABLE-FREQUENCY DRIVES

Of the two-thirds of U.S. electric power that is used for motors, it is estimated that about one-half of this goes into induction motors driving fans and pumps. These motors are all nearly constant speed if supplied by a constant 60-Hz source (see speed-torque curve in Figure 19–3a). Adjustments in flow rate are made either by turning the motor on and off (not very satisfactory) or more commonly by mechanically throttling the fan or pump's output (quite inefficient).

For fans it can be shown that great mechanical energy savings are possible (typically half or even two-thirds) if the fan can be run at slower speeds. (See torque curve of Figure 19–3b and recognize that shaft power in is $T\omega_m$.) Similar but somewhat reduced energy savings are available for many pump installations. It should be clearly recognized that these savings are available only if the fan or pump is to be run for some significant portion of time at less than full rating. But this is usually the case since almost all air-conditioning and many pumping installations must be overdesigned to ensure adequate capacity. Furthermore, ventilation and air-conditioning needs, a major application area, vary greatly with weather and with space use.

To accomplish this variation of fan or pump speed the controller concept of Figure 19–4 can be expanded into a more sophisticated device called a *variable-frequency drive.* * This controller accepts 60-Hz power input and provides a power output whose frequency is adjustable over a wide range. It has already been seen that induction-motor speed is nearly constant at a value just below the synchronous speed n_s given by Equation (19.4). To stay within motor ratings, output voltage should be reduced in proportion to frequency, and this is also accomplished by the controller. In some cases it may be desirable to have the frequency-change sequence be automatic or be controlled by some digital control equipment as in textile plants.

Alternatively the controller may convert ac input to dc output to allow the use of dc machines. Sophisticated controllers that accomplish this can also provide for variable-voltage dc output to control speed and torque with some precision. One-thousand-to-one smooth speed control is possible.

* The term *drive* to most engineers includes both controller and motor. But in much modern discussion the term is used to suggest only the controller. To be clear this book will use the terms *controller* and *motor* separately where possible.

Whether equipped with ac or dc motors, these sophisticated devices provide a soft start, meaning a gentle start mechanically and one which does not take excessive starting current from the supply. Such a start may be mandated by the process—in bottling for example. It also significantly reduces wear and tear on mechanical and electrical components.

These variable-frequency controllers may cost several times as much as the motor they control. (For example, at this writing a 5-hp class-b induction motor costs about $350. A 5-hp variable-frequency controller costs around $1500.) But the controller cost should really be compared to possible energy savings. And it is generally felt that energy prices will continue to increase as present coal and oil deposits are depleted and world population and industrialization increase. (See problem P19.4.)

Variable-frequency controllers can also be applied to synchronous motors.

An important problem in retrofitting or specifying variable-frequency controllers is cooling. Motors may not have enough cooling capability if run at slow speeds for extended periods of time. In some fan applications the motor is cooled by the air flow itself.

19.11 SELECTING AND MAINTAINING MOTORS

Two factors make for some bewilderment in specifying motors for specific applications: First, there are many types and sizes of motors available, a few of the most important of these having been discussed above. Second, there are numerous important parts of a motor's environment that may properly affect the kind and rating of the motor chosen—to mention some of the more important: the power supply available, the torque and speed needed for the load, starting and acceleration requirements, duty cycle to be expected (how many starts are required per hour? for example), ambient temperature, dust or explosive vapors present, maintenance capability of work group, types of motors presently used and maintained in plant, and dependability of motor equipment sources.

The motor and its controller should be considered together (and for a large motor also consider at the same time any protection needed). The advantages of variable-frequency drives should not be overlooked. Whether the motor is part of a product to be produced in volume or is for some factory floor application, the engineers will want to talk to one or more motor manufacturers about the possibilities and their recommendations. Electric motor manufacture is a very competitive business in the United States. Handbooks and other literature sources may be helpful, but the state of the art in motors is changing rapidly.

In sizing motors it should be kept in mind that lightly loaded motors suffer in efficiency and power factor. Most motors can be overloaded substantially for short periods of time without harm. "Substantially" is 25% or even 50%. A "short period of time" is one in which the motor does not have time to get too hot—for a 5- or 10-hp motor, usually 5 min or so. Like transformers, motors are primarily limited by temperature. Too high a temperature suffered for too long a period of time causes

their insulation to deteriorate. For some applications a need for frequent starting may dictate a larger machine.

Motor maintenance like any other maintenance is principally a matter of systematic, scheduled attention. Most small electric motors today are built with lifetime lubrication devices. Except in poor environments, little or no attention is needed for them until they must be replaced. Larger motors usually have lubrication requirements specified by the maker. All motors benefit in extended life and reliability by being kept reasonably free of dirt that would impede their cooling. Moisture is usually bad for them also.

Explosion-proof design relies on the integrity of motor cases. The parts of these cases (often halves) are designed with very wide flanges, to allow for the fact that an internal explosion will force them apart and allow hot gas to blow through to the outside. The idea is to have the flanges wide enough (several inches) so that escaping burning gases are cooled below a temperature which can ignite combustible gases outside the motor. Close spacing of flange closure bolts limits flange separation. Good maintenance practice requires that when these machines are reassembled the flanges be clean and undamaged. All bolts must be replaced and properly torqued. No holes can be left unplugged in the case.

Special classes of motors are produced for special environments, such as drip proof (all case openings in the motor case are in the bottom half) or splash proof (liquid drops or solid particles projected at not less than 100° from the vertical cannot enter the motor) or totally enclosed.

Many motors are costly enough to make rewinding economically worthwhile when their insulation finally fails. Most cities of any size have motor repair shops which can perform this work, often on a rapid emergency basis. Bearings can be replaced and commutators redressed.

It is common to provide *thermal protection* for many motors by including in the windings a bimetallic thermal switch which will open the motor circuit when the windings get too hot. Most of these automatically reclose when the motor cools. But some require resetting by pushing a button.

19.12 SUMMARY

Motors convert electrical power into mechanical shaft power ($P_{\text{shaft}} = \omega_m T$, which gives watts output where speed is in rad/s and torque in N-m). Connected to a power source, except for synchronous machines, torque output is a function of speed, and speed will establish itself at the point where motor torque and the torque the load requires are equal. Each type of motor is characterized by its own torque-speed relation, displayed as a T-n diagram.

Induction motors, rugged and inexpensive, are by far the most common type in industry. Motors larger than about 1 hp are almost always polyphase. The induction motor runs at nearly constant speed, a few percent below some synchronous speed n_s. For 60-Hz supply n_s in rpm can be 3600, 1800, 1200, etc. Single-phase motors must be provided with special starting equipment, which may be troublesome at times. Induction motors run with a poor power factor.

Synchronous motors develop torque at synchronous speed by falling back slightly in mechanical (and electrical) phase. They are provided with starting in some other mode, usually as an induction motor.

Direct-current motors require maintained commutators, and a dc supply unless run on an electronic inverter system. The shunt machine's principal advantage is that speed can be controlled over a wide range with good torque. Direct-current series motors are ideal for traction and other loads requiring high torque at low speeds and low torque at high speeds. Properly constructed series machines can be operated on either dc or ac as universal motors and are much used in tools like electric drills.

Motor efficiency is generally in the range of 60% to 90% with smaller and lightly loaded motors in the lower end, or worse, and some very large motors better. 75% is often taken as a crude estimate. Motor loading is limited by temperature rise from losses, making possible for many types considerable overloading for short periods. Motors tend to draw sufficient power from the line to accommodate their loads. Thus if run at less than rated voltage they overheat when fully loaded.

Induction motors and some other types can be advantageously started, controlled, and run with electronic power supplies which convert 60-Hz three-phase ac to variable-frequency ac (or dc). These electronic drives are expensive but often provide great power savings for fan and pump operation. They overcome to some degree the fixed speed of the induction machine and provide softer starts.

FOR FURTHER STUDY

Ollie I. Elgerd, *Basic Electric Power Engineering,* Addison-Wesley, Reading, MA, 1977.

A. E. Fitzgerald et al., *Electrical Machinery,* 4th ed. McGraw-Hill, New York, 1983.

Harit Majmudar, *Introduction to Electrical Machines,* 2nd ed., Worcester Polytechnic Institute, Worcester, MA, 1984 (available from WPI Bookstore, Worcester, MA 01609).

Leander W. Matsch and J. Derald Morgan, *Electromagnetic and Electromechanical Machines,* 3rd ed., Harper & Row, New York, 1986.

PROBLEMS

Easy Drill Problems (answers at end of chapter)

D19.1. A three-phase motor is rated at 10 hp, 220 V, 1750 rpm at 85% pf. How many kW of mechanical power does the motor produce at full load? Assuming it is 80% efficient, how many electrical kW does it require?

D19.2. Find the line current of the motor in D19.1.

D19.3. Find the shaft torque delivered to the load by the motor of D19.1.

D19.4. Find the slip in percent for the motor of D19.1.

D19.5. **(a)** At what speed would a 24-pole synchronous machine operate?
(b) Recalculate for a power supply frequency of 50 Hz.

D19.6. The motor of Example 19.3 is furnished with a starter which reduces applied voltage to 60% of its rated value. What is the largest torque load it can just start?

Application Problems

P19.1. The motor in D19.1 is supplied with 85% of the voltage for which it is rated. Assume power factor and efficiency remain about constant. For a mechanical load requiring the same full-load torque, find the line current drawn. What percentage of rated line current will this be?

P19.2. At what speed will the motor operating under the conditions of P19.1 run? Make a plot of speed versus voltage supply for voltages from 70% to 100% of rated. (Assume a straight-line *T-n* characteristic in this region.)

P19.3. **(a)** For this same motor, plot line current versus supply voltage.
(b) Assume that half the rated losses of the motor are caused by a resistance that the line current encounters and that the remainder of losses are independent of line current. Plot losses in watts versus line voltage (70–100% rated) under the assumption of rated full-load torque.

P19.4. An existing 5-hp induction motor runs at about 1750 rpm driving a fan at approximately three-quarters load for 3000 hours a year. It is estimated that 40% of the energy used by the fan can be saved by installing a variable-frequency controller at a cost of $1500.00. Expected life for the controller is 10 years. Electric power costs 10 cents per kWh. Your company's current minimum acceptable rate of return (MARR) is 20% before taxes. Is the new controller installation justified and if so how much will it save per year? Assume that the motor alone has an average efficiency of 75% and that motor and controller together have a nearly constant efficiency of 73%.

P19.5. Resolve P19.4 considering that the new soft start and lower speed capability will extend the life of the recently installed motor and ancillary mechanical equipment (costing $950) from 10 to 20 years.

Extension Problems

E19.1. Assume that the graph of Figure 19–3a applies to a 50-hp, 1170-rpm motor. The motor with its connected fan load has a moment of inertia of 25 kg-m². Assume that the fan torque requirement, Figure 19–3b, can be approximated as $T = 0.05 + 1.053\ n^2$, where T is expressed as a fraction of rated motor torque and n as a fraction of motor synchronous speed. Assume for this problem that the motor is started across the line.
(a) How long will it take the motor to come up to 85% of synchronous speed?
(b) Plot motor speed versus time from start.

E19.2. Suppose that a controller is provided so that the motor in problem E19.1 is started on half voltage to limit the starting current drawn and that the controller automatically switches over to full voltage at 60% of synchronous speed. Repeat problem E19.1 under these circumstances.

E19.3. Using the loss and temperature rise concepts of Section 18.3, assume that machine losses under rated conditions are 25% due to losses proportional to voltage supply level, 25% to fixed mechanical losses, and 50% to losses in winding resistance due to load currents.

(a) Assume a rated rise of 40°C. Make a plot of temperature rise versus supply voltage from 70% to 100% total.
(b) Make a plot of temperature rise versus load from 80% to 120% rated.

Study Questions

1. Motors work by interaction between what two physical phenomena?
2. How many watts are equivalent to 1 hp?
3. Sketch carefully a typical induction-motor torque-speed (*T-n*) curve. Add several additional curves to the same sketch showing the effect of rotor resistance on starting torque.
4. Sketch on the same axes two *T-n* curves for the same induction motor, the second with two-thirds the voltage supply of the first.
5. Why is it bad practice to run a motor on voltages lower than its rating for any extended period of time?
6. Why are motors larger than about 1 hp started at reduced voltages?
7. What are the three principal types of large motors?
8. Sketch typical shunt and series dc motor *T-n* curves.
9. What is the shunt dc motor's greatest advantage?
10. Why is the unusual *T-n* curve of the series motor advantageous for traction. (Consider, for example, a train crossing the Rocky Mountains.)
11. List the six highest synchronous motor speeds available in the United States in rpm and rps.
12. How are synchronous motors usually started?
13. Explain how a universal motor's *T-n* characteristic (essentially the same as the series dc motor characteristic) is advantageous in operating a geared electric hand drill.
14. What does the term *explosion proof* mean as applied to motors? By what means is this characteristic obtained in design?
15. Give three reasons why it is disadvantageous to use an ac motor which is much larger than needed for its application. Which of these reasons apply to dc motors?
16. What is a thermal protector and how is it used in motor design?
17. Why does reducing a fan's speed save large quantities of electrical energy?
18. List some advantages and disadvantages of applying variable-frequency controllers.

ANSWERS TO DRILL PROBLEMS

D19.1. 7.46 kW, 9.33 kW
D19.2. 28.8 A
D19.3. 40.7 N-m (or 30.0 lb-ft)
D19.4. 2.8%
D19.5. 300 rpm, 250 rpm
D19.6. 223 N-m

Chapter 20

Rotating Machinery Basics

This chapter presents basic theory to show how the external motor characteristics described in Chapter 19 come about. In addition to being of strong technical interest to the engineer, this theory will help in retention of Chapter 19 material. The purpose of that chapter was to introduce in a somewhat qualitative way the various types of motors, their characteristics, and their applications. Those wishing to start with the present chapter before the last one should at least scan the figures and captions of Chapter 19 first.

The mechanism of losses and efficiency is generally about the same for all types of motors. Yet it is less complex to deal with in the dc machine. The same can be said for speed and speed regulation in many types of motors. Therefore this chapter goes into some detail with dc motor calculations. Quantitative experience developed with this material will carry over by analogy to ac motors.

The chapter also contains a small amount of material on rotating machines as generators.

A centerpiece in understanding rotating machines is seeing that *all* machines, whether operating as motors or generators, are generating voltage and *at the same time* experiencing motor forces. Section 20.1 begins with this point.

20.1 THE LAWS OF MOTOR AND GENERATOR ACTION

Figure 20–1 shows a conductor in a magnetic field of density B webers per square meter (or B *tesla*). The arrows (flux lines) of Figure 20–1a suggest the field flowing out of a north magnetic pole and into a south pole through the space between them, as described in the magnetic circuits of Section 18.5. This field is of course continuous and not actually composed of individual lines. The lines in the figure serve to indicate field direction. Also, by their density, they suggest flux density.