1

Induction Motor Characteristics

1.1 THREE-PHASE INDUCTION MOTORS

In the integral horsepower sizes, i.e., above 1 hp, three-phase induction motors of various types drive more industrial equipment than any other means. The most common three-phase (polyphase) induction motors fall within the following major types:

NEMA (*National Electrical Manufacturers Association*) design B: Normal torques, normal slip, normal locked amperes
NEMA design A: High torques, low slip, high locked amperes
NEMA design C: High torques, normal slip, normal locked amperes
NEMA design D: High locked-rotor torque, high slip
Wound-rotor: Characteristics depend on external resistance

Multispeed: Characteristics depend on design—variable torque, constant torque, constant horsepower

There are many specially designed electric motors with unique characteristics to meet specific needs. However, the majority of needs can be met with the preceding motors.

1.1.1 NEMA Design B Motors

The NEMA design B motor is the basic integral horsepower motor. It is a three-phase motor designed with normal torque and normal starting current and generally has a slip at the rated load of less than 4%. Thus, the motor speed in revolutions per minute is 96% or more of the synchronous speed for the motor. For example, a four-pole motor operating on a 60-Hz line frequency has a synchronous speed of 1800 rpm or a full-load speed of

$$\begin{aligned} 1800 - (1800 \times \text{slip}) &= 1800 - (1800 \times 0.04) \\ &= 1800 - 72 \\ &= 1728 \text{ rpm} \end{aligned}$$

or

$$1800 \times 0.96 = 1728 \text{ rpm}$$

In general, most three-phase motors in the 1- to 200-hp range have a slip at the rated load of approximately 3% or, in the case of four-pole motors, a full-load speed of 1745 rpm. Figure 1.1 shows the typical construction for a totally enclosed, fan-cooled NEMA design B motor with a die-cast aluminum single-cage rotor.

Figure 1.2 shows the typical speed-torque curve for the NEMA design B motor. This type of motor has moderate starting torque, a pull-up torque exceeding the full-load torque, and a breakdown torque (or maximum torque) several times the full-load torque. Thus, it can provide starting and smooth acceleration for most loads and, in addition, can sustain temporary peak loads without stalling. The NEMA performance standards for design B motors are shown in Tables 1.1–1.3.

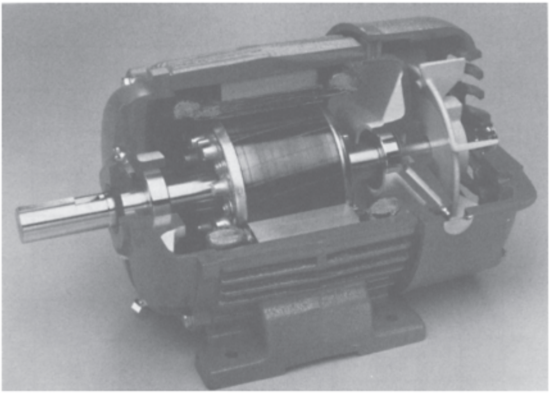

FIGURE 1.1 NEMA design B totally enclosed, fan-cooled polyphase induction motor. (Courtesy Magnetek, St. Louis, MO.)

In the past, there were no established standards for efficiency or power factor for NEMA design B induction motors. However, NEMA had established standards for testing and labeling induction motors. Recently, NEMA has established efficiency standards for energy-efficient polyphase induction motors. These standards are discussed in detail in Chapter 2.

1.1.2 NEMA Design A Motors

The NEMA design A motor is a polyphase, squirrel-cage induction motor designed with torques and locked-rotor current that exceed the corresponding values for NEMA design B motors. The criterion for classification as a design A motor is that the value of the locked-rotor current be in excess of the value for NEMA design B motors. The NEMA design A motor is usually applied to special applications that cannot be served by NEMA design B motors, and most often these applications require motors with higher than normal breakdown torques to meet the requirements of high transient or short-duration loads. The NEMA design A motor is also applied to loads requiring extremely low slip, on the order of 1% or less.

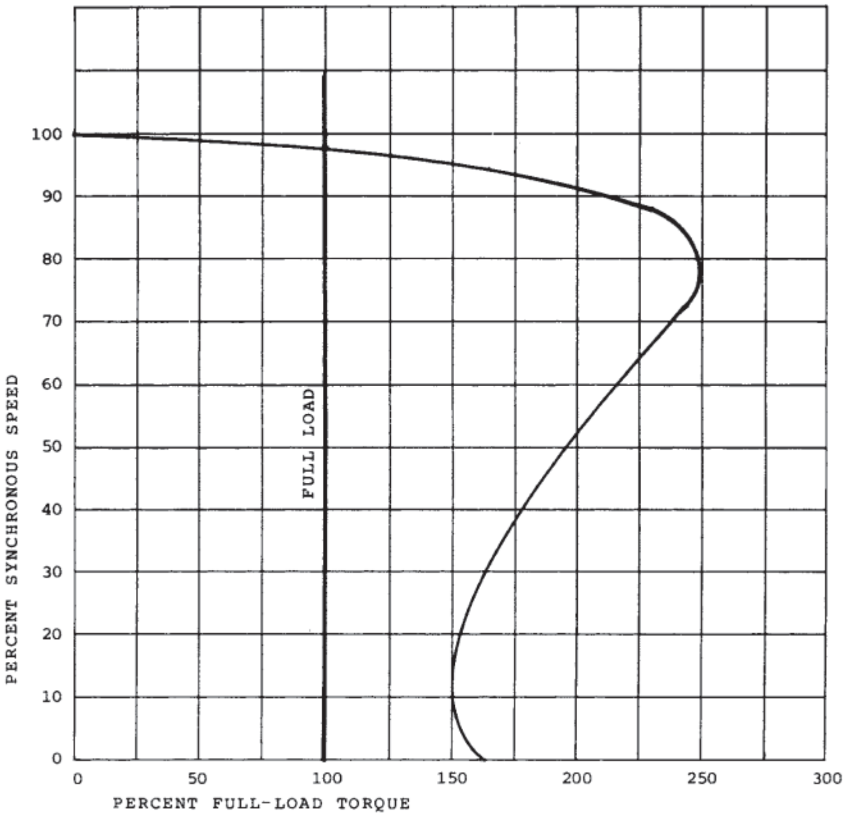

FIGURE 1.2 NEMA design B motor speed-torque curve.

1.1.3 NEMA Design C Motors

The NEMA design C motors is a squirrel-cage induction motor that develops high locked-rotor torques for hard-to-start applications. Figure 1.3 shows the construction of a drip-proof NEMA design C motor with a double-cage, die-cast aluminum rotor. Figure 1.4 shows the typical speed torque curve for the NEMA design C motor. These motors have a slip at the rated load of less than 5%.

TABLE 1.1 Locked-Rotor Torque of NEMA Design A and B Motors[a,b]

	Synchronous speed, 60 Hz			
hp	3600 rpm	1800 rpm	1200 rpm	900 rpm
1	—	275	170	135
1.5	175	250	165	130
2	170	235	160	130
3	160	215	155	130
5	150	185	150	130
7.5	140	175	150	125
10	135	165	150	120
15	130	160	140	125
20	130	150	135	125
25	130	150	135	125
30	130	150	135	125
40	125	140	135	125
50	120	140	135	125
60	120	140	135	125
75	105	140	135	125
100	105	125	125	125
125	100	110	125	120
150	100	110	120	120
200	100	100	120	120
250	70	80	100	100

[a] Single-speed, polyphase, squirrel-cage, medium-horsepower motors with continuous ratings (percent of full-load torque).
[b] For other speeds and ratings, see NEMA Standard MG1-12.38.1.
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The NEMA performance standards for NEMA design C motors are shown in Tables 1.3–1.5.

1.1.4 NEMA Design D Motors

The NEMA design D motor combines high locked-rotor torque with high full-load slip. Two standard designs are generally offered, one

TABLE 1.2 Breakdown Torque of NEMA Design A and B Motors[a,b]

	Synchronous speed, 60 Hz			
hp	3600 rpm	1800 rpm	1200 rpm	900 rpm
1	—	300	265	215
1.5	250	280	250	210
2	240	270	240	210
3	230	250	230	205
5	215	225	215	205
7.5	200	215	205	200
10	200	200	200	200
15	200	200	200	200
20	200	200	200	200
25	200	200	200	200
30	200	200	200	200
40	200	200	200	200
50	200	200	200	200
60	200	200	200	200
75	200	200	200	200
100	200	200	200	200
125	200	200	200	200
150	200	200	200	200
200	200	200	200	200
250	175	175	175	175

[a] Single-speed, polyphase, squirrel-cage, medium-horsepower motors with continuous ratings (percent of full-load torque).
[b] For other speeds and ratings, see NEMA Standard MG1-12.39.1.
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with full-load slip of 5–8 % and the other with full-load slip of 8–13%. The locked-rotor torque for both types is generally 275–300% of full-load torque; however, for special applications, the locked-rotor torque can be higher. Figure 1.5 shows the typical speed-torque curves for NEMA design D motors. These motors are recommended for cyclical loads such as those found in punch presses, which have

TABLE 1.3 Locked-Rotor Current of NEMA Design B, C, and D Motors[a,b,c]

hp	Locked-rotor current A	NEMA design letter	Code letter
1	30	B, D	N
1.5	40	B, D	M
2	50	B, D	L
3	64	B, C, D	K
5	92	B, C, D	J
7.5	127	B, C, D	H
10	162	B, C, D	H
15	232	B, C, D	G
20	290	B, C, D	G
25	365	B, C, D	G
30	435	B, C, D	G
40	580	B, C, D	G
50	725	B, C, D	G
60	870	B, C, D	G
75	1085	B, C, D	G
100	1450	B, C, D	G
125	1815	B, C, D	G
150	2170	B, C, D	G
200	2900	B, C	G
250	3650	B	G

[a] Three-phase, 60-Hz, medium-horsepower, squirrel-cage induction motors rated at 230 V.
[b] For other horsepower ratings, see NEMA Standard MG1-12.35.
[c] The locked-rotor current for motors designed for voltages other than 230 V shall be inversely proportional to the voltage.
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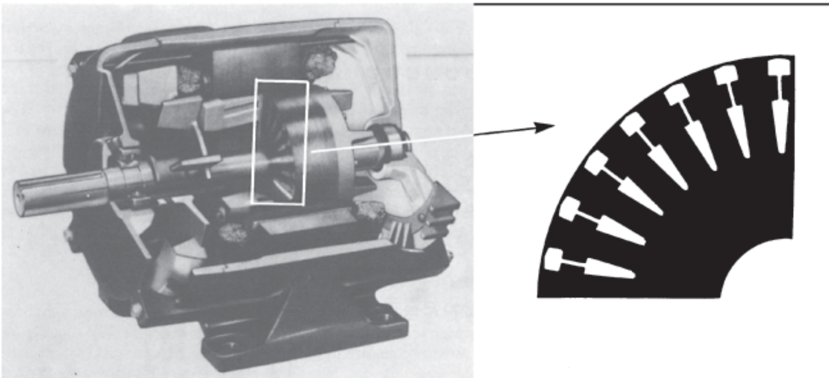

FIGURE 1.3 NEMA design C drip-proof polyphase induction motor. (Courtesy Magnetek, St. Louis, MO.)

stored energy systems in the form of flywheels to average the motor load and are excellent for loads of short duration with frequent starts and stops. The proper application of this type of motor requires detailed information about the system inertia, duty cycle, and operating load as well as the motor characteristics. With this information, the motors are selected and applied on the basis of their thermal capacity.

1.1.5 Wound-Rotor Induction Motors

The wound-rotor induction motor is an induction motor in which the secondary (or rotating) winding is an insulated polyphase winding similar to the stator winding. The rotor winding generally terminates at collector rings on the rotor, and stationary brushes are in contact with each collector ring to provide access to the rotor circuit. A number of systems are available to control the secondary resistance of the motor and hence the motor's characterstics. The use and application of wound-rotor induction motors have been limited mostly to hoist and crane applications and special speed-control

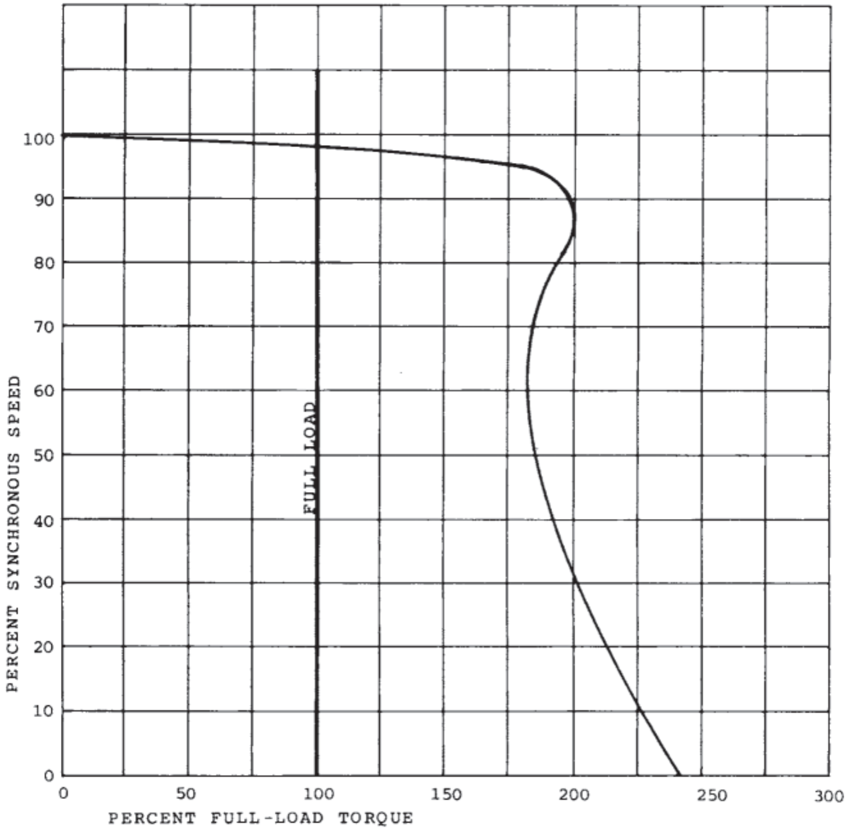

FIGURE 1.4 NEMA design C motor speed-torque curve.

applications. Typical wound-rotor motor speed-torque curves for various values of resistance inserted in the rotor circuit are shown in Fig. 1.6. As the value of resistance is increased, the characteristic of the speed-torque curve progresses from curve 1 with no external resistance to curve 4 with high external resistance. With appropriate control equipment, the characteristics of the motor can be changed

TABLE 1.4 Locked-Rotor Torque of NEMA Design C Motors[a]

	Synchronous speed, 60 Hz		
hp	1800 rpm	1200 rpm	900 rpm
3	—	250	225
5	250	250	225
7.5	250	225	200
10	250	225	200
15	225	200	200
20–200 inclusive	200	200	200

[a] Single-speed, polyphase, squirrel-cage, medium-horsepower motors with continuous ratings (percent of full-load torque), MG1-12.38.2.
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TABLE 1.5 Breakdown Torque of NEMA Design C Motors[a]

	Synchronous speed, 60 Hz		
hp	1800 rpm	1200 rpm	900 rpm
3	—	225	200
5	200	200	200
7.5–200 inclusive	190	190	190

[a] Single-speed, polyphase, squirrel-cage, medium-horsepower motors with continuous ratings (percent of full-load torque), MG1-12.39.2.
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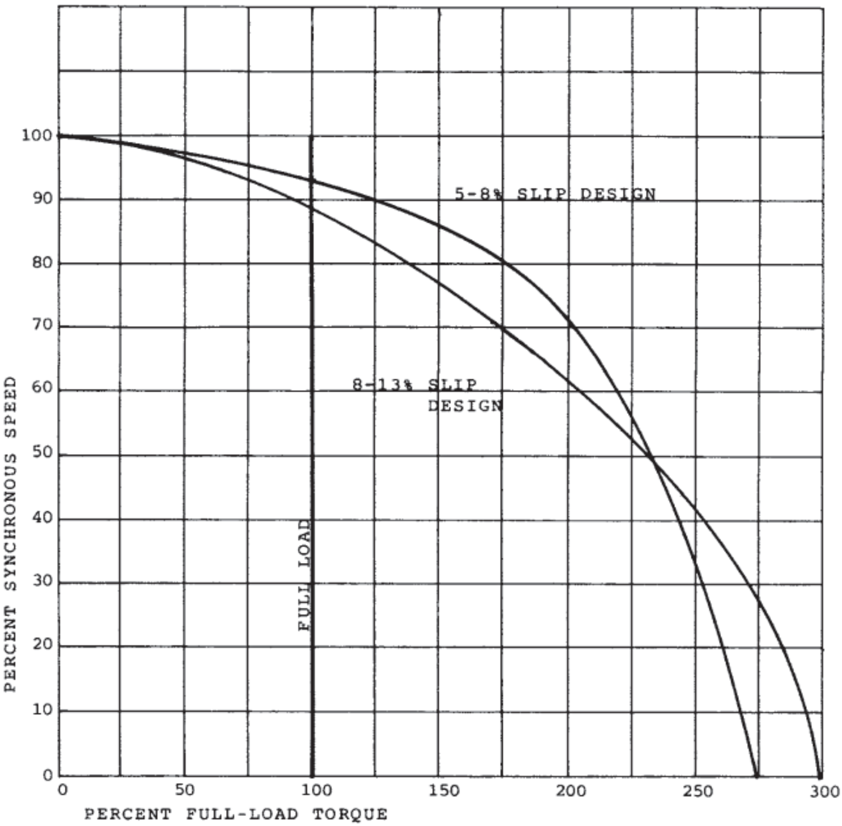

FIGURE 1.5 NEMA design D motor speed-torque curves: 5–8% and 8–13% slip.

by changing this value of external rotor resistance. Solid-state inverter systems have been developed that, when connected in the rotor circuit instead of resistors, return the slip loss of the motor to the power line. This system substantially improves the efficiency of the wound-rotor motor used in variable-speed applications.

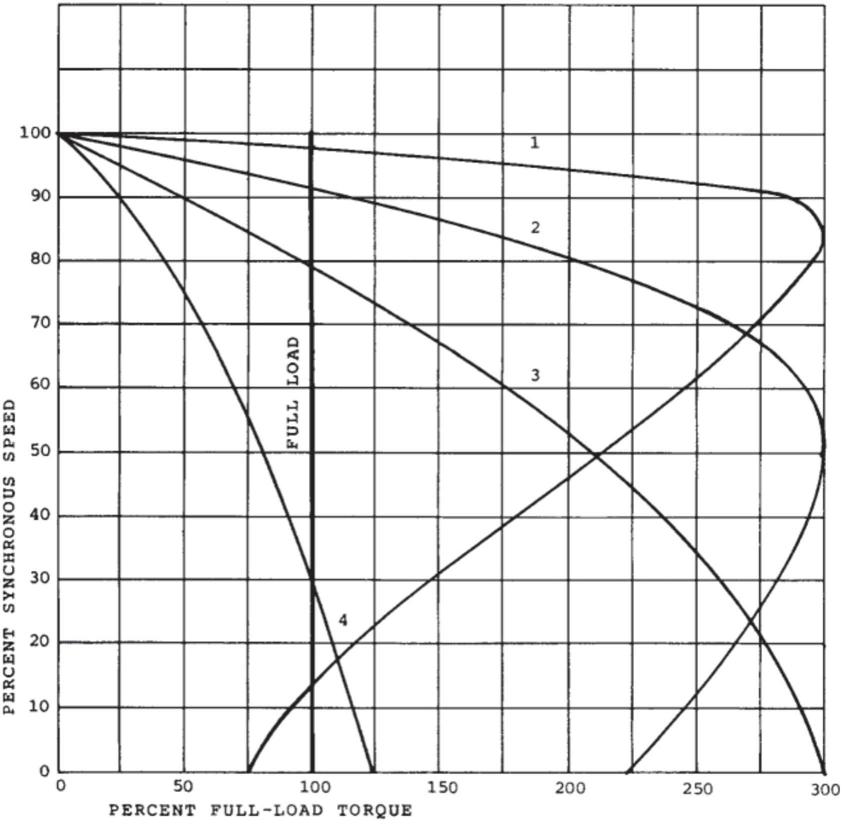

FIGURE 1.6 Wound-rotor motor speed-torque curves: 1, rotor short-circuited; 2–4, increasing values of external resistance.

1.1.6 Multispeed Motors

Motors that operate at more than one speed, with characteristics similar to those of the NEMA-type single-speed motors, are also available. The multispeed induction motors usually have one or two primary windings. In one-winding motors, the ratio of the two speeds must be 2 to 1; for example, possible speed combinations are 3600/

1800, 1800/900, and 1200/600 rpm. In two-winding motors, the ratio of the speeds can be any combination within certain design limits, depending on the number of winding slots in the stator. The most popular combinations are 1800/1200, 1800/900, and 1800/600 rpm. In addition, two-winding motors can be wound to provide two speeds on each winding; this makes it possible for the motor to

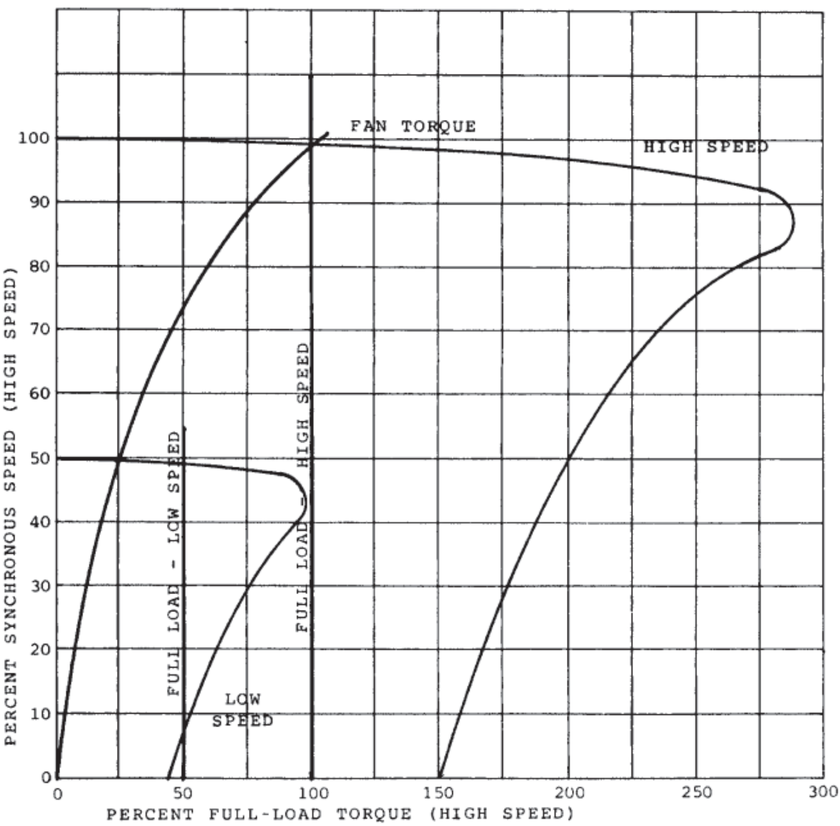

FIGURE 1.7 Speed-torque curves for a variable-torque, one-winding, two-speed motor.

operate at four speeds, for example, 3600/1800 rpm on one winding and 1200/600 rpm on the other winding.

Multispeed motors are available with the following torque characteristics.

Variable Torque. The variable-torque multispeed motor has a torque output that varies directly with the speed, and hence the

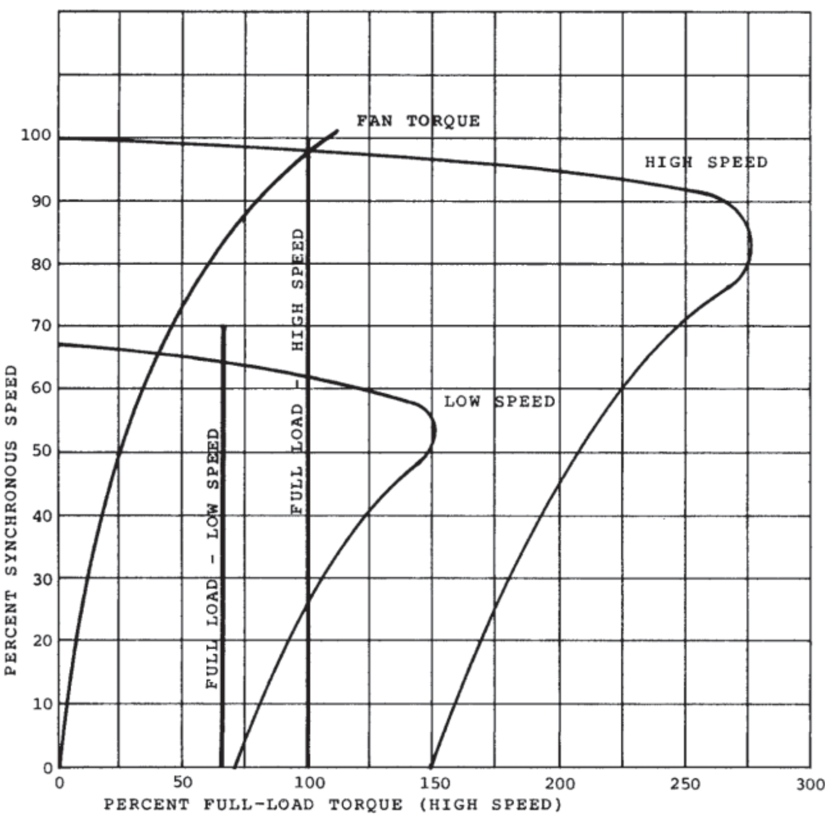

FIGURE 1.8 Speed-torque curves for a multispeed variable-torque motor with two windings, two speeds, and a four-pole to six-pole ratio.

horsepower output varies with the square of the speed. This motor is commonly used with fans, blowers, and centrifugal pumps to control the output of the driven device. Figure 1.7 shows typical speed-torque curves for this type of motor. Superimposed on the motor speed-torque curve is the speed-torque curve for a typical fan where the input horsepower to the fan varies as the cube of the fan speed. Another popular drive for fans is a two-winding

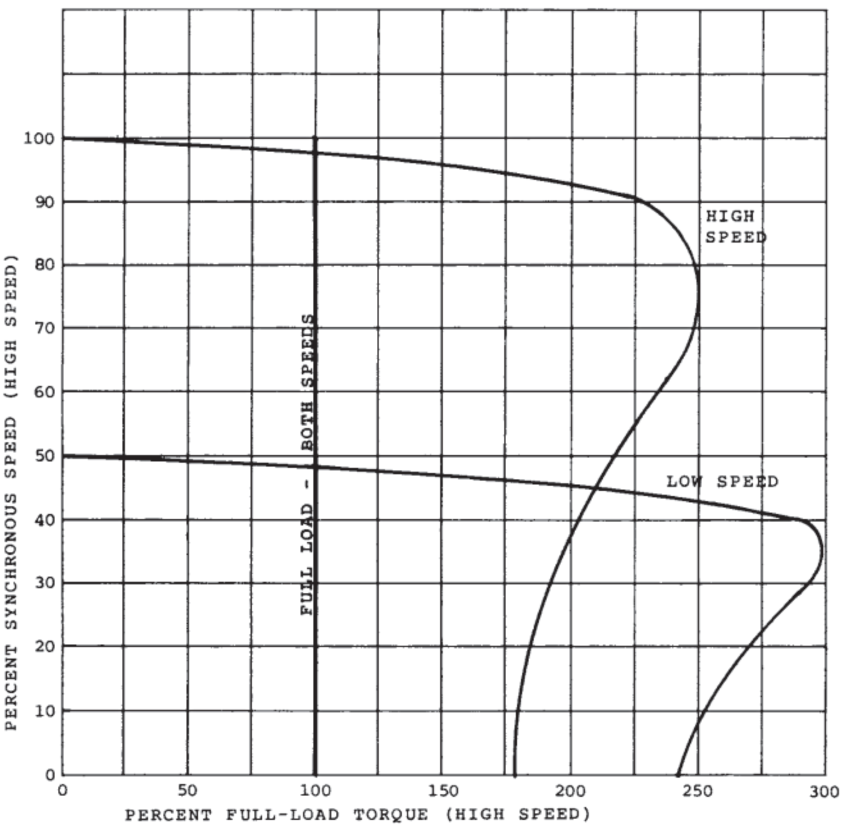

FIGURE 1.9 Speed-torque curves for a constant-torque, one-winding, two-speed motor.

two-speed motor, such as 1800 rpm at high speed and 1200 rpm at low speed. Figure 1.8 shows the typical motor speed-torque curve for the two-winding variable-torque motor with a fan speed-torque curve superimposed.

Constant Torque. The constant-torque multispeed motor has a torque output that is the same at all speeds, and hence the horsepower

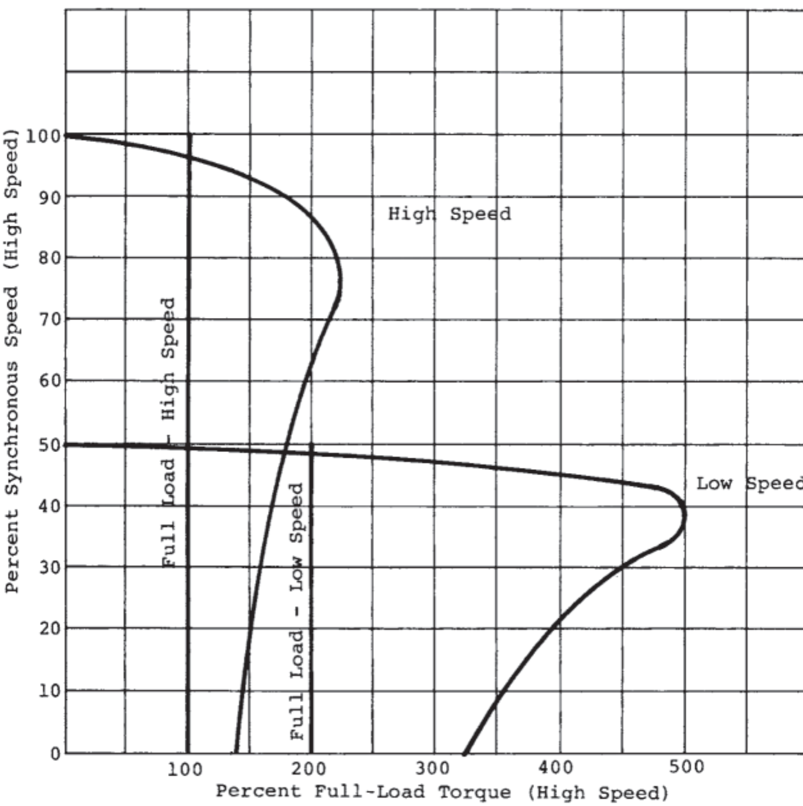

FIGURE 1.10 Speed-torque curves for a constant-horsepower, one-winding two-speed motor.

output varies directly with the speed. This motor can be used with friction-type loads such as those found on conveyors to control the conveyor speed. Figure 1.9 shows typical speed-torque curves.

Constant Horsepower. The constant-horsepower multispeed motor has the same horsepower output at all speeds. This type of motor is used for machine tool applications that require higher torques at lower speeds. Figure 1.10 shows typical speed-torque curves.

1.2 SINGLE-PHASE INDUCTION MOTORS

There are many types of single-phase electric motors. In this section, the discussion will be limited to those types most common to integral-horsepower motor ratings of 1 hp and higher.

In industrial applications, three-phase induction motors should be used wherever possible. In general, three-phase electric motors have higher efficiency and power factors and are more reliable since they do not have starting switches or capacitors.

In those instances in which three-phase electric motors are not available or cannot be used because of the power supply, the following types of single-phase motors are recommended for industrial and commercial applications: (1) capacitor-start motor, (2) two-value capacitor motor, and (3) permanent split capacitor motor.

A brief comparison of single-phase and three-phase induction motor characteristics will provide a better understanding of how single-phase motors perform:

1. Three-phase motors have locked torque because there is a revolving field in the air gap at standstill. A single-phase motor has no revolving field at standstill and therefore develops no locked-rotor torque. Anauxiliary winding is necessary to produce the rotating field required for starting. In an integral-horsepower single-phase motor, this is part of an RLC network.
2. The rotor current and rotor losses are insignificant at no load in a three-phase motor. Single-phase motors have appreciable rotor current and rotor losses at no load.

3. For a given breakdown torque, the single-phase motor requires considerably more flux and more active material than the equivalent three-phase motor.
4. A comparison of the losses between single-phase and three-phase motors is shown in Fig. 1.11. Note the significantly higher losses in the single-phase motor.

The general characteristics of these types of single-phase induction motors are as follows.

1.2.1 Capacitor-Start Motors

A capacitor-start motor is a single-phase induction motor with a main winding arranged for direct connection to the power source and an auxiliary winding connected in series with a capacitor and starting switch for disconnecting the auxiliary winding from the power source after starting. Figure 1.12 is a schematic diagram of a capacitor-start motor. The type of starting switch most commonly used is a centrifugally actuated switch built into the motor. Figure

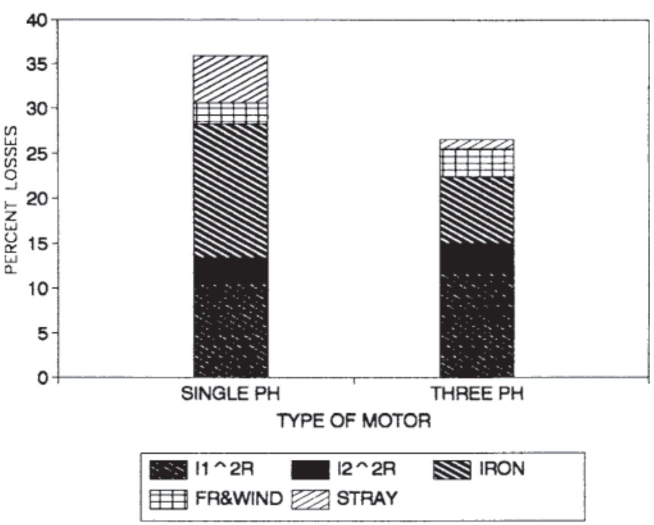

FIGURE 1.11 Percent loss comparison of single- and three-phase motors.

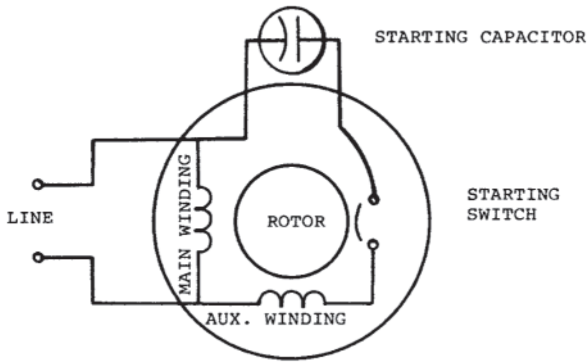

FIGURE 1.12 Capacitor-start single-phase motor.

1.13 illustrates an industrial-quality drip-proof single-phase capacitor-start motor; note the centrifugally actuated switch mechanism.

However, other types of devices such as current-sensitive and voltage-sensitive relays are also used as starting switches. More recently, solid-state switches have been developed and used to a

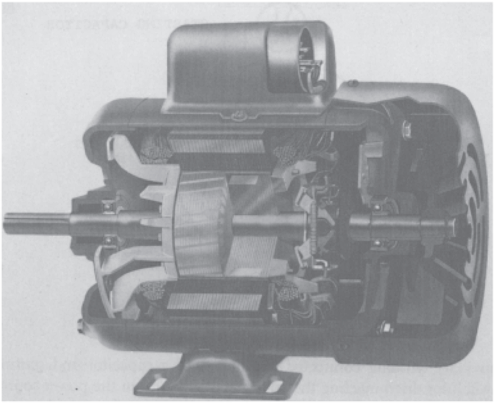

FIGURE 1.13 Capacitor-start single-phase motor. (Courtesy Magnetek, St. Louis, MO.)

limited extent. The solid-state switch will be the switch of the future as it is refined and costs are reduced.

All the switches are set to stay closed and maintain the auxiliary winding circuit in operation until the motor starts and accelerates to approximately 80% of full-load speed. At that speed, the switch opens, disconnecting the auxiliary winding circuit from the power source.

The motor then runs on the main winding as an induction motor. The typical speed-torque characteristics for a capacitor-start motor are shown in Fig. 1.14. Note the change in motor torques at the transition point at which the starting switch operates.

The typical performance data for integral-horsepower, 1800-rpm, capacitor-start, induction-run motors are shown in Table 1.6. There will be a substantially wider variation in the values of locked-rotor torque, breakdown torque, and pull-up torque for these single-phase motors than for comparable three-phase motors, and the same variation also exists for efficiency and the power factor (PF). Note that pull-up torque is a factor in single-phase motors to ensure starting with high-inertia or hard-to-start loads. Therefore, it is important to know the characteristics of the specific capacitor-start motor to make certain it is suitable for the application.

1.2.2 Two-Value Capacitor Motors

A two-value capacitor motor is a capacitor motor with different values of capacitance for starting and running. Very often, this type of motor is referred to as a capacitor-start, capacitor-run motor.

The change in the value of capacitance from starting to running conditions is automatic by means of a starting switch, which is the same as that used for the capacitor-start motors. Two capacitors are provided, a high value of capacitance for starting conditions and a lower value for running conditions. The starting capacitor is usually an electrolytic type, which provides high capacitance per unit volume. The running capacitor is usually a metallized polypropylene unit rated for continuous operation. Figure 1.15 shows one method of mounting both capacitors on the motor.

The schematic diagram for a two-value capacitor motor is shown in Fig. 1.16. As shown, at starting, both the starting and running

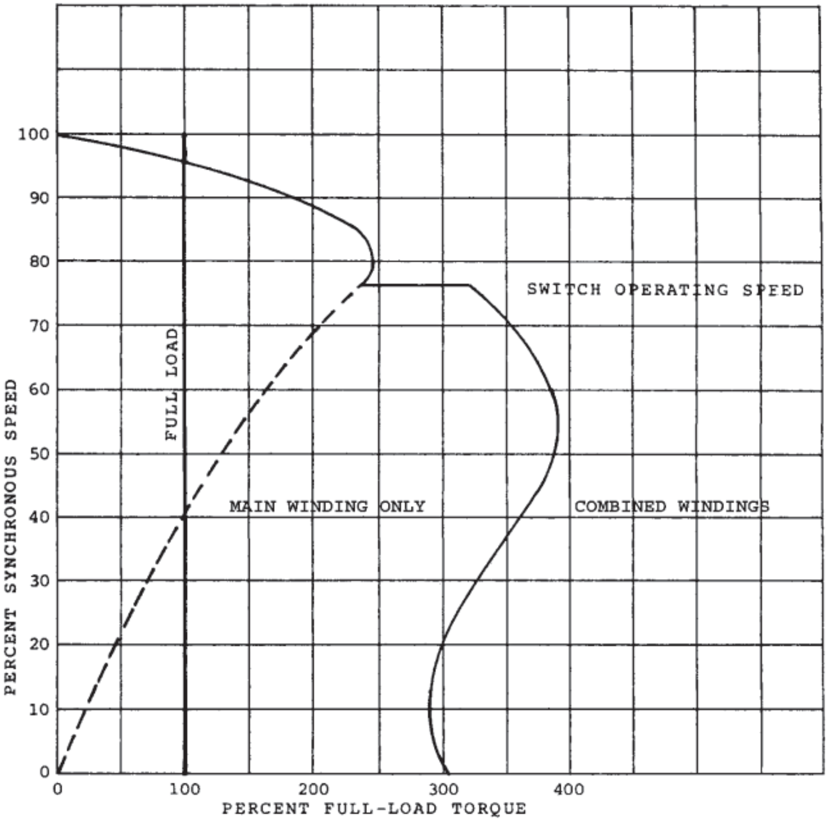

FIGURE 1.14 Speed-torque curve for a capacitor-start motor.

capacitors are connected in series with the auxiliary winding. When the starting switch opens, it disconnects the starting capacitor from the auxiliary winding circuit but leaves the running capacitor in series with the auxiliary winding connected to the power source. Thus, both the main and auxiliary windings are energized when the motor is running and contribute to the motor output. A typical

TABLE 1.6 Typical Performance of Capacitor-Start Motors[a]

	Full-load performance					Torque, lb-ft		
hp	rpm	A	Eff.	PF	Torque	Locked	Breakdown	Pull-up
1	1725	7.5	71	70	3.0	9.9	7.5	7.6
2	1750	12.5	72	72	6.0	17.5	14.7	11.5
3	1750	17.0	74	79	9.0	23.0	21.0	18.5
5	1745	27.3	78	77	15.0	46.0	32.0	35.0

[a] Four-pole, 230-V, single-phase motors.
Source: Courtesy Magnetek, St. Louis, MO.

speed-torque curve for a two-valve capacitor motor is shown in Fig. 1.17.

For a given capacitor-start motor, the effect of adding a running capacitor in the auxiliary winding circuit is as follows:

Increased breakdown torque: 5–30%
Increased lock-rotor torque: 5–10%
Improved full-load eciency: 2–7 points

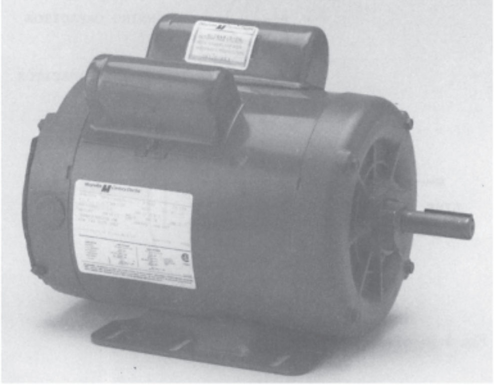

FIGURE 1.15 Two-value capacitor, single-phase motor. (Courtesy Magnetek, St. Louis, MO.)

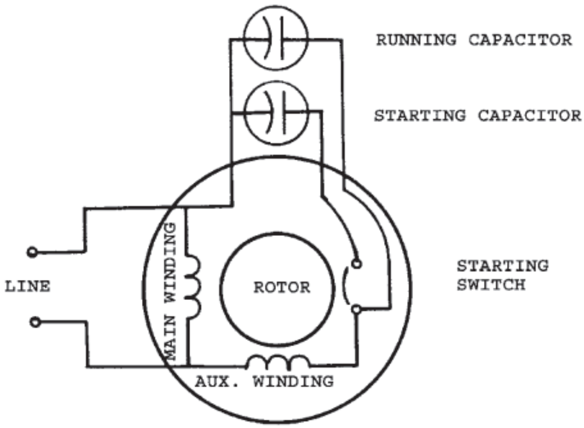

FIGURE 1.16 Two-value capacitor, single-phase motor.

Improved full-load power factor: 10–20 points
Reduced full-load running current
Reduced magnetic noise
Cooler running

The addition of a running capacitor to a single-phase motor with properly designed windings permits the running performance to approach the performance of a three-phase motor. The typical performance of integral-horsepower, two-value capacitor motors is shown in Table 1.7. Comparison of this performance with the performance shown in Table 1.6 for capacitor-start motors shows the improvement in both efficiency and the power factor.

The optimum performance that can be achieved in a two-value capacitor, single-phase motor is a function of the economic factors as well as the technical considerations in the design of the motor. To illustrate this, Table 1.8 shows the performance of a single-phase motor with the design optimized for various values of running capacitance. The base for the performance comparison is a capacitor-start, induction-run motor with no running capacitor. Table 1.9 shows that performance improves with increasing values

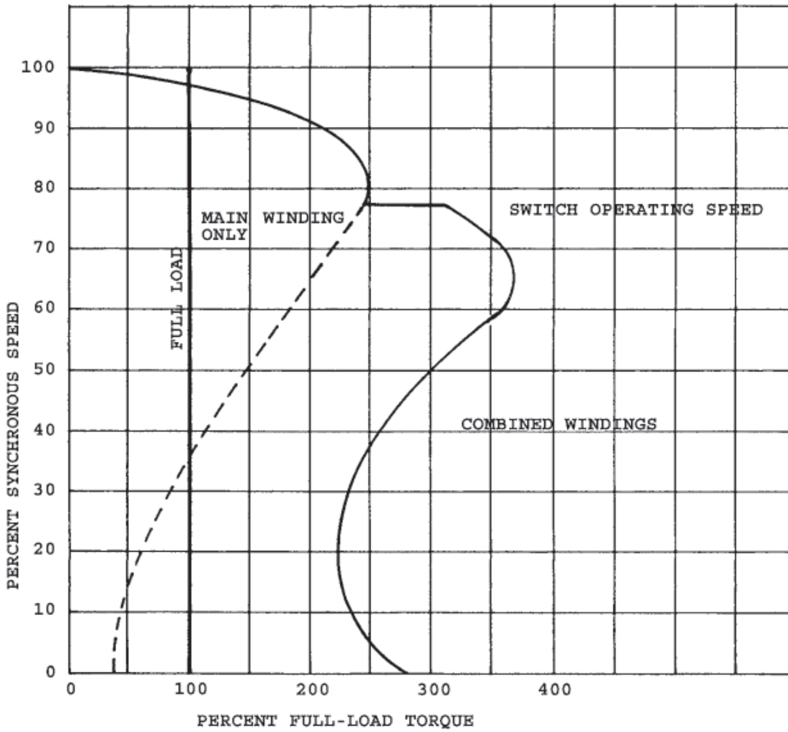

FIGURE 1.17 Speed-torque curve for a two-value capacitor motor.

of running capacitance and that the motor costs increase as the value of running capacitance is increased. The payback period in years was calculated on the basis of 4000 hr/yr of operation and an electric power cost of 6¢/kWh. Note that the major improvement in motor performance is made in the initial change from a capacitor-start to a two-value capacitor motor with a relatively low value of running capacitance. This initial design change also shows the shortest payback period.

The determination of the optimum two-value capacitor motor for a specific application requires a comparison of the motor costs and the energy consumptions of all such available motors. It is

TABLE 1.7 Typical Performance of Two-Value Capacitor Motors[a]

	Full-load performance					Torque, lb/ft		
hp	rpm	A	Eff.	PF	Torque	Locked	Breakdown	Pull-up
3	1760	14.0	78	90	9.0	25	23	22
5	1760	25.0	82	80	15.0	46	35	32
7.5	1750	32.0	86	88	22.5	45	56	45
10	1750	38.0	86	96	30.0	56	72	56

[a] Four-pole, 230-V, single-phase motors.
Source: Courtesy Magnetek, St. Louis, MO.

recommended that this comparison be made by a life-cycle cost method or the net present worth method (outlined in Chapter 7).

The efficiency improvement and energy savings of a specific product line of pool pump motors when the design was changed from capacitor-start motors to two-value capacitor motors are illustrated by Table 1.9 and Figs. 1.18 and 1.19. Based on the same operating criterion used above, i.e., 4000-hr/yr operation at power costs of 6¢/kWh, the payback period for these motors was 8–20 months.

TABLE 1.8 Performance Comparison of Capacitor-Start and Two-Value Capacitor Motors

	Type of motor				
	Capacitor start	Two-value capacitor			
Running capacitor, MFD	0	7.5	15	30	65
Full-load efficiency	70	78	79	81	83
Full-load PF	79	94	97	99[a]	99[a]
Input watts reduction, %	0	10.1	11.5	13.3	15
Cost, %	100	130	140	151	196
Approximate payback period	—	1.3	1.6	1.8	2.9

[a] Leading power factor.

TABLE 1.9 Efficiency Comparison: Standard and Energy-Efficient 3600-rpm, Single-Phase Pool Motors

hp	Standard efficient motors	Energy-efficient motors
0.75	0.677	0.76
1.00	0.709	0.788
1.50	0.749	0.827
2.00	0.759	0.85
3.00	0.809	0.869

Source: Courtesy Magnetek, St. Louis, MO.

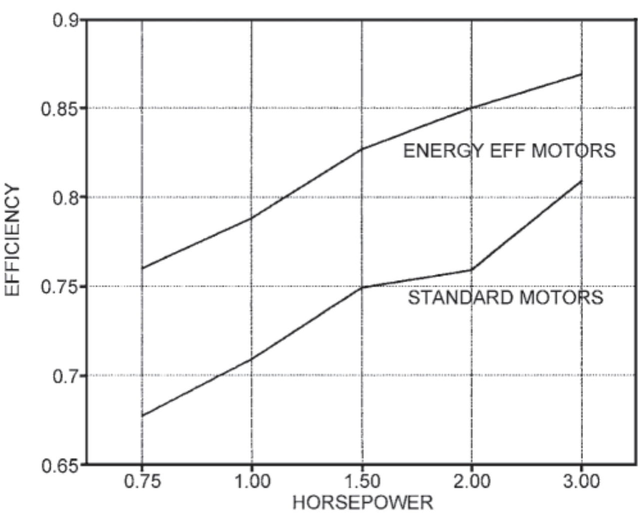

FIGURE 1.18 Efficiency comparison of energy-efficient and standard pool pump single-phase motors. (Courtesy Magnetek, St. Louis, MO.)

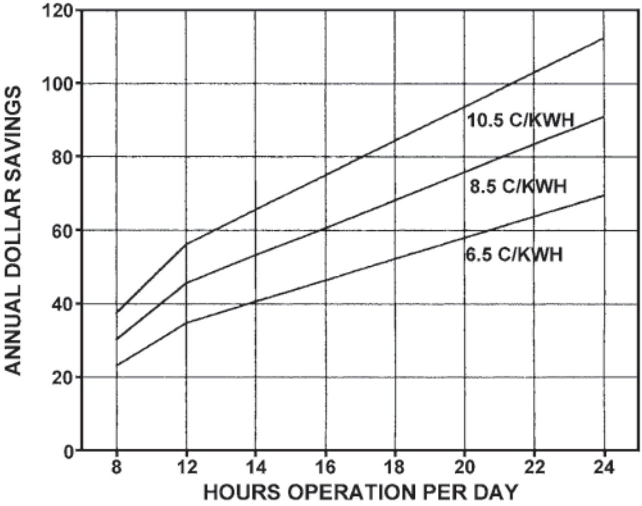

FIGURE 1.19 Annual savings for a 1-hp energy-efficient pool motor operating 365 days/yr. (Courtesy Magnetek, St. Louis, MO.)

1.2.3 Permanent Split Capacitor Motors

The permanent split capacitor motors, a single-phase induction motor, is defined as a capacitor motor with the same value of capacitance used for both starting and running operations. This type of motor is also referred to as a single-value capacitor motor. The application of this type of single-phase motor is normally limited to the direct drive of such loads as those of fans, blowers, or pumps that do not require normal or high starting torques. Consequently, the major application of the permanent split capacitor motor has been to direct-driven fans and blowers. These motors are not suitable for belt-driven applications and are generally limited to the lower horsepower ratings.

The schematic diagram for a permanent split capacitor motor is shown in Fig. 1.20. Note the absence of any starting switch. This type of motor is essentially the same as a two-value capacitor motor

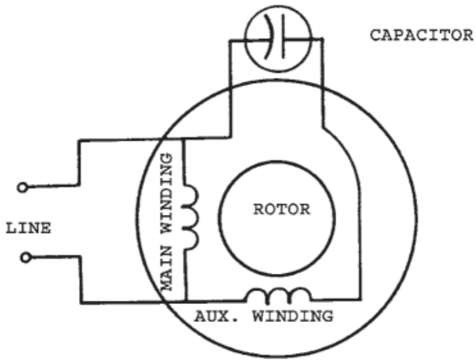

FIGURE 1.20 Permanent split capacitor single-phase motor.

operating on the running connection and will have approximately the same torque characteristics. Since only the running capacitor (which is of relative low value) is connected in series with the auxiliary winding on starting, the starting torque is greatly reduced. The starting torque is only 20–30% of full-load torque. A typical speed-torque curve for a permanent split capacitor motor is shown in Fig. 1.21. The running performance of this type of motor in terms of efficiency and power factor is the same as a two-value capacitor motor. However, because of its low starting torque, its successful application requires close coordination between the motor manufacturer and the manufacturer of the driven equipment.

A special version of the capacitor motor is used for multiple-speed fan drives. This type of capacitor motor usually has a tapped main winding and a high-resistance rotor. The high-resistance rotor is used to improve stable speed operation and to increase the starting torque. There are a number of versions and methods of winding motors. The most common design is the two-speed motor, which has three windings: the main, intermediate, and auxiliary windings. For 230-V power service, a common connection of the windings is called the T connection. Schematic diagrams for two-speed T-connected motors are shown in Figs. 1.22 and 1.23. For

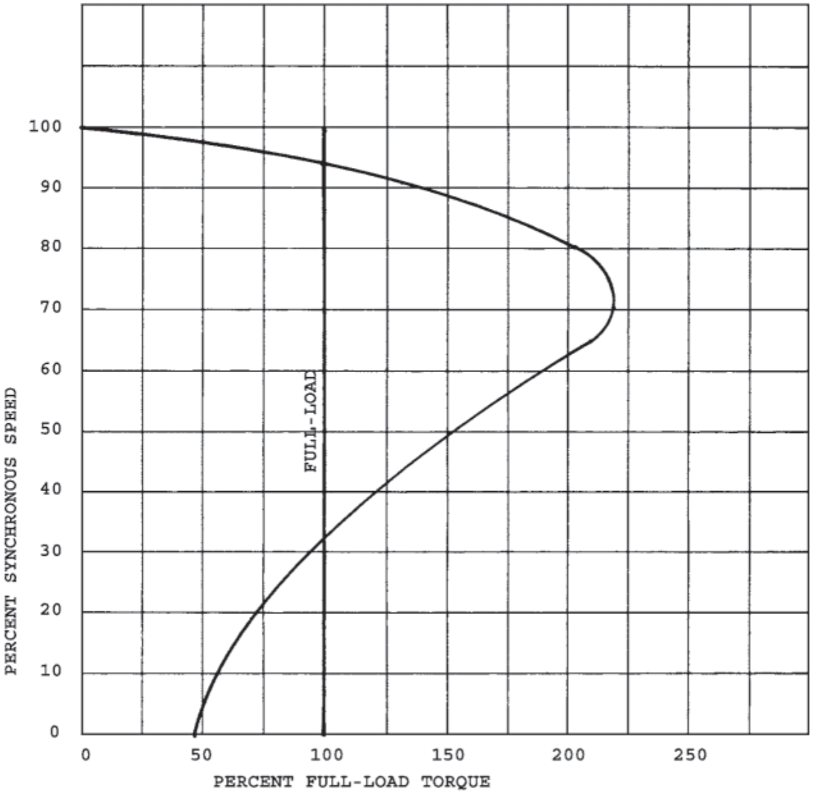

FIGURE 1.21 Speed-torque curve for a permanent split capacitor motor.

high-speed operation, the intermediate winding is not connected in the circuit as shown in Fig. 1.23, and line voltage is applied to the main winding and to the auxiliary winding and capacitor in series. For low-speed operation, the intermediate winding is connected in series with the main winding and with the auxiliary circuit as shown in Fig. 1.23. This connection reduces the voltage applied across both the main wind ing and the auxiliary circuit, thus reducing the torque

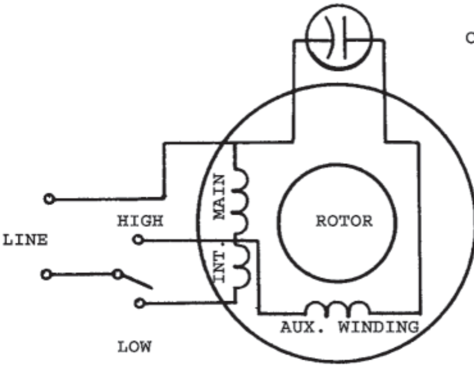

FIGURE 1.22 Permanent split capacitor single-phase motor with a T-type connection and two-speed operation.

the motor will develop and hence the motor speed to match the load requirements. The amount of speed reduction is a function of the turns ratio between the main and intermediate windings and the speed-torque characteristics of the driven load. It should be recognized that, with this type of motor, the speed change is obtained by letting the motor speed slip down to the required low

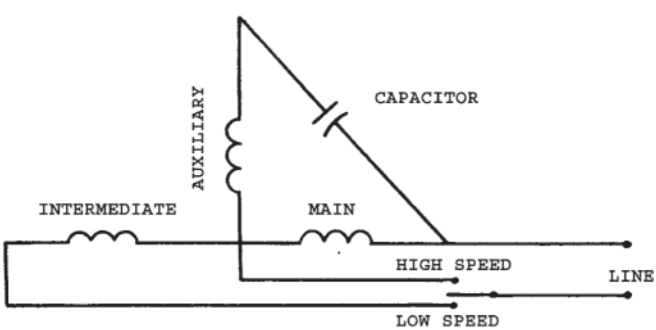

FIGURE 1.23 Permanent split capacitor single-phase motor with a T-type connection and a winding arrangement.

speed; it is not a multispeed motor with more than one synchronous speed.

An example of the speed-torque curves for a tapped-winding capacitor motor is shown in Fig. 1.24. The load curve of a typical fan load is superimposed on the motor speed-torque curves to show the speed reduction obtained on the low-speed connection.

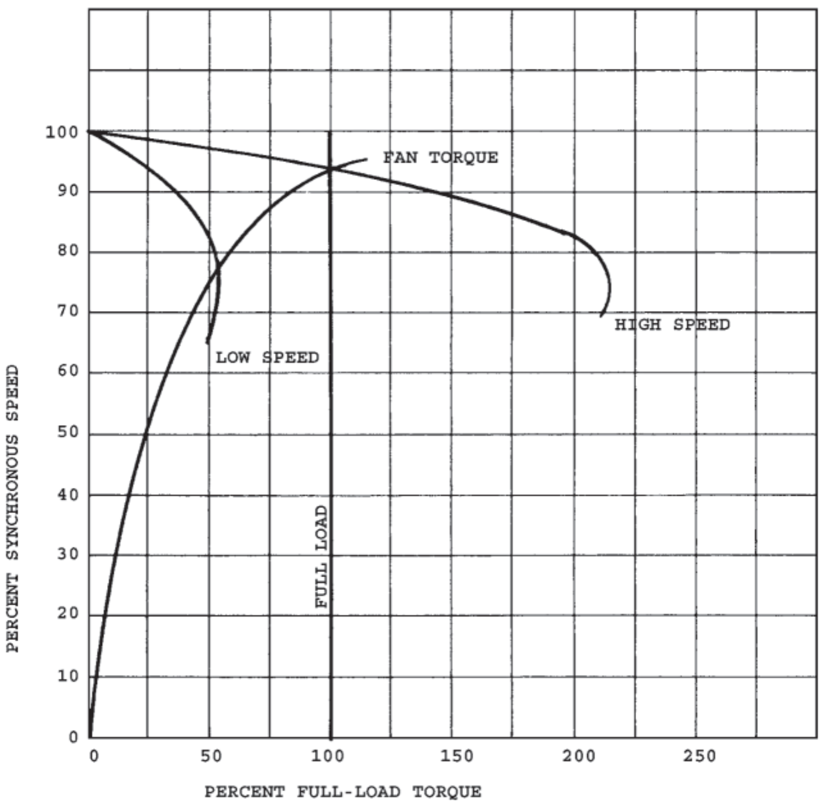

FIGURE 1.24 Speed-torque curves for a permanent split capacitor single-phase motor with a tapped winding.