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Fundamentals of Electric Power Conversion

Volume 1: Operating Characteristics and Testing of AC Induction Motors

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R E P O R T   S U M M A R Y

Fundamentals of Electric Power Conversion

Volume 1: Operating Characteristics and Testing of AC Induction Motors

The prominence of ac motor-driven systems in the energy consumption field has made them the target of numerous efficiency improvements. This report describes how induction motors work, explains their characteristics, and discusses induction motor testing.

INTEREST CATEGORIES

Plant electrical systems and equipment
Industrial
Utility planning studies

KEYWORDS

Motors
Induction motors
Energy efficiency

BACKGROUND Because of its simplicity and reliability, the induction motor is the most commonly used type of electric motor. Induction motors range in size from the fractional horsepower, single-phase motors found in household appliances such as refrigerator and air conditioner compressors, pumps, and fans to polyphase motors rated at thousands of horsepower for industrial applications. EPRI report TR-101264—*Assessment of Electric Motor Technology: Present Status, Future Trends, and R&D Needs*—offers a more detailed assessment of electric motor technology.

OBJECTIVES

- To describe the fundamental concepts that explain the operation of an induction motor.
- To discuss typical induction motor operating characteristics, nameplate rating, National Electrical Manufacturers Association (NEMA) design classifications, and tests.

APPROACH The principal investigator developed simple techniques for presenting basic principles of motor operation and performance characteristics such as speed-torque relationships, motor losses and efficiency, power factor versus speed, and many other salient application parameters. He presented the information from a nontechnical applications, marketing, motor planning, managerial perspective, with emphasis on energy-efficient motor replacement.

RESULTS Today, most of the available literature on electric motors is written for individuals with a high technology background. Through EPRI-sponsored workshops and projects, it has become apparent that a need exists for straightforward, qualitative information on ac induction motor technologies. The work described in this report provides a simple but comprehensive review for those interested in ac induction motor operating concepts. In particular, the report presents technical theories in a practical, informative manner. With a basic understanding of the underlying principles of motor operation explained in Volume 1, the nontechnical reader will have the necessary prerequisites for *Volume 2: Energy-Efficient Polyphase AC Induction Motors.*

EPRI PERSPECTIVE Electric motors keep American industry productive. Motor-driven processes and systems now represent nearly 70% of all the electricity used in the United States. Both utilities and their customers recognize the investment of motors in manufacturing products and providing services. Thus, many motor users are beginning to compare efficiencies of motors, types of motors, annual hours of motor operation, and motor loads. Escalating fuel and capital costs will continue to create strong incentives to strive for the highest possible motor system efficiency. Meeting this objective will require that motor users learn more about basic motor function, the electrical parameters that describe motor performance, and energy-efficient motor applications.

PROJECT
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Fundamentals of Electric Power Conversion

Volume 1: Operating Characteristics and Testing of AC Induction Motors

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ABSTRACT

Its rugged nature and straightforward design make the induction motor the most commonly used type of electric motor. This motor ranges in size from the fractional-horsepower, single-phase motors found in household appliances to polyphase motors rated at thousands of horsepower for industrial applications. Volume 1 of this report describes the function of induction motors, their characteristics, and induction motor testing. Volume 2 describes the characteristics of high-efficiency induction motors, with emphasis on the techniques used to obtain high efficiency. This two-volume report is written in nontechnical language and is intended for readers who require background from an applications, marketing, motor planning, or managerial perspective.

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Section 1
Introduction

Due to its simplicity and ruggedness, the induction motor is the most commonly used type of electric motor. Induction motors range in size from the fractional-horsepower, single-phase motors found in household appliances such as refrigerator and air-conditioner compressors, pumps and fans to polyphase motors rated at thousands of horsepower used in industrial applications.

The induction motor was invented in 1886 by Nicoli Tesla. It is said that after he conceived of the idea, he did all of the design work in his head and that the first one he built worked the first time he tried it. It is certainly a tribute to Tesla's great genius that, although many improvements have been made in induction motor design over the years, the basic operating characteristics of the induction motor remain the same as those of Tesla's first motor constructed over 100 years ago.

This report describes how induction motors work, explains their characteristics, and discusses induction motor testing.

Section 2
Principles of Induction Motor Operation

There are three fundamental concepts which combine to explain the operation of an induction motor. These are:

1. Polyphase currents flowing in distributed windings produce rotating magnetic fields.
2. Time-varying magnetic fields induce currents in closed (shorted) windings which in turn produce magnetic fields.
3. Attraction of the rotor and stator magnetic fields result in torque in a direction to align the windings and magnetic structures which produce the fields.

In this section, these three concepts are discussed and are used as the basis for a qualitative picture of induction motor operation.

2.1 Production of rotating magnetic fields

Figure 2–1(a) shows the form of the magnetic field produced by a single coil of wire carrying a current I. This form of magnetic field is commonly called a dipole field and can be thought of as having north (N) and south (S) magnetic poles as shown. Figure 2–1(b) shows in schematic form that the general form of this magnetic field is unaltered if this coil is placed in slots in the *stator* structure of an induction motor. The stator is the stationary component of an induction motor and serves to produce the magnetic fields which cause the motor to operate. The stator core is made of magnetic steel which greatly enhances the strength of the magnetic field produced by the coil. This does not alter the dipole nature of the magnetic field, the alignment of which is indicated by the large arrow in figure 2–1(b). The line along which this magnetic field is aligned is commonly known as the magnetic axis of the coil.

Figure 2–2 shows how two coils can be used to produce a rotating magnetic field in a stator structure. In this figure, two coils are placed in the stator such that their magnetic axes are perpendicular. In figure 2–2(a), a current $i_1 = I_o$ is flowing in the first coil while the current i_2 in the second coil is zero. Figure 2–2(b) shows the situation when current i_1 is zero and a current $i_2 = I_o$ is applied to the second coil. Notice that the direction of the magnetic field has rotated by 90° degrees in the clockwise direction. If the current i_2 is then reduced to zero and the current in the first coil is reversed from its value in figure 2–2(a), the magnetic field will rotate an additional 90° as shown in figure 2–2(c). Finally, the rotation can be completed (figure 2–2(d)) if the current i_1 is again reduced to zero and the current i_2 is reversed from its value in figure 2–2(b).

In a practical induction motor, the stator slots are distributed uniformly around the stator inner radius and many coils are connected to form *phase windings*. Figure 2–3 shows

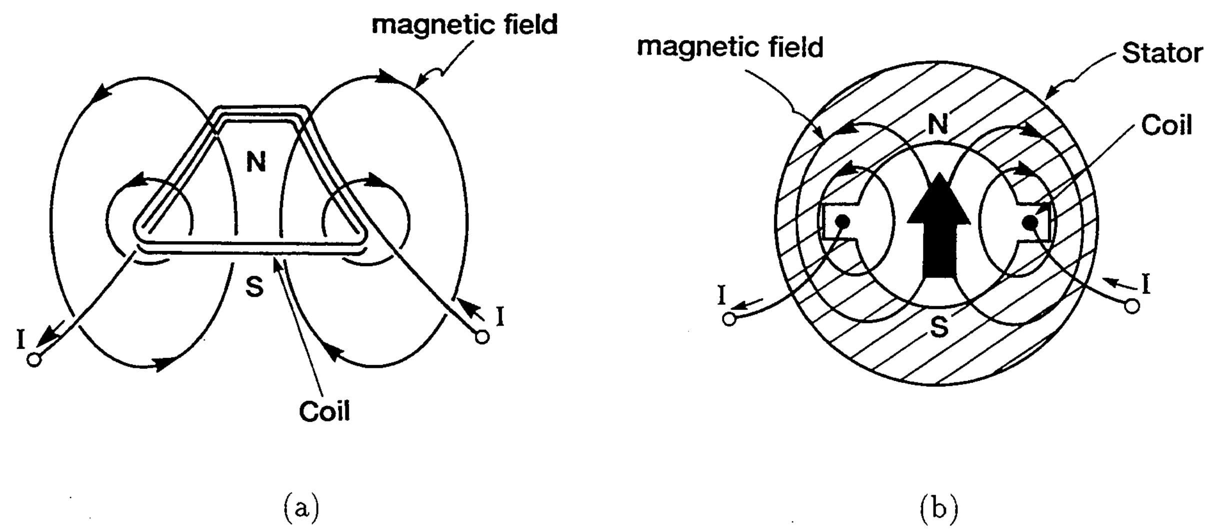


Figure 2–1: (a) Magnetic field produced by a current flowing in a coil. (b) Magnetic field produced by a single coil placed in slots in an induction motor stator structure.

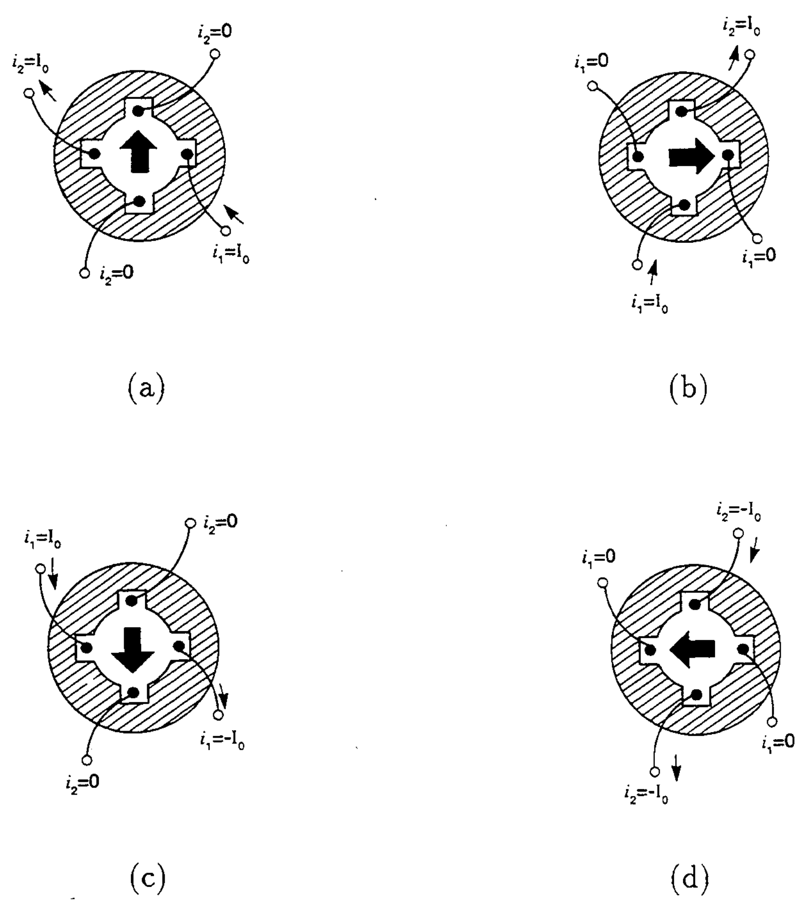


Figure 2–2: Magnetic fields produced by currents in a two-phase winding. (see the discussion in the text).

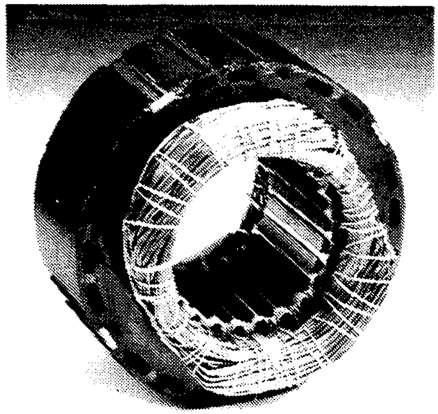


Figure 2–3: The stator structure of a single-phase induction motor showing the main and starting windings. As discussed in section 5, this winding distribution is similar to that of a two-phase motor. (Courtesy General Electric Company)

the stator structure of a practical induction motor. Each phase winding makes a magnetic field similar to that of a single coil. Thus, the two-coil configuration shown schematically in figure 2–2 can be used to describe the performance of a practical two-phase induction motor.

In normal operation, sinusoidal currents are applied to induction motor windings. Figure 2–4 shows a plot of the phase currents versus time for a two-phase motor. The currents in this figure can be described mathematically as:

phase 1:

$$i_1(t) = \sqrt{2}I\cos(2\pi f t) \tag{1}$$

and phase 2:

$$i_2(t) = \sqrt{2}I\sin(2\pi f t) \tag{2}$$

where f is known as the frequency of the currents (measured in Hertz (abbreviated as Hz)). In the US, electric power is generated at a frequency of 60 Hz. A set of currents of this form is known as a balanced, two-phase set of currents because the currents are of equal magnitude and separated by 90° in time phase (i.e. one current is at maximum as the other goes through zero).

Notice from figure 2–4 that the times t_a, t_b, t_c and t_d correspond directly to the four current distributions of figures 2–2(a), (b), (c), and (d). For example, at time t_b, current i_1 is zero and current i_2 is at its maximum value, corresponding to the situation of figure 2–2(b). Thus we see that balanced, two-phase currents applied to the stator of a two-phase motor create a magnetic field that rotates one revolution during one cycle (i.e. in time $T = 1/f$) of the applied currents. For a frequency of 60 Hz, the period $T = 1/60$ second and the magnetic field distribution in this two phase machine will rotate at a speed of 60 revolutions per second or 3600 revolutions per minute (rpm).

A similar situation occurs with three-phase motors. A three-phase motor has three sets of windings, uniformly distributed around the stator inner radius with their magnetic axes

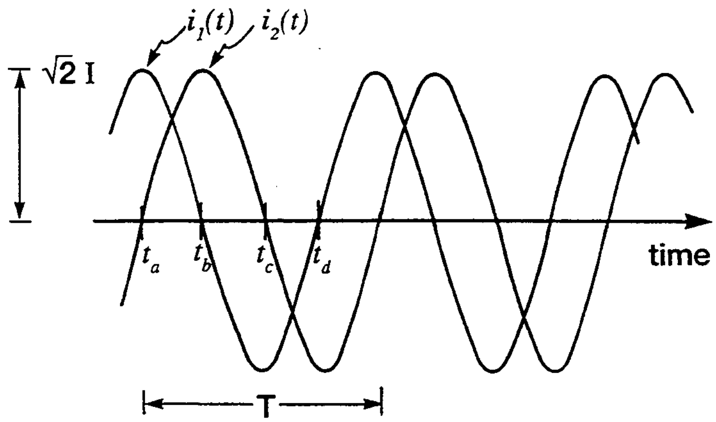


Figure 2–4: Balanced, two-phase currents

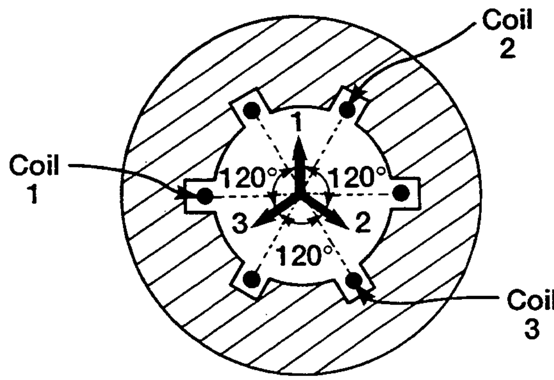


Figure 2–5: Schematic view of the stator of a three-phase induction motor showing the magnetic axes of the three phase windings.

displaced by 120° from each other as shown schematically in figure 2–5. When balanced, three-phase currents of the form

$$i_1(t) = \sqrt{2}I\cos(2\pi ft) \tag{3}$$

$$i_2(t) = \sqrt{2}I\cos(2\pi ft - 120°) \tag{4}$$

$$i_3(t) = \sqrt{2}I\cos(2\pi ft + 120°) \tag{5}$$

are applied to the phase windings, the result will be a magnetic field that rotates through one complete revolution in time $T = 1/f$ seconds.

The above discussion applies to what are known as 2-pole winding distributions. This means that the windings are arranged so that they produce only one set of north/south poles which are created when a given phase is energized with current. Often times, stators are constructed with 4, 6 or even more poles.

The 4 pole configuration is quite common (see figure 2–6). Because there are twice as many poles around the stator inner radius, the magnetic field will rotate only one half of a rotation during one cycle of the applied currents. Thus, for a given frequency of applied current, the magnetic field for a 4-pole configuration will rotate at half the speed of that for

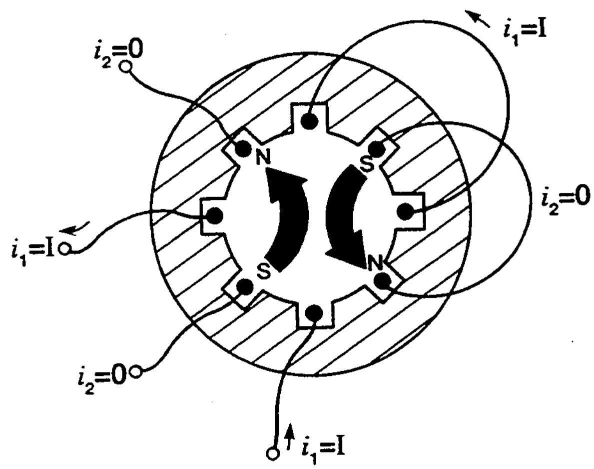


Figure 2–6: Schematic view of a 2-phase, 4-pole stator showing magnetic field distribution with current flowing in phase 1

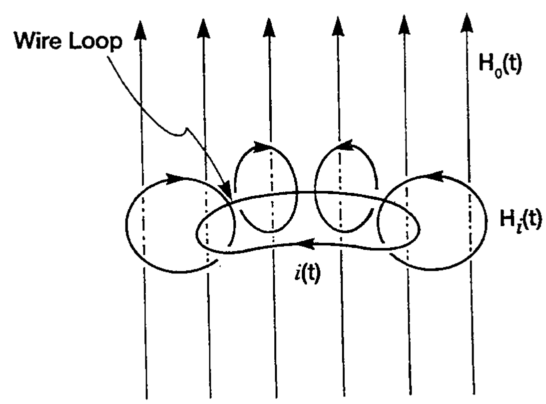


Figure 2–7: In the presence of a time-varying magnetic field $H_o(t)$, a current $i(t)$ is induced in a closed loop of wire

a 2-pole configuration. Specifically, the magnetic field of a 4-pole motor with 60 Hz applied currents will rotate at 30 revolutions per second (1800 rpm).

2.2 Induced currents due to time-varying magnetic fields

A fundamental law of electromagnetism (known as *Faraday's law*) states that electric fields are produced by time-varying magnetic fields. For example, if the current in a coil of wire varies with time, the magnetic fields produced by that coil of wire will also vary with time and there will be electric fields produced in the space surrounding the coil. An important consequence of Faraday's law is that when time-varying magnetic fields are produced in regions of space containing metallic conductors, the resultant electric fields will produce currents in the conductors which in turn will produce additional magnetic fields. This is illustrated in figure 2–7. In this figure, drawn at a time when the applied field $H_o(t)$ is increasing in magnitude in the upward direction, a current $i(t)$ can be seen to have been induced in a closed loop of wire.

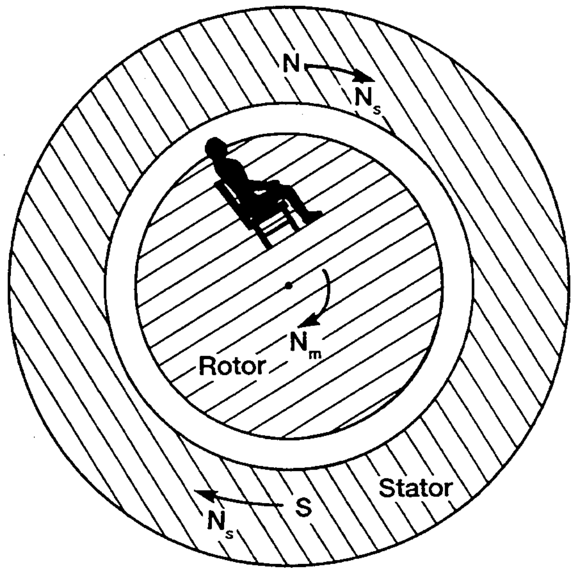


Figure 2–8: Schematic motor showing the stator magnetic field rotating at a speed of N_s rpm and a rotor rotating at N_m rpm. Also shown is an observer fixed to the rotor.

Figure 2–7 also shows the field $H_i(t)$ that is produced by the induced current $i(t)$. Notice that, inside the wire loop, this field is in the direction opposite to that of the applied field $H_o(t)$. This is an example of a principle called *Lenz's law*, which states that the induced current will be in such a direction as to produce magnetic fields which oppose any changes in the magnetic fields through the coil[1].

In devices such as inductors and transformers, time variation of magnetic fields is caused simply by the time variation of currents which produce them. However, in electromechanical devices such as induction motors, there is an additional source of time varying fields. Specifically, time variation of the magnetic fields within the motor can be produced by the relative motion of a rotor with respect to the rotating magnetic field produced by the stator windings.

This relative motion is fundamental to the operation of the induction motor. Consider the schematic motor shown in figure 2–8. The stator currents, at frequency f_s, produce a magnetic field (indicated by its north (N) and south (S) poles) which rotates at a speed of

$$N_s = \frac{120 f_s}{P} \tag{6}$$

rpm (known as *synchronous speed*) with respect to the stationary stator, where P is the number of magnetic poles. Also shown in the figure is the cylindrical, inner component of the motor called the *rotor*. The rotor is that component of an induction motor that is free to rotate and from which the motor transmits mechanical torque to its load.

In figure 2–8, the rotor is shown to be rotating at a speed of N_m rpm. Notice, that to

[1] More formally, Lenz's law can be stated as saying that the induced current will produce magnetic fields which oppose any change in the flux linkages of the coil

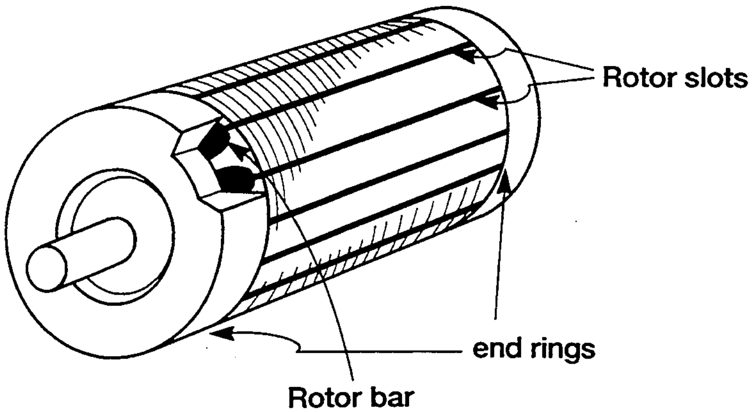


Figure 2–9: Schematic view of the rotor of a squirrel-cage induction motor. Rotor bars and slots can be seen where the end ring is shown partially cut away.

an observer sitting on the rotor, the stator flux wave appears to be rotating at a speed of $N_r = (N_s - N_m)$ rpm. In other words, the observer on the rotor will see the stator magnetic field varying at a frequency

$$f_r = \frac{(N_s - N_m)P}{120} \tag{7}$$

It is common to define a quantity called *slip*, referred to by the symbol s, as

$$s = \frac{N_s - N_m}{N_s} \tag{8}$$

This name refers to the fact that the rotor is "slipping" with regard to the stator magnetic field. It is for this reason that induction motors are referred to as being *asynchronous* machines; this is to distinguish them from synchronous machines in which the rotor rotates at the same speed as (i.e. in synchronism with) the stator magnetic field. From equations 6 and 8, it is possible to write equation 7 as

$$f_r = sf_s \tag{9}$$

In other words, the observer on the rotor sees the stator magnetic field varying at *slip frequency*, equal to the stator electrical frequency multiplied by the rotor slip.

Figure 2–9 shows a schematic view of the rotor of a *squirrel-cage* induction motor. The rotor is made up of laminated magnetic material with slots similar to those on the stator. In the squirrel-cage rotor, these slots are filled with solid conducting material (typically aluminum or copper), commonly called rotor bars. All of the rotor bars are shorted together by conducting rings at each end of the rotor. The net result is a conducting structure which is quite similar to the revolving exercise wheels which are often placed in pet hamster cages. Figure 2–10 is a cutaway view of a three-phase squrrel-cage induction motor.

Squirrel-cage induction motors are by far the most commonly used motor type because of their simplicity of construction and their reliability. *Wound-rotor* induction motors are

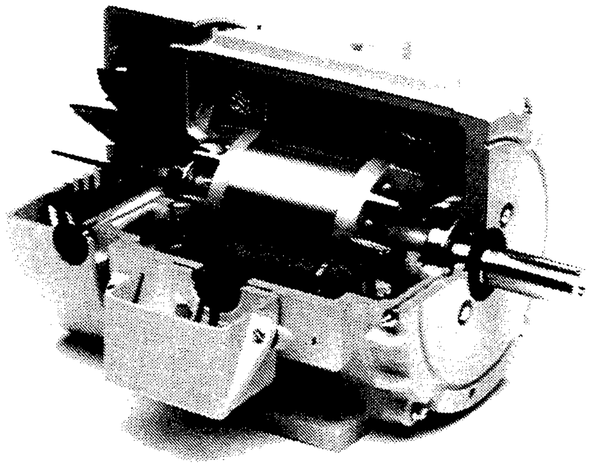


Figure 2–10: Cutaway view of a three-phase squirrel-cage induction motor. (Courtesy General Electric Company)

constructed with rotor windings which are similar to the windings on induction motor stators. These windings, whose terminals are connected to slip rings, are then shorted, either directly at the slip rings or through external resistors. Although the ability to connect external resistance provides flexibility not obtainable with squirrel-cage motors, the additional expense and complexity of wound-rotor motors preclude their use in most applications.

As we have seen, currents of slip frequency ($f_r = sf_s$) are induced in the rotor conductors as the rotor slips past the synchronously-rotating magnetic fields produced by the stator winding. These currents will in turn produce a magnetic field which will rotate at a speed of

$$N_r = \frac{120 f_r}{P} \tag{10}$$

with respect to the rotor. It can easily be shown that

$$N_m + N_r = N_s \tag{11}$$

In other words the rotor magnetic field rotates at the same speed as (i.e. in synchronism with) the stator magnetic field. Thus, even though the rotor rotates asynchronously, the torque in an induction motor is produced by stator and rotor magnetic fields which rotate synchronously.

2.3 Torque production

In the last section, we saw that when the rotor of an induction machine slips with respect to the rotating magnetic field produced by currents flowing in the motor's stator windings, currents will be induced in the rotor which will in turn produce a rotating magnetic field.

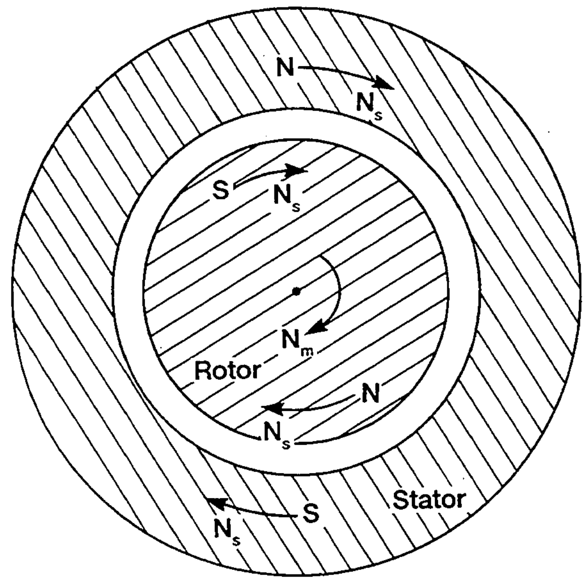


Figure 2–11: Schematic view of the stator and rotor magnetic fields. The rotor field rotates at the same speed N_s as that of the stator but lags behind the stator field.

This magnetic field will rotate synchronously with that produced by the stator currents. In addition, consistent with Lenz's law, the rotor field will tend to be in a direction in opposition to the stator field (e.g., its N pole will be aligned so as to tend to cancel the S pole of the stator).

Because of the electrical resistance inherent in the rotor conductors, this cancellation will not be perfect; the two fields will not perfectly align. This situation is illustrated in figure 2–11 where it can be seen that the stator and rotor fields both rotate at synchronous speed N_s but that the rotor field lags behind that of the stator. In a fashion similar to that which produces force between two bar magnets (attraction between opposite poles), there will be a force (in this case more correctly a torque since the motion is rotary) tending to align the two magnetic fields.

We have just described the basic operating principle of an induction motor. The magnetic field of the stator will produce a torque "pulling" on the magnetic field of the rotor, and thus on the rotor itself. This torque will be proportional to the strength of the two magnetic fields. Thus one can immediately see that the induction motor will produce no torque when the rotor rotates at synchronous speed (slip $s = 0$) since there will be no induced rotor currents and hence no rotor-produced magnetic field. As the slip increases from zero (i.e. the rotor slows down from synchronous speed), the rotor currents will begin to increase and correspondingly, so will the torque. The details of the torque versus speed characteristic of an induction motor are discussed in the following section.

Section 3
Induction Motor Operating Characteristics

In the previous section, we discussed the basic operating principles of an induction motor. In this section we will discuss typical induction motor operating characteristics.

3.1 Speed-torque characteristic

Figure 3–1 shows the speed-torque characteristic of a typical induction motor. Notice that, as expected, the induction motor develops no torque at synchronous speed (slip $s = 0$). Also note that the torque increases as the motor speed N_m drops below synchronous speed N_s. This continues until rotor inductance effects limit the torque to a maximum value, known as the breakdown torque and indicated by T_{max} in the figure. The torque drops below this value for higher values of slip.

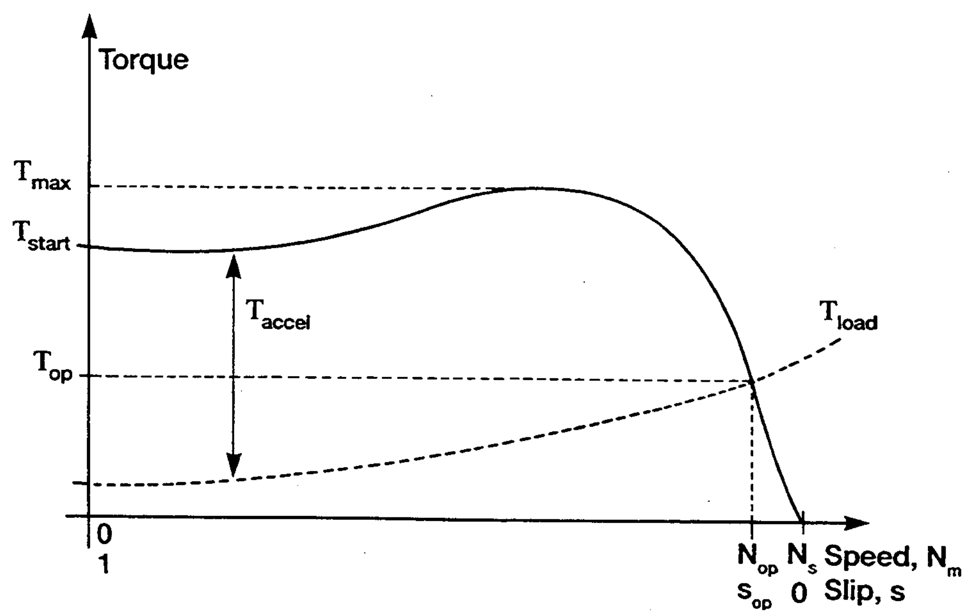


Figure 3–1: Induction motor speed-torque characteristic

Figure 3–1 also shows a typical load characteristic. Note that when the motor is first energized, its speed is zero and its torque is indicated by the value T_{start} in the figure. As long as this *starting torque*, commonly known as the *locked-rotor torque*, is greater than the load torque at zero speed, the motor will begin to accelerate the load. At any given speed, the difference between the motor torque and the load torque is the accelerating torque, indicated by T_{accel} in figure 3–1.

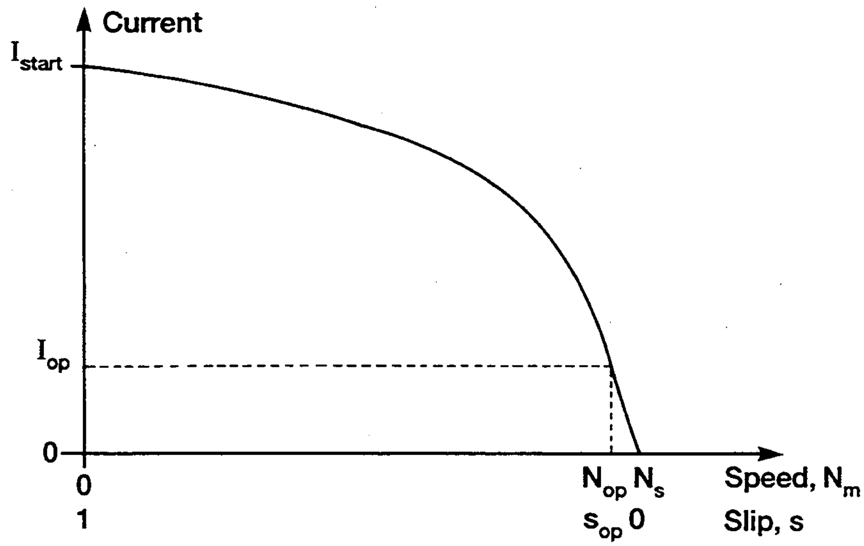


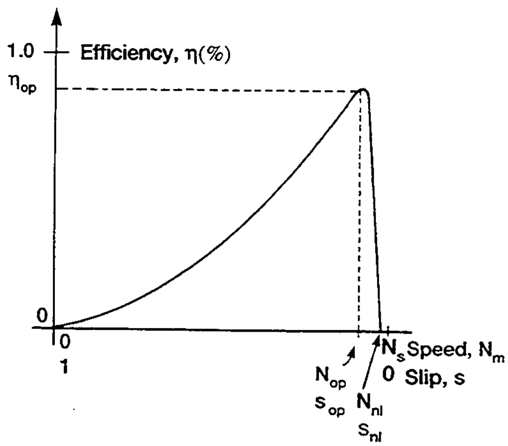
Figure 3–2: Induction motor speed-current characteristic

Positive accelerating torque causes the motor speed to increase. Thus, from figure 3–1, it can be seen that the motor speed will contine to accelerate up to the point where the load and motor torque curves intersect, at which point the accelerating torque is zero and thus the motor will no longer continue to accelerate. For a given load, this intersection defines the operating point of the motor and its load. The motor speed will be N_{op} and its torque will be T_{op} as indicated in figure 3–1. Notice that the operating point of an induction motor is determined by both the motor and the load characteristics and thus to achieve desired operation, the motor must be in some sense matched to the characteristics of the load.

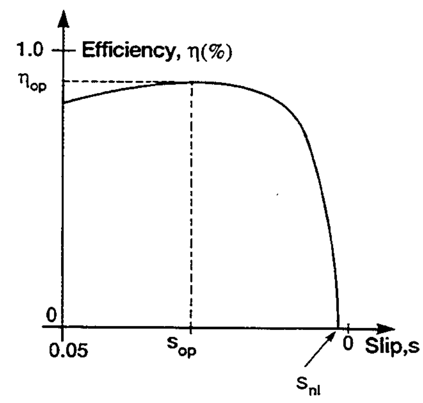
For most induction motors, the slip at full load is small and the speed at full load is thus close to synchronous speed. A typical example is a 4-pole, 60 Hz motor whose synchronous speed is 1800 rpm and whose full-load speed is 1765 rpm, corresponding to a full-load slip of 0.019 (equivalently, this is often referred to as a slip of 1.9%). As the load on this machine is reduced from its rated value, the speed will increase; when this machine is unloaded, its speed will be somewhere between 1799 and 1800 rpm, with just enough slip to produce the torque required to supply the motor's rotational losses.

3.2 Speed-current characteristic

Figure 3–2 shows a curve of current versus speed for a typical induction motor. Notice that the motor current is relatively high for low speeds (high slip) and begins to drop only for low slips. In general, induction motors draw much larger currents under starting conditions and as they accelerate to operating speed (up to six times rated current or higher) than they do under the steady-state operating conditions. In figure 3–2, the starting current I_{start} can be seen to be significantly larger than operating current I_{op}.



(a)



(b)

Figure 3–3: Induction motor speed-efficiency characteristic

3.3 Efficiency

Figure 3–3(a) shows a curve of induction motor efficiency versus speed. Figure 3–3(b) shows this same curve over a slip range of 0 to 0.05 (zero to 5%) which includes the normal operating range of this particular motor. The efficiency η of an induction motor (in %) is defined as 100 times the ratio of output power to input power.

$$\eta = 100\% \times \frac{P_{out}}{P_{in}} \tag{12}$$

This can also be written as

$$\eta = 100\% \times \frac{P_{in} - P_{loss}}{P_{in}} \tag{13}$$

where

P_{in} = Power input
P_{out} = Power output
P_{loss} = Power loss within the motor

Induction motor losses can be sub-divided into catogories according to their source and physical mechanism. A common subdivision is given by

$$P_{loss} = P_{diss} + P_{core} + P_{rotation} + P_{stray} \tag{14}$$

Here

P_{diss} represents the I^2R (ohmic) heating in the stator and rotor conductors of the motor.

P_{core} is the core loss corersponding to hysteresis and eddy-current loss in the rotor and stator magnetic material.

$P_{rotation}$ is the rotational loss due to friction and windage losses associated with the rotor, the bearings and the cooling fan.

P_{stray} is known as the stray-load loss and corresponds to the remaining losses within the motor which do not fall into the above categories. These losses are produced by mechanisms such as space-harmonic fluxes and time-harmonic currents. They are typically small and are also somewhat difficult to analyze.

Note that the efficiency of an induction motor is zero at zero speed because there is no power output from the motor. The efficiency is also zero when the motor is operating with no load; no load operation corresponds to a speed (N_{nl} in figure 3–3(b)) slightly less than synchronous speed at which the motor is producing only enough power to supply its own rotational losses. Typically, an induction motor will achieve its maximum efficiency at or somewhat below its rated load.

3.4 Power factor

A curve of power factor versus speed is shown in figure 3–4(a). Figure 3–4(b) shows this same curve over a slip range of 0 to 0.05 which includes the normal operating range of this particular motor. For a three-phase motor operating under balanced conditions, the power factor [2] pf can be determined as

$$pf = \frac{P_{in}}{\sqrt{3}V_{l-l}I} \tag{15}$$

where

P_{in} = Motor input power
V_{l-l} = Motor line-line terminal voltage (rms)
I = Motor phase current (rms)

The power factor of an induction motor can best be understood with reference to figure 3–5 which shows the steady-state equivalent circuit for an induction motor. This equivalent circuit, which will not be discussed in detail here, serves as the basis for the analysis of steady-state induction motor performance [3].

[2] For a more complete discussion of power and power factor, the reader is referred to "ELECTRIC POWER BASICS: END-USE, Taking the mystery out of electrical energy, power, efficiency, and power factor", EPRI, CU.3038R.10.91

[3] For details of the derivation of this equivalent circuit and its use in the analysis of induction motor performance, the reader is referred to C. Kingsley, Jr., A.E. Fitzgerald and S.D. Umans, ELECTRIC MACHINERY, fifth edition, McGraw-Hill Book Co., New York, 1990

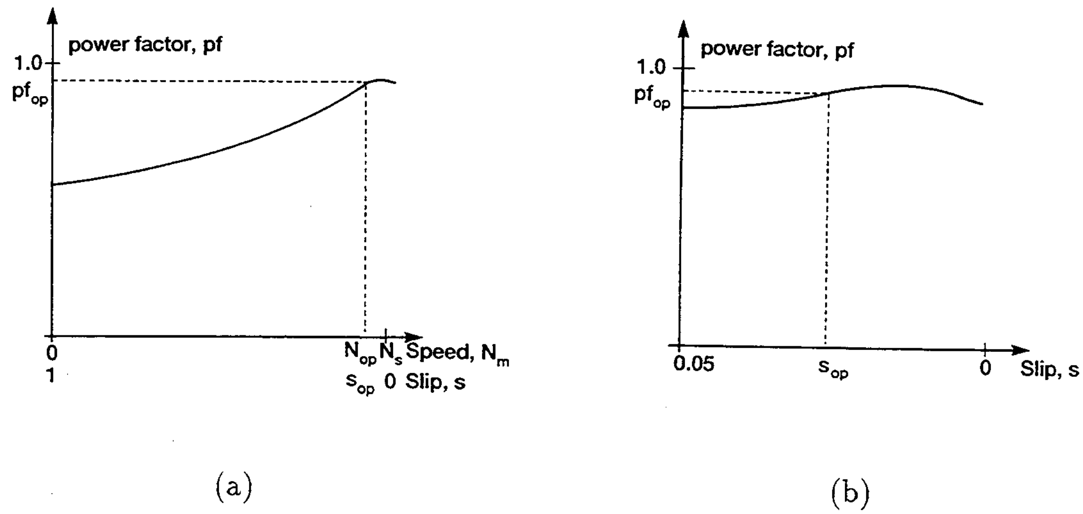


Figure 3–4: Induction motor speed-power factor characteristic

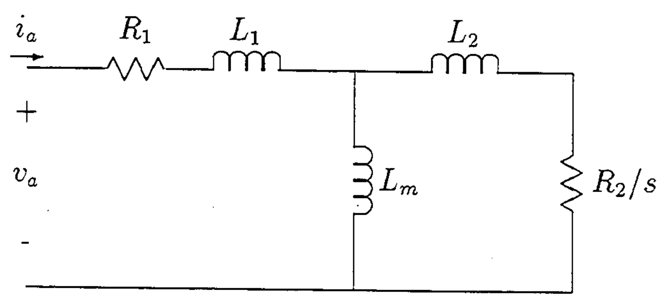


Figure 3–5: Single-phase, steady-state equivalent circuit of an induction motor

Notice that the equivalent circuit contains both resistors (R_1 and R_2/s) and inductors (L_1, L_2 and L_m). The resistors correspond both to power dissipation in the induction motor and to its output power. The inductors correspond to energy stored in the magnetic fields within the induction motor. As we have seen, these magnetic fields are integral to the operation of induction motors. As a result, the current supplied to an induction motor must not only supply the losses and output power but also supply its magnetic energy requirements. For this reason, induction motors always operate at a lagging (i.e. inductive) power factor less than unity ($pf < 1.0$).

Although lagging power factor is an inherent characteristic of induction motors, it is possible to improve the power factor which is seen by the electric system to which they are connected. As with any inductive circuit, the addition of capacitors (which operate at leading power factor) can be used to supply the magnetic stored energy required by the induction

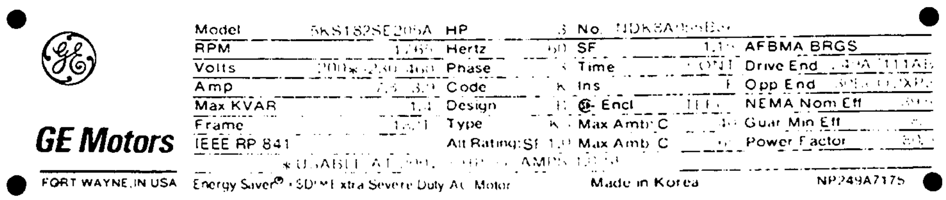


Figure 3–6: Typical induction motor nameplate. (Courtesy General Electric Company)

motor [4]. It is important to recognize that the addition of these capacitors does not effect the operating conditions within the motor. Rather, the capacitors supply a component of the motor current that would otherwise be supplied by the power system, thus reducing the supply current required to operate the motor.

There are many ways in which power factor correction capacitors can be connected to an induction motor. They can be connected directly at the terminals of individual motors or they can be connected at a local feeder to correct the power factor of a group of motors. In recent years, various schemes have been proposed in which the capacitors are connected to auxilliary motor windings. In all cases, the result is the same; the motor power factor is improved and the current drawn from the supply is reduced. As a rule of thumb, in order to avoid problems with a phenomenon known as *self excitation* which can cause damage to the motor, it is common to avoid adding sufficient capacitance to fully correct the motor power factor to unity.

3.5 Motor nameplate and rating

Figure 3–6 shows the nameplate from a typical three-phase induction motor. The information found on the motor nameplate describes the major operating characteristics of the motor at its rated (maximum load) operating point. In most cases, damage to the motor may result if the conditions of rated-load operation are exceeded.

NEMA standard MG 1[5] specifies the information to be included on induction motor nameplates. For medium sized polyphase induction motors, this information includes:

- Manufacturer's type and frame designation. The frame designation refers to a NEMA standard framesize (see NEMA MG 1).
- Full-load horsepower.

[4]Power factor correction is discussed in detail in "ELECTRIC POWER BASICS: END-USE, Taking the mystery out of electrical energy, power, efficiency, and power factor", EPRI, CU.3038R.10.91

[5]NEMA Standards Publication No. MG 1, National Electrical Manufacturers Association, 2101 L Street, N.W., Washington, D.C. 20037

• Rated voltage. NEMA standards state that the motor should be able to operate successfully at rated load with voltage variations up to plus or minus 10% of this value when operated at rated frequency.

• Full-load current. When operated at rated voltage and frequency, the motor current can be expected to be within 10% of this value.

• Approximate rpm at full-load.

• Electrical operating frequency.

• Maximum ambient operating temperature. This is the maximum ambient temperature at which the motor can be operated at its rated conditions.

• NEMA nominal efficiency. This value describes the nominal efficiency as measured on a representative population of motors of a given design [6].

• kVA code. This is a code letter which can be used to determine the locked-rotor (zero-speed) kVA of the motor [7]. This number in turn can be used to calculate the locked-rotor current (also known as the starting current or inrush current) of the motor.

• NEMA design letter. These letters are used to loosely categorize the motor operating characteristics. These characteristics are described in greater detail in section 3.6.

• Service factor. The service factor is a multiplier which, when applied to the rated horsepower of a motor, indicates a permissible horsepower loading which can be carried by that motor when the motor voltage and frequency are maintained at their nameplate values. When the motor is operated at any service factor greater than unity, its current, speed, efficiency and power factor may be different than their nameplate values. It should be emphasized that operation at higher than rated output power will result in motor temperatures in excess of those corresponding to operation at rated load. Although this operation is permissible and will not cause immediate damage to the motor, it is likely to somewhat accelerate aging of the motor insulation and to reduce its lifetime.

For the motor whose nameplate is shown in figure 3–6, the nameplate indicates the following values:

- Frame 182T

- 3 horsepower

- 230/460 Volts. This is a dual-voltage motor. It can be connected to operate at either of these two voltages.

- 7.8/3.9 Amps. These are the full-load currents corresponding to the two voltage connections. The higher current corresponds to the lower supply voltage.

[6] See NEMA MG 1, sections 12.54 and 12.55

[7] See NEMA MG 1, section 10.37

- 1765 RPM. This motor will operate at approximately 1765 rpm at full load.

- 60 Hertz. This motor is intended to operate on a 60 Hz ac system.

- 40° C maximum ambient temperature.

- 89.5% nominal efficiency. Note that this nameplate also indicates that the manufacturer guarantees that the full-load efficiency of this motor will not be less than 88.5%.

- Code K. The kVA code of this motor indicates (with reference to section 10.37.2 of NEMA MG 1) that the locked-rotor kVA for this motor falls in the range of 8.0 - 9.0 kVA per horsepower. For this 3 HP motor, this indicates that the locked rotor kVA will fall in the range of 24 to 27 kVA. This can be used to calculate the locked-rotor current as being between 60.2 and 67.8 amperes when operated at 230 volts and one half of this value when operated at 460 volts.

- Design B.

- SF 1.15. The service factor of this motor is 1.15. Thus if it is operated at rated voltage and frequency, it can be safetly operated at a output power of $1.15 \times 3 = 4.45$ horsepower.

The name plate of this motor also indicates that its enclosure is classified by NEMA as being totally-enclosed, fan-cooled (Enc. TEFC). The term "totally-enclosed" indicates that the motor construction in such a fashion as to prevent the free exchange of air between the inside and outside of the motor case. The term "fan-cooled" indicates that the motor is cooled by a fan mounted on the motor shaft, external to the motor case, which is surrounded by a shroud which both for safety reasons and to channel the cooling air along the outside of the motor case. Other common enclosure classifications are:

- Dripproof - Such motors have an open frame construction, permitting outside air to enter the machine to provide cooling, with ventilation openings constructed such that motor operation will not be hampered by liquid or solid particles which strike the motor at any angle from 0 to 15 degrees downward from the vertical.

- TENV (totally-enclosed, non-ventilated) - In smaller motor sizes, acceptable cooling of a totally-enclosed motor may be obtained without the need for a cooling fan.

- Explosion-proof - This is a totally-enclosed motor which can withstand an explosion of a specified gas or vapor within the motor and which is constructed to prevent the ignition of the gas or vapor surrounding machine by sparks or explosions within the machine.

3.6 NEMA design classifications

NEMA has defined various classifications for medium-size, polyphase induction motors. They are characterized by specifications of starting current, locked-rotor torque, breakdown torque

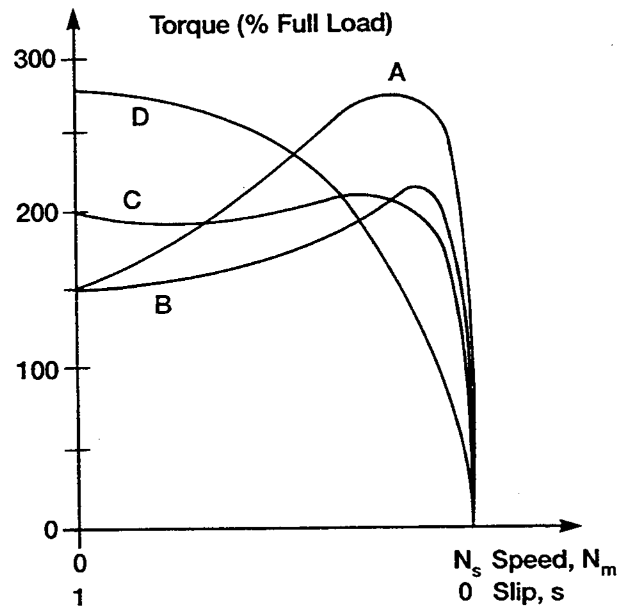


Figure 3–7: Typical speed-torque curves for NEMA design A, B, C and D squirrel-cage induction motors

and slip at full load. These classifications can be useful as a preliminary criterion in the selection of a motor for a specified appliation. However, it should be pointed out that these classifications are not intended to be design specifications and thus there can be considerable variation in the characteristics of similar motors of differing designs and manufacturer within any given NEMA design classification.

Figure 3–7 shows typical speed-torque curves for NEMA design A, B, C and D polyphase, squirrel cage motors. Table 3–1 briefly describes the general characteristics of these four NEMA design classes.

The different characteristics of the various motor NEMA design classes, as indicated in figure 3–7 and table 3–1, are obtained through variations in rotor and stator designs. Specifically, the shapes of the rotor bars are varied to take into account the fact that frequency of the rotor currents is proportional to the rotor slip, as seen in equation 9. The designer takes advantage of the fact that higher rotor-current frequency (lower rotor speed) tends to force rotor-bar currents to the top of the rotor slot. This change in the current pattern with frequency causes corresponding changes in rotor resistance and inductance which in turn change the torque and current characteristics of the motor. A wide variety of rotor bar shapes (deep bar, double-squirrel-cage, etc.) have been devised to provide the many available motor characteristics.

Table 3–1: Characteristics of NEMA design A, B, C and D motors

Design	A	B	C	D
Starting current	High	Medium	Medium	Medium
Starting torque	Medium	Medium	High	Very high
Maximum torque	High	Medium	Medium	Very high

APPLICATIONS

Design A and B: Fans, blowers, rotary pumps, unloaded compressors, loads with low inertia.

Design C: High inertia loads such as large centrifugal blowers, fly wheels, and pulverizers. Also loads requiring high starting torques such as piston pumps and conveyers.

Design D: Very high inertia loads and loads which require very high starting torques. Loads which require large speed variations such as punch presses. Cranes, hoists and elevators.

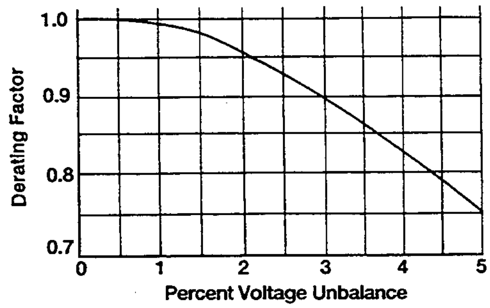


Figure 3–8: Derating curve for unbalanced operating conditions

3.7 Effects of unbalanced voltages

Although polyphase induction motors are designed to operate under balanced operating conditions, such conditions are not always found in practice. Unbalanced voltages result in additional losses and reduced torque production from the motor. In order to prevent damage to the motor, NEMA standard MG-1 defines a derating factor by which a motor's rated horsepower should be multiplied under unbalanced operating conditions[8]. The NEMA curve for derating factor as a function of percent voltage unbalance is shown in figure 3–8, where the percent voltage unbalance is defined as 100% times the ratio of the maximum voltage deviation from the average to the average voltage.

[8]See NEMA MG 1, section 14.35

Section 4
Induction Motor Tests

A number of tests have been defined for the measurement of polyphase induction motor performance. In this section a few of the most common tests are described. IEEE Standard 112-1984 [9] should be referred to for a more complete discussion of induction motor testing.

4.1 Instrumentation

Testing of induction motors typically involves measurements of electrical quantities such as:

CURRENT - Current is measured by an instrument called an *ammeter* which measures the magnitude of the current. Depending upon the application, an ammeter may be connected directly to the line in which the current is to be measured or it may be connected via a device called a current transformer. A three-phase motor has three phases and thus three currents should be measured. Most induction motor stator windings are either delta connected or ungrounded-Y connected. For these connections, the phase currents must sum to zero at any given instant in time and thus appropriate instrumentation of only two phases can be used to determine the magnitudes of all three phase currents. If the induction motor operating conditions are balanced, such measurements would show that the three phase currents are equal in magnitude.

VOLTAGE - Voltage is measured by an instrument called a *voltmeter* which measures the magnitude of the voltage. Depending upon the application, a voltmeter may be connected directly to the line in which the voltage is to be measured or it may be connected via a device called a potential transformer. On three-phase motors it is common to measure the three phase-to-phase (commonly referred to as line-to-line) voltages, although, because these voltages must sum to zero at any instant of time, instrumentation of only two phases is required to obtain these three measurements. Alternatively, if the motor is connected grounded-Y, the three phase-to-ground (commonly referred to as line-to-ground) voltages can be measured. Under balanced operating conditions, the magnitudes of the three voltages (either line-to-line or line-to-ground) will be found to be equal.

POWER - Power is measured by an instrument called a *wattmeter*. For three-phase motors, a three-phase wattmeter can be used. This instrument uses measurements of the motor terminal voltages and currents to determine the total power input (measured in units of watts or kilo-watts) to the motor. Alternatively, it is possible to measure the power input to the individual phases and

[9] "IEEE Standard Test Procedure for Polyphase Induction Motors and Generators", Institute of Electrical Engineers, Inc, 345 East 47th Street, New York, NY 10017

Table 4–1: Values of κ for equation 16

Power	Torque	κ
HP	Newton-meters	7124
kW	Newton-meters	9549
HP	pound-feet	5257
kW	pound-feet	7047

to sum the result to obtain the total power input. Under balanced conditions, the total power input will be equal to three times that of any individual phase. Wattmeters are commonly connected to motor terminals using current and/or potential transformers.

In order to test an induction motor over its range of operating conditions, some sort of load is required. In some cases, the motor is simply tested while it is in service and thus its operating load is used. However, often it is desireable to test the motor under laboratory conditions in which the load can be carefully controlled and for which more careful measurements can be made. In such cases, the motor is typically connected to a device called a *dynamometer*. This is a generic name for any load which can be varied in a controllable fashion and which is instrumented to provide a measurement of the motor shaft torque.

There are many ways to measure torque. In some cases, the motor torque is determined from a measurement of the reaction torque on the dynamometer. The most direct method for torque measurement is by the use of a device called a *rotating torque transducer*. This is essentially a shaft section which is inserted between the motor shaft and its load. Strain guages mounted on the load-cell shaft provide a direct measurement of shaft torque. Special instrumentation is required to couple signals on to and off of the rotating shaft and to convert the strain guage signals into torque measurements.

Mechanical output power can be determined from the torque measurement and a measurement of the motor speed. The motor shaft speed can be measured by a device called a *tachometer*. There are many varieties of tachometer, including shaft-mounted dc and ac generators and various forms of encoders which determine speed from digital pulses generated as the motor shaft rotates. Once the motor speed N_m in rpm and torque T are known, the output power P_{out} can be calculated as

$$P_{out} = \frac{TN_m}{\kappa} \tag{16}$$

where the value of κ depends upon the units of torque and power, as shown in table 4–1.

Finally, it is common during testing to measure stator winding temperature. This measurement is performed to insure that the motor is not damaged during testing as well as to verify motor performance. Temperature can be measured using thermometers, thermocouples and thermistors. The average stator winding temperatures can be determined by shutting the motor off and quickly measuring the dc winding resistance and calculating temperature from a known relationship between dc resistance and temperature.

4.2 No-load test

For this test, the induction motor is operated at rated voltage and frequency with no mechanical load connected to its output terminal. Motor voltage, current and input power are measured. This test can be used to determine quantities such as:

- No-load motor loss. This loss consists predominantly of stator-winding, core and rotational losses. It is common to assume that the core and rotational losses are constant over the range of motor operation and thus this test provides approximate values for these losses corresponding to loaded operating conditions.
- The no-load test measurements are used to derive some of the parameters for the equivalent circuit of figure 3–5.

4.3 Locked-rotor test

For this test, the rotor of the induction motor is held in place so that it can not rotate. This can be done by either physically locking the rotor in place or by connecting the motor to a load whose starting torque requirement is greater than that which can be supplied by the motor. The conditions of this test correspond to starting conditions of the motor. Under these conditions, if the motor is operated from its rated voltage, it will draw considerably in excess of rated current and will rapidly overheat. Thus this test must be performed quickly. Normally, it is performed at reduced voltage and the results are scaled to their rated-voltage values.

A locked rotor test can be used to determine quantities such as:

- Starting current. This is the current which the motor will draw as it begins to accelerate its load. This current is typically considerably in excess of the rated-load current of the motor. When started, the motor will continue to draw relatively high current until it reaches a speed approaching its rated speed as can be seen from figure 3–2. The amount of time that is required to reach rated speed is a function of both the motor and load characteristics. The motor starter must be properly chosen so that its contactor does not open and trip the motor off line before the motor gets up to speed.
- Starting torque. This is the motor torque which is available to accelerate the load when the motor is initially energized at zero speed (see figure 3–1).

4.4 Tests under load

Using a dynamometer, it is possible to test an induction motor over a wide range of steady-state load conditions. Such tests can be used to determine characteristics such as:

- Motor torque as a function of speed.
- Motor current as a function of speed.
- Motor efficiency as a function of load. The motor efficiency η (in %) can readily be determined from measurements of motor input power P_{in} and output power P_{out} as

$$\eta = 100\% \times \frac{P_{out}}{P_{in}} \tag{17}$$

Load test data can be displayed, either in the form of curves or tables. Test data is often available from motor suppliers when motors are purchased. Such test data can be extremely useful in examining the performance of a specific motor in a given application. This is most apparent when one recognizes that very few motors are operated exactly at their nameplate rating.

Section 5
Single-phase Induction Motors

Most small, fractional-horsepower induction motors are *single-phase* motors. As is discussed in section 2.1, balanced, two-phase currents applied to the windings of a two-phase motor produce a rotating magnetic field. This rotating magnetic field is fundamental to induction motor operation.

If only one phase of a two-phase motor is excited by a sinusoidal current, the result will be a magnetic field that remains stationary in space but varies in magnitude. At one instant of time, the magnetic field will point in a given direction along the phase magnetic axis; a half cycle later, the field will have reversed direction. Because the magnetic field does not rotate, no torque will be produced on a stationary rotor placed in this magnetic field.

From the above description, it is difficult to see how a single-phase motor can operate. However, further analysis would show that this alternating magnetic field is equivalent to two half-magnitude rotating magnetic fields of equal magnitude rotating in opposite directions. When a stationary rotor is placed in such a magnetic field, the resultant torques produced by these two magnetic field components are equal in magnitude but opposite in direction, resulting in no net torque on the rotor.

This can be seen in figure 5–1 which shows, in simplified form, the torque as a function of rotor speed produced by the two rotating components of the single-phase magnetic field and the corresponding net torque. Note that each of the magnetic field components produces the torque characteristic of a two-phase motor with magnetic fields rotating in opposite directions. As expected, the two component torques sum to zero at zero speed.

It can also be seen that the net torque is non-zero when the rotor is rotating. In fact, the net torque when the rotor is rotating is quite similar in form to the torque produced by a two-phase motor with its magnetic field rotating in that direction. The consequence of this is that if the rotor of a single phase motor can somehow be made to rotate in any given direction, the motor will then continue to operate, producing torque in that direction. It should be pointed out that the component of the stator magnetic field which rotates in the direction opposite to that of the rotor will produce a negative component of torque as well as losses. Thus a single phase motor will tend to be less efficient than its two-phase counterpart.

How then does a single-phase motor start? Single-phase motors actually include a second winding, known as the starting winding. In construction they are quite similar to a two-phase motor (see figure 2–3). In order to get starting torque, the current in this second winding must be out of phase with that of the main winding; ideally the two currents would be 90° out of phase as are the currents in a balanced two-phase set (equations 1 and 2).

Because there is only a single voltage available to drive the two windings, the desired phase shift in current is achieved by various methods, including:

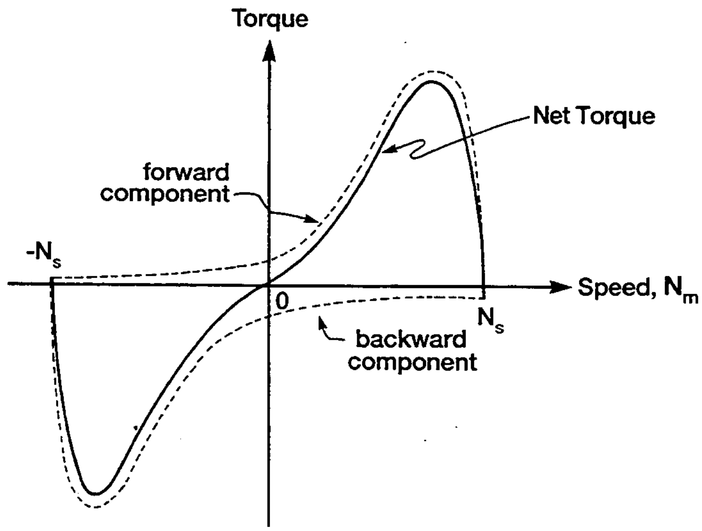


Figure 5–1: Torque components in a single-phase motor showing the component torques (forward and backward) and the net torque

- *Capacitor-start motor.* In this scheme, a capacitor is put in series with the starting winding. The value of this capacitance is chosen to give a starting winding current (magnitude and phase) that is optimal for starting the motor. Because the motor impedance changes with rotor speed (see the effective resistance R_2/s in figure 3–5 which varies with rotor speed), the value of this capacitor is not optimal for running conditions. As a result, it is common practice to use a centrifugal switch to disconnect the starting capacitor when the motor gets up to speed, in which case the motor is operated with only its main winding energized.

- *Capacitor-start, capacitor-run motor.* This motor is similar to the capacitor-start motor. It differs only in that when the starting capacitor is switched out, a second capacitor is switched in series with the starting winding. This second capacitor is designed to optimize the motor performance at full load and the motor thus operates with both windings energized in a fashion similar to that of a two-phase motor. The result is a motor which operates more efficiently and with an improved power factor as compared to a capacitor-start motor.

- *Resistance-start motor.* In this type of motor, the phase shift of the starting winding current is produced by constructing a starting winding with more resistance (as compared with its inductance) than the main winding. Such a winding is usually easily recognizeable because it is wound with wire of smaller diameter than that used in the main winding. Use of this high-resistance winding will result in a phase shift similar to that produced by the capacitor in the capacitor-start motor. Typically, to avoid overheating the motor, this starting winding is disconnected by a centrifugal switch as the motor reaches operating speed.

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