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Introduction to Electric Motors

Electric motors are devices that convert electric energy into magnetic energy and finally into mechanical energy. Electromagnetism is the basis of electric motor operation by generating magnetic forces necessary to produce either rotational or linear motion. For rotating electric motors, it is the interaction between the stator and rotor magnetic fields that creates motor torque to drive external loads.

Today, electric motors come in a wide variety of types, sizes, operating characteristics, and configurations to suit different applications. They are used almost everywhere in the world, including industrial drives, household appliances, medical devices, electronic products, robots, electric vehicles, machine tools, spacecrafts, and military equipment. As one of the fastest growing industrial sectors, electric motor manufacturing represents a major industry worldwide. Today, electric-motor-driven systems account for approximately 45% of total global electricity consumption. By 2030, energy consumption from electric motors is expected to rise to 13,360 terawatt hour (TWh) per year. End users now spend USD 565 billion per year on electricity used in electric-motor-driven systems; by 2030, that could rise to almost USD 900 billion [1.1]. In the United States, motor-driven equipment accounts for 64% of the electricity consumed in the manufacturing sector. That is approximately 290 billion kilowatt hours (kWh) of power per year [1.2]. There are more than 40 million electric motors used in manufacturing operation [1.3]. In addition, more than 95% of an electric motor’s life-cycle cost is the energy cost. In China, it is estimated that about 60% of the annual power generation is consumed through motor-driven systems. All these clearly show how important it is to take a variety of measures to promote electric motor efficiency for the energy saving and carbon emission reduction.

1.1 History of Electric Motors

The discoveries of phenomena of static electricity can be traced back in ancient Greece about 2600 years ago. However, there was little real progress until the English scientist William Gilbert in 1600 described the electrification of many substances and coined the term electricity, the Greek word for amber.

Hans Oersted discovered electromagnetism in 1820 and additional works were made by a number of other scientists such as William Sturgeon, Joseph Henry, Ander Marie Ampere, Michael Faraday, and Thomas Davenport. In 1831, Michael Faraday discovered electromagnetic induction, the principle behind the electric motor and generator. This discovery was crucial in allowing electricity to be transformed from a curiosity into a powerful new technology.

Using a broad definition of motion as meaning any apparatus that converts electric energy into motion, it is widely accepted that Michael Faraday invented the first direct
current (DC) electric motor in 1821. This motor was basically used to confirm his concept of electric motor and had no actual value in application. He succeeded in building the practical electric motor 10 years later. Following his groundbreaking work, many scientists contributed to the developments of electric motors. William Sturgeon invented the first practical electric motor in the United Kingdom in 1832 [1.4]. The first US patent on electric motor was granted in 1837 to Thomas Davenport [1.5]. In 1887, Nikola Tesla introduced the world’s first alternating current (AC) motor and gained a US patent in the next year [1.6]. Three-phase cage-rotor induction motors (IMs) were invented by Mikhail Dolivo-Dobrovolsky during 1889–1890 [1.7]. Even today, this type of motors is still in service for the vast majority of commercial applications.

1.2 Motor Design Characteristics

Electric motors are manufactured in a variety of types and configurations. Typically, an electric motor assembly is formed from a collection of parts, including a stator, a rotor, a shaft, a pair of end bells, bearings, and a motor housing supporting and enclosing the various components. In addition to these primary motor components, some motors may include electronic components that are used to modify operating characteristics for particular applications.

Motor design characteristics are the essential elements in the motor design and manufacturing processes. To select appropriate motors for specific applications, these design characteristics must be well understood.

1.2.1 Motor Torque

Torque is a measurement of the turning force acting on an object to cause that object rotating or twisting about an axis or pivot. Torque, like work, is measured as Newton meter (N-m) in the International System of Units (SI system) or pound-foot (lb-ft) in the English system. However, unlike work that only occurs during displacement, torque may exist even though no displacement or rotation occurs. A typical example is the static holding torque.

1.2.1.1 Static and Dynamic Torque

Torque can be divided into two major categories, either static or dynamic torque. From the standpoint of physics, the system is considered static if it has no angular or linear acceleration. Static torque refers to the amount of torque that an electric motor produces at zero speed (i.e., the motor is in a real static state) with the power output \( P_{\text{out}} = 0 \). By contrast, dynamic torque refers to the amount of torque that an electric motor produces at variable speeds of rotation with load applied (i.e., the motor is in a dynamic state) with \( P_{\text{out}} > 0 \). Simply, static torque is associated with forces that do not involve angular acceleration/deceleration, and dynamic torque is associated with dynamic forces that arise from acceleration/deceleration, following Newton’s second law.

Some motor manufacturers may provide the information of continuous static torque rating for customers, indicating the motor is capable of supplying that static torque at zero speed of rotation continuously. However, this information may be not very useful in motor
selection because it does not define the continuous torque available from the motor at a specific speed (or in a range of speeds) to drive external load.

As a continuous torque rating is provided at a specific rated speed (or in a range of speeds), the torque is thus the dynamic torque, indicating the capability of the motor to provide up to a corresponding rated torque continuously. Furthermore, the maximum torque appearing on the motor nameplate refers to the highest dynamic torque for the motor at rated motor speed.

As shown in Figure 1.1, when a force vector $\mathbf{F}$ acts on a solid body at the point $A$ to make the body rotate about its axis through the point $O$, the torque vector $\mathbf{T}$ around the point $O$ is obtained by crossing product of the radial displacement vector $\mathbf{r}$ and the force vector $\mathbf{F}$:

$$\mathbf{T} = \mathbf{r} \times \mathbf{F} \quad (1.1)$$

The direction of the torque vector $\mathbf{T}$ is determined by the right-hand rule, that is, it is perpendicular to both $\mathbf{r}$ and $\mathbf{F}$. Correspondingly, the magnitude of the torque acting on the body is

$$T = rF \sin(\theta) \quad (1.2)$$

where the moment arm $r = OA$, defined as the distance from the axis to the point where the force is applied, and $\theta$ is the measure of the smaller angle between the displacement vector $\mathbf{r}$ and the force vector $\mathbf{F}$. It is worth to note that torque calculated from Equation 1.2 can be either static or dynamic torque depending on whether $F$ is static or dynamic force.

For a rotating system with a fixed axis, the dynamic torque on the rotating system along axis of rotation is determined by the rate of change of the system angular momentum:

$$T = \frac{dM_s}{dt} \quad (1.3)$$
where \( M_a \) is the angular momentum of the rotating system, measured in N-m-s. \( M_a \) can be expressed as the product of the polar moment of inertia of the rotating system \( J_p \) and the rotating speed \( \omega \), that is,

\[
M_a = J_p \omega \tag{1.4}
\]

As a result, the torque on the rotating system can be expressed as

\[
T = \frac{d(J_p \omega)}{dt} = J_p \frac{d\omega}{dt} = J_p \alpha \tag{1.5}
\]

where \( \alpha \) is the angular acceleration of the rotating system, measured in rad/s\(^2\). This equation indicates that for electric motors, the less the motor inertia, the less torque the motor needs to produce to meet a desired acceleration rate. As a result, it is advantageous to minimize motor inertia to the greatest extent to maximize acceleration.

Servomotors are typically expected to accelerate loads from a stop to a given velocity and then decelerate the loads once again to a stop at precise position. Accordingly, to move or stop loads as fast as possible, the angular acceleration/deceleration \( \alpha \) must be maintained high enough. As a result, the motor’s polar moment of inertia \( J_p \) has to be kept at very low levels. For this reason, the motor inertia must be taken into account in the earlier stage of motor design.

### 1.2.1.2 Motor Torque in Motor-Load System

When a motor drives a load machine to perform work, it usually connects with some power transmission components such as coupling and gearbox. For demonstration purpose, a two-shaft gearbox is shown in Figure 1.2. The gear ratio \( \gamma_g \) is defined as the rotating speed of the gearbox input shaft that is directly coupled with the rotor shaft to the rotating speed of the gearbox output shaft, which is directly coupled with the load machine, that is,

\[
\gamma_g = \frac{\omega_o}{\omega_i} = \frac{\omega_m}{\omega_l} \tag{1.6}
\]

where

\( \omega_i \) and \( \omega_o \) are the rotating speeds of the input and output shaft of the gearbox,

\( \omega_m \) and \( \omega_l \) are the rotating speeds of the motor and load, respectively.

Unlike other components, because the input and output shaft of a gearbox have different rotating speeds, the inertia of each shaft must be calculated separately.

To determine the motor torque required for the system, a concept of reflected load inertia is introduced as the equivalent inertia of the load seen by the motor:

\[
J_{sl} = J_c + J_{i,gb} + \frac{J_{o,gb} + J_l}{\gamma_g^2} \tag{1.7}
\]

where \( J_c \) and \( J_l \) are the inertias of the coupling and load machine, respectively. This equation indicates that load inertia is reduced by the square of the gear ratio, which can be
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The torque required at the motor thus becomes

\[ T_m = (J_m + J_{rl}) \alpha_m = \left( J_m + J_c + J_{i,gb} + \frac{J_{o,gb} + J_l}{\gamma_s^2} \right) \alpha_m \]  \hspace{1cm} (1.8)\]

The motor angular acceleration \( \alpha_m \) has the relationship with the load angular acceleration \( \alpha_l \) [1.8]:

\[ \alpha_m = \alpha_l \gamma_s \]  \hspace{1cm} (1.9)\]

Combining the aforementioned equations yields

\[ \alpha_l = \frac{\alpha_m}{\gamma_s} = \frac{T_m}{\gamma_s \left( J_m + J_c + J_{i,gb} + \frac{J_{o,gb} + J_l}{\gamma_s^2} \right)^{-1}} \]  \hspace{1cm} (1.10)\]
Taking the derivative of \( \alpha_i \) with respect to \( \gamma_g \), it follows that

\[
\frac{d\alpha_i}{d\gamma_g} = T_m \left[ (I_i + I_{o,gb}) - (I_m + I_c + I_{i,gb}) \right] \gamma_g^2 \left[ (I_i + I_{o,gb}) + (I_m + I_c + I_{i,gb}) \gamma_g^2 \right]^{-2}
\]

(1.11)

Let \( d\alpha_i/d\gamma_g = 0 \); thus,

\[
(I_i + I_{o,gb}) = (I_m + I_c + I_{i,gb}) \gamma_g^2
\]

(1.12)

Thus, the optimum gear ratio is found at

\[
\gamma_g = \sqrt{\frac{I_i + I_{o,gb}}{I_m + I_c + I_{i,gb}}}
\]

(1.13)

The torque on a motor shaft can be measured using a number of strain gages to the shaft in a proper orientation. This allows directly measuring torsional shear strains that can be calibrated to output torque.

1.2.1.3 Continuous Torque

It is the interaction of the stator revolving field and the rotor induced field that produces the motor torque to drive load machines. Consequently, the motor torque is a function of both the field and armature currents and acts on both the rotor and stator simultaneously. The continuous rated torque \( T_r \) (in N-m) of a motor can be determined from its rated power \( P_r \) (in W) and rated rotor angular speed \( \omega_r \) (in rad/s):

\[
T_r = \frac{P_r}{\omega_r}
\]

(1.14)

At normal operation, a motor provides a continuous torque, known as nominal torque, to drive an external load device smoothly. It can be seen from the previously mentioned equation that for a given motor power, the continuous torque is inversely proportional to the motor rotating speed. In practice, the continuous torque generated in a motor commonly has a cyclic variation as a result of the cyclic permeance variation that occurs as the rotating member moves with respect to the stationary member. The instantaneous torque of a motor can be expressed as (Figure 1.3)

\[
T(t) = T_o + T_p(t)
\]

(1.15)

where \( T_o \) and \( T_p(t) \) are the mean component and the periodic component of the motor torque, respectively.

1.2.1.4 Peak Torque

The motor peak torque, which is always associated with the peak current, is the maximum torque a motor can produce for short periods of time without exceeding the motor
temperature limit or safe operating torque. A motor that operates under a peak torque condition is typically associated with a quick temperature rise. When the motor temperature exceeds the allowable value, it will cause degradation of insulation materials, irreversible demagnetization of permanent magnets (PMs) in PM motors (PMMs), and winding damage and, in turn, lead to the degradation of motor performance or even motor failure.

Peak torque contains two components \([1.9]\): (1) acceleration torque as inflicted by inertia forces with the maximum angular acceleration and (2) constant torque due to all other non-inertial forces such as gravity, friction, preloads, and other push–pull forces.

The continuous torque and peak torque curves are usually determined through motor testing and provided by motor manufacturers.

1.2.1.5 Stall Torque

The stall torque is the torque that a motor produces at zero rotating speed where \( P_{\text{out}} = 0 \). The stall torque, also known as locked rotor torque (LRT), can be measured with the rotor being locked. For a DC motor, the motor torque has a linear relationship with the motor rotating speed. The maximum torque occurs at zero rotating speed and zero torque occurs at maximum rotating speed. For an IM, the stall torque can be calculated as \([1.10]\)

\[
T_s = \frac{C_1k_2(P_{\text{in,s}} - P_s - P_{\text{sc}})}{n_s}
\]  

(1.16)

where

- \( C_1 \) is a reduction factor (0.9 \( \leq C_1 \leq 1.0 \)) to account for nonfundamental losses
- \( k_2 = 9.549 \) for torque in the unit of N-m
- \( P_{\text{in,s}} \) is the input power to stator (in W)
- \( P_s \) is the stator FR loss (in W)
- \( P_{\text{sc}} \) is the stator iron core loss (in W)
- \( n_s \) is the synchronous speed in the unit of rpm
1.2.1.6 Cogging Torque and Reduction Methods

The torque generated from a PMM usually consists of two components: the effective driving torque, which is basically proportional to the supplied electric current, and the no-current torque, which is independent of the current, such as cogging torque.

Cogging torque originates from the interaction between rotor-mounted PMs and the stator teeth, which produces reluctance variations depending on rotor position [1.11]. As depicted in Figure 1.4, when the rotor rotates, the magnets attached to the rotor successively pass through the stator teeth and slot openings, resulting in the periodic variations of the magnetic field. During the process, the PM rotor tends to lock onto the position where the permeability reaches the largest. When the rotor deviates from this equilibrium position, tangential forces are produced between the magnets and stator teeth, either to return the rotor back to the old equilibrium position or to push the rotor to the next equilibrium position, leading to cogging torque.

Cogging torque is highly undesirable because it is the major cause of motor vibration and acoustic noise, particularly at light loads and low speeds. Even for high-speed applications, lower cogging torque always benefits smooth operation. For instance, in a servo system, the motor may come to a stop and then accelerate to another high speed after the stop. As the motor approaches zero speed, it is often to use settling time or settling error to measure how smoothly the motor approaches zero speed. This can definitely be impacted by cogging torque.

Because the rotor always tends to lock onto a position where it is aligned with the stator poles, it makes precise positioning of the rotor difficult. In addition, cogging torque is also an important source of torque ripples that have adverse effects in many demanding motion control applications.

Motor manufacturers often adopt the cogging torque ratio to quantitatively describe the level of cogging torque. This torque ratio is defined as the absolute cogging torque, which is characterized as peak-to-peak cogging torque, to the rated continuous torque. It is widely accepted that for regularly controlled servo systems, the maximum cogging torque ratio should keep under 5%. More ideally, for precisely controlled servo systems, the cogging torque ratio is 2% or less. Cogging torque below 1% really requires special design. For example, in some high-precision film roller systems that need super smooth operation at

![Figure 1.4](image)

**FIGURE 1.4**
As a rotor rotates, magnets successively pass through stator teeth and slot, leading to different magnetic flux distributions, as shown earlier for magnet-teeth (solid circle) and magnet-slot (dashed circle) conditions.
very low speeds, an effective solution is to use DC torque motors for excellent operation. Three-phase brushless motors have been designed for very smooth telescope azimuth motion, that rotate at extremely slow earth rates of rotation of one revolution in 24 h. It is worth to note that each application may allow for different extremes of cogging torque.

Though cogging torque can be calculated accurately using numerical approaches such as finite element methods (FEMs), with simplified motor models, analytical methods may provide greater physical insight into the mechanism of cogging torque production. This is especially useful at the initial stage of the motor design. One approach to predict cogging torque is represented by [1.12]

\[ T_{cog} = -\frac{\phi_g^2}{2} \frac{dR}{d\theta} \]  

(1.17)

where
- \( \phi_g \) is the air gap flux
- \( R \) is the air gap reluctance
- \( \theta \) is the position of the rotor

This equation indicates that in order to reduce cogging torque, either the air gap flux \( \phi_g \) or the rate of change of the air gap reluctance \( dR/d\theta \) must be minimized. In practice, cogging torque is reduced by forcing the air gap reluctance \( R \) as close as possible to constant with respect to rotor position.

Another method for calculating cogging torque in PMMs was proposed by Lu et al. [1.13]:

\[ T_{cog} = -\frac{p_r B_r l_m}{2 \mu \mu_r} \frac{d\Phi}{d\theta} \]  

(1.18)

where
- \( p_r \) is the number of magnet pole pairs
- \( B_r \) is the remanent magnetic flux density at \( H=0 \)
- \( \Phi \) is the magnetic flux calculated over a surface perpendicular to its direction of magnetization
- \( l_m \) is the magnet length along the magnetization direction
- \( \mu \) and \( \mu_r \) are the permeability of free space and the relative permeability of the magnet material, respectively

This equation shows that the magnitude of cogging torque is proportional to the number of magnet pole pairs, the remanent flux density value, the magnet length in the direction of magnetization, and the variation of the magnetic flux with respect to the rotor position. It has shown a good agreement of the predicted cogging torque with the cogging torque calculated using Maxwell stress method and measured results.

There are a number of techniques available for reducing cogging torque:

- The most effective way in practice to reduce cogging torque is to skew either the stator teeth relative to the rotor centerline (Figure 1.5) or rotor magnets relative to the stator teeth, where Figure 1.6 is for step-skewing of segmented magnets
**FIGURE 1.5**
Skewed stator teeth with respect to its centerline for reducing cogging torque, where $\theta$ is the skew angle.

**FIGURE 1.6**
Step-skewed permanent magnets relative to stator teeth for reducing cogging torque.
and Figure 1.7 [1.14] is for skewing whole magnets. More detailed descriptions can be found in reference [1.15]. Skewing stator teeth needs special care in stacking steel laminations. Skewing whole magnets may have smoother rotor performance than step-skewing segmented magnets. However, it is to be noted that rotor skewing may also decrease the rotor saliency and thus reduces the back electromotive force (EMF) and motor effective torque. All forms of skewing will reduce the back EMF and motor effective torque as skewing affects total flux linkage to the coils.

b. Another technique is to use a fractional number of slots per pole. The use of this method not only reduces the amplitude of the cogging torque but also increases the fundamental order. This is because the stator slots are located at different relative circumferential positions with respect to the edges of the magnets [1.16–1.18]. To address the problem, the parameter \( q \), which is defined as the slot number per pole \( n_{slot} \) divided by the phase number \( N_{phase} \), is introduced as

\[
q = \frac{N_{slot}}{2p_rN_{phase}} = \frac{n_{slot}}{N_{phase}}
\]  

(1.19)

where

- \( p_r \) is the number of pole pair
- \( N_{slot} \) is the number of the stator slots

The fractional slot winding arrangement with \( q < 1 \) is attractive for lower cogging torque. The investigations have shown that the cogging torque of the fractional slot motors can be less than 1% of the rated torque. In the case of multipole machines, the cogging torque of 0.05% could be estimated [1.19].

**FIGURE 1.7**
Skewed PMs on rotor core for reducing cogging torque.
c. The reduction in cogging torque can be also achieved by modulating drive current waveform [1.20].

d. It is a well-established fact that the magnet pole arc can have a large effect on the magnitude of the cogging torque [1.21,1.22]. The optimization of the magnet pole arc can reduce the harmonics of the air gap flux wave and the permeance wave [1.23].

e. Another technique is called magnet segmentation in which a pole magnet consists of several elementary magnet segments with the same polarities [1.24]. Furthermore, as shown in Figure 1.8, the segmented magnets may be selected with different thickness and lengths to obtain more sinusoidal flux density waves [1.25].

f. The shape of the magnetic pole has a strong impact on the uniformity of the stator–rotor air gap. A comparison of uniform and nonuniform air gap with different pole shapes of magnets is illustrated in Figure 1.9. It has been reported that the nonuniform pole shape of magnets can reduce cogging torque as high as 50% [1.25]. The normalized cogging torque to the peak torque between uniform air gap and nonuniform air gap is given in Figure 1.10. The simulation studies of the pole surface effect on cogging torque were performed by Lao et al. [1.26].

g. Other mechanical factors can affect cogging torque. Geometry factors such as rotor or magnet concentricity of the magnetic air gap can create eccentric magnet to stator teeth flux linkage. These variations in flux linkage can cause variations in cogging torque and torque ripple.

h. In order to achieve decreasing torque ripple, iron losses, and cogging torque for interior PM (IPM) synchronous machines, Soleimani et al. [1.27] proposed a novel structure of rotor. In their design, three layers of PM have been used and each layer has a fragmental trapezoid structure, as shown in Figure 1.11. With the optimized dimensions and shapes of the buried rotor magnets, the cogging torque ratio of 1.82% is achieved, comparing with torque ratio of 5% in conventional IPM machines.
1.2.1.7 Torque Ripple

PM synchronous motors usually generate torque ripple during their normal operation. The studies of Hsu et al. [1.28] have revealed that torque ripple can be classified into four types depending on the nature of their origin:

- **Pulsating torque**, which is inherently produced by the trapezoidal back EMF. The torque ripples caused by pulsating torque may be reduced by purposely produced fluctuating counter torques.
- **Fluctuating torque**, which is produced by altering the magnitudes of phase current in the same ratio.
Reluctance cogging torque, which is produced by nonuniformly distributed air gap permeance associated with the teeth and PMs. Actually, this type of torque exists even when the motor is not energized.

Inertia and mechanical system torques, which are generated by the dynamic motions of the mechanical components of motor. They are affected by the driven device.

Later, Holtz and Springob [1.29] have investigated the different sources of torque ripple in PM machines, including the distortion of the stator flux linkage distribution, variable magnetic reluctance at the stator slots, and secondary phenomena. In addition, the feeding power converter also contributes to torque ripple due to the time harmonics in the current waveform’s time-varying delays between the commanded and the actual current.

1.2.2 Motor Speed

There are a few terms to describe rotational motion. Angular speed represents the change in angle per unit of time, typically measured in radians per second (rad/s) in the SI system and in degrees per second in the English system. Rotational speed is the measurement of revolutions per unit of time, expressed as either revolutions per second (Hz) or revolutions per minute (rpm). It is to be noted that speed is a scalar quantity and velocity is a vector. Thus, the difference between angular (or rotational) speed and angular (or rotational) velocity is that the latter contains the information of the rotational direction. Angular speed $\omega$ (in rad/s) and rotational speed $n$ (in rpm) can be converted into each other:

$$\omega = \frac{\pi n}{30}$$

(1.20)
1.2.2.1 Continuous Speed

The continuous speed of a motor is an important design parameter, defining the nominal speed at which the motor continuously operates at the rated voltage and current to drive the full motor load. It depends on the number of the motor pole, the frequency of AC, and the amount of torque.

1.2.2.2 Peak Speed

The peak speed is the maximum speed a motor can reach during operation. It must be noted that at the peak rotating speed, all rotating components are subject to high centrifugal forces. Even a tiny unbalance in a high rotating speed system can cause severe motor vibration or serious damage of rotating components. Therefore, the motor peak speed needs to be carefully determined during motor design phase.

1.2.2.3 Speed Ripple

Speed or velocity ripple refers to the variations in steady-state speed in time. Velocity ripple values are usually defined as a percentage (%) of deviation from the ideal value. In practice, torque ripple has the tendency to cause speed ripple.

There are a large number of factors that affect motor velocity ripple and torque ripple [1.30], including

- Load-to-rotor inertia ratio
- Motor pole count—higher pole count leads to lower ripple
- Encoder resolution
- Commanded velocity
- System bandwidth (different between an analog and a digital drive)
- Commutation type (sinusoidal vs. trapezoidal commutation)
- System trajectory update rate (when using a digital drive)
- Natural (harmonic) frequencies of the system as a whole
- Mechanical resonance of motor components
- Mechanical friction in the system
- Physical alignment of mechanical components
- Inherent performance variances between two like components
- Load damping
- Consistency of the AC supply voltage to the drive (i.e., power supply integrity)
- Sampling rate/resolution of the tachometer (or velocity-measuring device)

1.2.3 Torque Density

Torque density is defined as the ratio of the nominal continuous torque $T$ to the motor volume $V$, as the measure of the torque-carrying capability per unit volume. High torque density and high efficiency are two of the most desirable features for electrical motors. Torque density is a measure of the torque-carrying capability per unit volume of a motor, expressed in units of N/m$^2$ or lb./ft$^2$. Torque density is a system property since it depends
on the design of motor components and their interconnections. One of the main design goals in motor design is to improve torque density of motors.

1.2.4 Motor Power and Power Factor

The power output \( P_{\text{out}} \) of rotary motors is expressed as the product of the motor torque and the angular rotating speed, that is,

\[
P_{\text{out}} = T \omega
\]  

(1.21)

Since the angular rotating speed \( \omega \) (in \( \text{rad/s} \)) is related to the rotating speed \( n \) (in \( \text{rpm} \)) as \( \omega = \pi n / 30 \), Equation 1.21 can be also expressed as

\[
P_{\text{out}} = \frac{\pi n T}{30}
\]  

(1.22)

When an IM is connected to a power supply but still at rest, it appears just like a short-circuited transformer, drawing a very high current known as the locked rotor current (LRC). The torque corresponding the LRC is defined as the LRT. A motor that exhibits a high starting current will generally produce a low starting torque, and vice versa. Both the torque and current of the locked rotor are a function of the terminal voltage of the motor. Under a constant voltage, the torque and current vary with the rotor speed during the motor acceleration/deceleration process.

The most important two parameters for motor performance are motor efficiency and power factor. In the electric power industry, power factor \( PF \) is defined as the ratio of real power \( P_{\text{real}} \) to apparent power \( P_a \). As shown in Figure 1.12, power factor \( PF \) (where \( 0 \leq PF \leq 1 \)) can be also expressed as the cosine of the impedance phase angle \( \phi \):

\[
PF = \cos \phi = \frac{P_{\text{real}}}{P_a}
\]  

(1.23)

The power supply system provides both real and reactive power to operate the motor. Useful mechanical work is developed from real power \( P_{\text{real}} \) and is measured in watts (W)

[FIGURE 1.12]
The power triangle: the relationship of real power, reactive power, and apparent power.
or kilowatts (kW). For AC motors, reactive power \( P_{\text{react}} \) is to develop magnetic fields. It is worth to note that reactive power does not provide any mechanical work. From the power triangle in Figure 1.12, apparent power \( P_a \) can be expressed as

\[
P_a = \sqrt{P_{\text{real}}^2 + P_{\text{react}}^2}
\]  

(1.24)

Power factor depends upon motor load. When a motor is in normal operation, the electric current drawn by the motor varies with the external load. Under a no-load condition such as the motor start, the power factor is minimum, typically 0.1–0.25. As the shaft load increases, the load current through the stator windings increases significantly, and consequently, the power factor increases until reaching the maximum at the full-load point. Then, the power factor falls again as the motor approaches the full speed. In engineering practice, \( PF \) is determined at each load point using the following formula:

\[
PF = \frac{P_{\text{in}}}{\sqrt{3} VI}
\]  

(1.25)

where

\( P_{\text{in}} \) is the motor input power
\( V \) and \( I \) are line-to-line voltage and current, respectively

The full-load power factor of an IM can vary from 0.5 for a small low-speed motor up to 0.9 for a large high-speed machine.

### 1.2.5 Torque–Speed Characteristics

In the power industry, a commonly used method of displaying motor performance characteristics graphically is to use motor torque–speed curves, as shown in Figure 1.13 for
a typical DC motor. There are two pairs of parameters used to define the DC motor performance: one pair of torque, which includes peak torque $T_p$ and rated torque $T_r$, and another pair of speed, which includes peak speed $\omega_p$ and rated speed $\omega_r$. Since the peak torque occurs at $\omega = 0$, it is also called the stall torque. The peak rotating speed is also called no load speed because the motor generates no torque at the point. As depicted in the figure, the linear relationship between the motor torque and the rotating speed can be expressed as

$$T = T_p \left(1 - \frac{\omega}{\omega_p}\right) \quad \text{(1.26)}$$

As shown in Equation 1.21, the motor output power is the product of torque and angular rotating speed. Thus, the power of a DC motor is given as

$$P_{\text{out}} = T_p \omega \left(1 - \frac{\omega}{\omega_p}\right) \quad \text{(1.27)}$$

This indicates that $P_{\text{out}} = 0$ at both $\omega = 0$ and $\omega = \omega_p$. Differentiating $P_{\text{out}}$ with respect to $\omega$ and letting $dP_{\text{out}}/d\omega = 0$, the maximum power output is found to occur at $\omega = \omega_p/2$ where $T = T_p/2$. However, at this operating point, the motor efficiency is rather low, causing higher power losses and higher temperature rises. For optimal continuous performance, the operating speed may be set between 70% and 90% of the no load speed and the operating torque between 10% and 30% of the stalled torque [1.31]. The optimum operating zone is shown in Figure 1.13 as a small triangle.

With the two pairs of parameters (torque and speed), two motor operation zones can be identified: the intermittent duty zone and the continuous duty zone. In the intermittent duty zone, the motor operates intermittently with a higher torque. This is especially useful when a rotor requires frequent starts and frequent reversals in rotating direction. In such cases, extra torque is required to overcome the inertia of the load as well as the rotor itself. However, it is specially noted that in the intermittent duty zone, the motor can only produce torque and speed for a limited amount of time; otherwise, it will cause the motor overheating. As the combination of torque and speed produced by the motor falls in the continuous operation zone, the motor can be loaded until the rated torque remains constant for a speed range up to the rated speed. In this zone, the motor can run as long as needed without any chance of overheating. The slope of the torque–speed curve represents inherent motor damping. For DC motors, damping is a constant.

The torque–speed characteristics of a typical AC IM are displayed in Figure 1.14. When the motor is initially started from standstill at the starting current $I_s$, the starting torque (also called LRT) is produced by the motor to overcome the inertia of the motor drive system. The starting torque depends on the terminal voltage and the stator and rotor design. As the motor accelerates, the torque generated by the motor may drop slightly to the local minimum point known as the pull-up torque. In the case that the pull-up torque of the motor is less than that required by its application load, the motor will overheat and eventually stall. Then, a further increase in motor speed will lead to the increase in torque until it reaches the breakdown torque, which is the highest torque the motor can attain without stalling. Starting from this point, the continuous increase in speed causes the sharp
Introduction to Electric Motors

decrease in torque, as well as in motor current. When the motor reaches its full operation speed $\omega_r$, it is loaded to its full-load torque $T_r$ and the corresponding rated current $I_r$ and slip $s$. At the synchronous speed, no torque can be developed as zero slip ($s=0$) implies no induced rotor current ($I=0$) and thus no torque ($T=0$). This situation only occurs for motors that run while not connected to a load. Therefore, in the strict sense, an IM can never reach the synchronous speed.

In order to clearly present the relationship between rotor torque and speed, an absolute value of torque (usually N-m) is used in Figure 1.14. More frequently, torque is expressed in terms of a percentage of full-load torque, together with speed in terms of a percentage of synchronous speed.

The torque–speed curve for a servomotor is given in Figure 1.15. The whole working zone is defined by the peak torque line $T=T_p$, the peak speed line $\omega=\omega_p$, and a diagonal line equation

$$T = T_p - (T_p - T_{\infty}) \frac{\omega - \omega_k}{\omega_p - \omega_k}$$  \hspace{1cm} (1.28)

where $T_{\infty}$ is the peak torque at the motor maximum speed $\omega_p$ and $\omega_k$ is the speed at the knee in the peak envelop.
The two duty zones, that is, the intermittent duty zone and the continuous duty zone, are separated by the maximum continuous torque line, which is expressed as

$$T = T_p - (T_p - T_{ms}) \frac{\omega - \omega_k}{\omega_p - \omega_k}$$  \hspace{1cm} (1.29)

At normal operation, a motor runs at the continuous duty zone to provide a continuous torque to drive external loads.

Unlike DC motors, motor damping in AC motors always vary along with the motor speed.

1.2.6 Mechanical Resonance and Resonant Frequency

Mechanical resonance occurs when an external source amplifies the vibration level of a mass or structure at its natural frequency. For a rotating mass like a motor or a pump, this occurs at what is called the critical speed.

Every mechanical system can be resonated at a certain frequency, defined as resonant frequency. However, when two systems (e.g., a motor and a driven machine) are connected together by some power transmission components such as shaft coupling, gearboxes, and belts, it forms a new resonant frequency, based on all components in the system.

As illustrated in Figure 1.16, in a regular motor drive system, the total system inertia \(J_t\) is the sum of the motor inertia \(J_m\) and the reflected load inertia \(J_{rl}\):

$$J_t = J_m + J_{rl} = J_m + J_c + J_{i,gb} + \frac{J_{o,gb} + J_l}{\gamma^2}$$  \hspace{1cm} (1.30)

The unit of inertia is kg-m\(^2\) in the SI system and lb\(_m\)-ft\(^2\) in the English system. It is worth to note that 1 kg-m\(^2\) = 1 N-m-s\(^2\) and 1 lb\(_m\)-ft\(^2\) = 1/32.185 lb\(_r\)-ft-s\(^2\).
Because the motor-load system is not rigid (i.e., the stiffness is not infinitely large), as the motor torque is applied on the system, each of these connecting components twists slightly like a torsional spring.

To calculate the resonant frequency, motor and load inertias must be distinguished from each other. As discussed previously, load inertia is the inertia of the load reflected to the motor shaft $J_n$. It is the lumped inertia of the shaft coupling, gearbox, and driven load machine:

$$J_{rl} = J_c + J_{i,gb} + \frac{J_{o,gb} + J_l}{\gamma^2}$$

(1.31)

The total motor inertia $J_m$ is the lumped inertia of the rotor (including the rotor core and shaft), bearing, and other rotating components:

$$J_m = J_{\text{rotor}} + J_{\text{bearing}} + \sum J_{\text{other}}$$

(1.32)

The effects of interference fit on the shaft stiffness can vary depending on the actual interference fit. For a very tightly fitted rotor, the rotor assembly can be viewed as one body with variable outer diameters (ODs) along its axis. Thus, the rotor core virtually increases
the shaft stiffness. On the contrary, if the rotor is loosely coupled with the driven machine, its compliance can contribute to resonance.

For a rotor with a hollow shaft, the torsional stiffness (or spring constant) at each segment is calculated as

$$ S_{t,\text{rotor},i} = \frac{\pi \left( d_{\text{out},i}^4 - d_{\text{in},i}^4 \right) G}{32 l_i} $$

(1.33)

where

- $d_{\text{out},i}$ and $d_{\text{in},i}$ are the outer and inner diameter (ID) at $i$th segment, respectively
- $l_i$ is the length of the $i$th segment
- $G$ is the shear modulus of elasticity

It is noted that the stiffness of the motor shaft can be influenced by the various types of construction. In general, the machined or welded webs on the motor shaft can add significant stiffness (typically 10%–40% over the base shaft diameter stiffness), while keyed on laminations typically add minimal stiffness. A finite element analysis (FEA) has confirmed that with six welded spider arms on an IM shaft, the equivalent diameter is 7% larger than the base shaft diameter, which corresponded to a 33% increase in torsional stiffness [1.32].

Similarly, the torsional stiffness of the load system at each segment becomes

$$ S_{t,\text{load},i} = \frac{\pi \left( d_{\text{out},i}^4 - d_{\text{in},i}^4 \right) G}{32 l_i} $$

(1.34)

For a solid shaft, $d_{\text{in},i} = 0$.

Thus, the total torsional stiffness (spring constant) for the rotor and load machine are given as, respectively,

$$ S_{t,\text{rotor}} = \sum \left( \frac{1}{1/S_{t,\text{rotor},i}} \right) $$

(1.35a)

$$ S_{t,\text{load}} = \sum \left( \frac{1}{1/S_{t,\text{load},i}} \right) $$

(1.35b)

For two geared shafts with a gear ratio $\gamma_g$ (where $\gamma_g = \omega_i/\omega_o$), the torsional stiffness is given as [1.33]

$$ \frac{1}{S_{t,gb}} = \frac{1}{S_{t,i}} + \frac{1}{S_{t,o}/\gamma_g^2} $$

(1.36)

It follows that

$$ S_{t,gb} = \frac{S_{t,i} S_{t,o}}{S_{t,i} \gamma_g^2 + S_{t,o}} $$

(1.37)
Utilizing the analogy between the mechanical and electric systems, an electric circuit is developed for the total torsional stiffness $S_t$, as shown in Figure 1.17. Thus, $S_t$, which is measured in newton-meter per radians (N-m/rad), can be determined as

$$S_t = \frac{1}{\frac{1}{S_{t,\text{rotor}}} + \frac{1}{S_{t,c}} + \frac{1}{S_{t,gb}} + \frac{1}{S_{t,\text{load} / \gamma_s^2}}}$$

(1.38)

Resonant frequency (Hz) is thus calculated as

$$f_R = \frac{1}{2\pi} \sqrt{S_t \left( \frac{1}{J_m} + \frac{1}{J_{st}} \right)} = \frac{1}{2\pi} \sqrt{\frac{S_t (J_m + J_{st})}{J_m J_{st}}}$$

(1.39)

This shows that $J_m$ and $J_{st}$ have the same effect on the resonant frequency. From this equation, it can be seen that there are four ways to increase the system resonant frequency:

- Make the motor shaft more rigid—this increases the stiffness and, in turn, increases the overall torsional stiffness $S_t$.
- Reduce motor inertia—this actually increases the ratio of load-to-motor inertia, but it also results in higher performance of servo system.
- Reduce reflected load inertia.
- Increase stiffness of components attached/mounted to shafts.

In a direct drive system, a direct drive rotary (DDR) motor is connected with a load without using a gearbox (Figure 1.18). The coupling inertia is considered as a part of the load.
inertia. Therefore, the system model can be reduced to two lumped masses; the resonant frequency of the system is given by

\[ f_R = \frac{1}{2\pi} \sqrt{\frac{S_t (J_m + J_c)}{J_m J_r}} = \frac{1}{2\pi} \sqrt{\frac{J_m + (J_c + J_l)}{J_m (J_c + J_l)}} \]  

(1.40)

The torsional stiffness is

\[ S_t = \frac{1}{S_{t,\text{rotor}}} + \frac{1}{S_{t,c}} + \frac{1}{S_{t,\text{load}}} \]  

(1.41)

For a three-mass system shown in Figure 1.19, the resonant frequencies are [1.33]

\[ f_R = \frac{1}{2\pi} \sqrt{A \pm (A^2 - B)^{1/2}} \]  

(1.42)
An oversized and unnecessarily expensive motor.. Furthermore, it wastes energy. The load-to-motor response, reduce mechanical resonance, and minimize power dissipation. An inertia mismatch should stay within 10:1. Lower load-to-motor inertia ratios improve motor response, reduce mechanical resonance, and minimize power dissipation. An inertia mismatch of greater than 10:1 may cause motor speed oscillations (Figure 1.20), produce less than optimal response, waste power, and reduce system bandwidth.

In terms of efficiency, a 1:1 ratio between load and motor inertia provides the optimum power transfer. However, a 1:1 ratio is rarely useful in an actual application, because it requires an oversized and unnecessarily expensive motor. Furthermore, it wastes energy and may not perform to specifications [1.8]. In a typical servo system with a stiff coupling methodology, a load-to-motor inertial mismatch of 5:1 is generally accomplished.

However, in some cases, the inertia ratio for servomotors can be much higher than 5:1. As an example, direct drive elevator PM traction machines can have 40:1 inertia mismatches. More recently, Kollmorgen has developed a new generation of drive with digital biquadratic filters, enabling servomotors to be successfully applied to medical imaging gantry applications with high inertia mismatches up to 1000:1 [1.34]. To overcome the challenges of inertia mismatch, DDR motors, which directly couple to the load, have been developed in last two decades. DDR motors do not require a high degree of responsiveness and thus...
significantly reduce inertia mismatch concerns. Directly coupled motors have been successfully tuned to ratios as high as 1600:1 [1.35].

Some servomotor applications require larger inertia rotors to achieve good system controllability. This is due to mass or inertia acting as mechanical filters to load disturbances. The easiest way is to attach an inertia disk or wheel to the shaft [1.36]. If possible, it is preferred to arrange the inertia disk inside the motor or have a larger diameter rotor in the same frame size. Otherwise, the inertia disk has to be arranged outside of the motor (Figure 1.21). As an example, by adding an inertia wheel or wheels to servomotors, Kollmorgen's engineers increase the motor inertia by a factor of 7. Thus, low-inertial motors that have a 14:1 inertia ratio can be changed to medium-inertia motors with a 2:1 inertia ratio. Correspondingly, the resonant frequency decreases from almost 4 times the antiresonant frequency to about 1.6 times the antiresonant frequency.

1.2.8 Duty Cycle

In the power industry, duty cycle is a measure of the fraction of time that a power device is in an active state, that is, \( t_{on}/(t_{on} + t_{off}) \). For electric motors, duty cycle is defined as the ratio the motor produces rated continuous power divided by the total elapsed time. In fact, duty cycle is a variation of load over a given period of time. The load variation may have a repetitive pattern or a fluctuating pattern.

Duty cycle is used to determine the acceptable level of running time so that the rated motor temperature is not exceeded. For a fixed repetitive load pattern, duty cycle is determined as the ratio of on-time to total cycle period. When operating cycle is such that electric motors operate at idle or a reduced load for more than 25% of the time, duty cycle becomes a factor in sizing electric motors. Also, energy required to start electric motors (i.e., accelerating the inertia of the electric motor as well as the driven load) is much higher than for steady-state operation, so frequent starting could overheat the electric motor.

**FIGURE 1.20**
The effect of load-to-motor inertia ratio on motor speed response. For ratio >10, the speed response curve oscillates and asymptotically approaches to its final value in a long period of time.
FIGURE 1.21
Addition of an inertia disk either inside (a) or outside (b) of a motor to increase the rotor inertia (U.S. Patent 7,911,095) [1.36]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)
According to the applications of electric motors, a running load on an electric motor can be either steady or variable (e.g., follows a repetitive cycle of load variation or has pulsating torque shocks). For instance, electric motors in ventilating fans or blowers run continuously over an extensive period of time with almost constant loads. By contrast, electric motors in electric vehicle systems (EVSs) have wide variations in running loads. Elevator machines have typical duties of 120, 180, and 240 starts per hour ratings but may only run at those rates for a few hours a day during heavy traffic time. The temperature variations of electric motors under different operation conditions are presented in Figure 1.22.

**FIGURE 1.22**
Temperature variations under different operation conditions: (a) S1—continuous operation; (b) S2—short time operation; (c) S3—intermittent periodic operation, where the start current has no impact on temperature rise; and (d) S4—intermittent periodic operation, where the start current has an impact on temperature rise.
TABLE 1.1
Operating Conditions of Electric Motors

<table>
<thead>
<tr>
<th>Class</th>
<th>Motor Duty</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Continuous duty</td>
<td>The motor operates at a constant load over an extensive period of time to reach temperature equilibrium.</td>
</tr>
<tr>
<td>S2</td>
<td>Short-time duty</td>
<td>The motor operates at a constant load over a period of time not sufficient to reach the thermal equilibrium. The rest periods are long enough for the motor to cool down.</td>
</tr>
<tr>
<td>S3</td>
<td>Intermittent periodic duty</td>
<td>The motor operates with repeated cycles consisting of a constant output power period followed by an off period. Temperature equilibrium is never reached. Starting current has little effect on temperature rise.</td>
</tr>
<tr>
<td>S4</td>
<td>Intermittent periodic duty with starting</td>
<td>Sequential, identical start, run, and rest cycles with constant load. Temperature equilibrium is not reached, but starting current affects temperature rise.</td>
</tr>
<tr>
<td>S5</td>
<td>Intermittent periodic duty with electric braking</td>
<td>Sequence of identical duty cycles—starting, operation, braking, and rest. Thermal equilibrium is not reached.</td>
</tr>
<tr>
<td>S6</td>
<td>Continuous operation with intermittent load</td>
<td>Sequential, identical cycles of running with constant load and running with no load. No rest periods.</td>
</tr>
<tr>
<td>S7</td>
<td>Continuous operation periodic duty with electric braking</td>
<td>Sequential identical cycles of starting, running at constant load, and electric braking. No rest periods.</td>
</tr>
<tr>
<td>S8</td>
<td>Continuous operation with periodic changes in load and speed</td>
<td>Series of identical repeating duty cycles, where within each cycle the motor operates at several different load levels and speed. There is no stopped time and thermal equilibrium is not reached.</td>
</tr>
<tr>
<td>S9</td>
<td>Duty with nonperiodic load and speed variations</td>
<td>Load and speed vary periodically within the permissible operating range. Frequent overloading may occur.</td>
</tr>
<tr>
<td>S10</td>
<td>Duty with discrete constant loads and speeds</td>
<td>Duty with discrete number of load/speed combinations, with these maintained long enough to reach thermal equilibrium.</td>
</tr>
</tbody>
</table>

The International Electrotechnical Commission (IEC) defines ten duty cycle designations to describe operation conditions of electric motors, denoted S1–S10, as shown in Table 1.1 [1.37].

1.2.9 Motor Efficiency

The fast rising energy demands all over the world and continuously increasing energy costs have created motivations for many developed and developing countries to focus on energy saving and consumption reduction. Improvements in energy efficiency are most often achieved by producing more efficient machines or adopting more advanced technologies. Because electric motors consume a significant amount of electric energy, motor manufacturers in recent years have committed to the development of more efficient electric motors to save energy.

1.2.9.1 Definition of Motor Efficiency

Motor efficiency is a measure of how effectively a motor converts electrical energy into mechanical energy. Given as a percentage, motor efficiency is defined as the ratio of the power output $P_{out}$ to the power input $P_{in}$. Since the power output $P_{out}$ represents the difference between the power input $P_{in}$ and the variety of power losses $\sum P_{loss}$ and the
power input $P_{in}$ represents the summation of the power output $P_{out}$ and the variety of power losses $\sum P_{loss}$, motor efficiency can be expressed in several different forms:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - \sum P_{loss}}{P_{in}} = \frac{P_{out}}{P_{out} + \sum P_{loss}}$$  \hspace{1cm} (1.44)

This equation shows that in order to increase motor efficiency, it must minimize various power losses in motor, such as copper losses, iron losses, mechanical losses, and windage losses. Thus, the efficiency of electric motors can be boosted by the following [1.38]:

1. Reducing the copper losses in the motor windings. This can be done by increasing the cross-sectional area of the conductor or by improving the winding technique to reduce the winding length, especially at the end turns.
2. Using better materials for lowering eddy-current-related power losses.
3. Taking advantage of advanced nanotechnology to fabricate thinner laminations.
4. Improving the aerodynamics of motor ventilating system for reducing motor windage losses.
5. Applying more efficient cooling methods in motor cooling. (6) Improving manufacturing tolerances.

For electric motors, high efficiency and high torque density are two of the most desirable features. Today, motor efficiency is normally in the range of 80%–95%. Usually, larger motors with higher power output have higher efficiency than smaller motors. High-efficiency motors can provide significant benefits, including reductions in energy consumption and carbon emissions over their entire life cycles. Because operating costs comprise the majority of lifetime motor costs, even a 1% gain in efficiency can make a big difference to costs.

### 1.2.9.2 IEC Standards on Efficiency Classes of AC Electric Motors

In 2008, IEC published the standard IEC 60034-30: 2008 [1.39] on efficiency classes of AC electric motors. The scope of this standard covers almost all motors (e.g., standard, hazardous area, marine, and brake motors) but excluded motors made solely for converter operation and completely integrated into a machine:

- Single speed, three phase, and 50 and 60 Hz
- 2, 4, or 6 pole
- Rated output from 0.75 to 375 kW (1–500 hp)
- Duty type S1 (continuous duty) or S3 (intermittent periodic duty) with a rated cyclic duration factor of 80% or higher

This standard defines the requirements for the efficiency classes and aims to create a basis for international consistency. The international efficiency (IE) classes IE1, IE2, and IE3 defined in this standard are based on test methods specified in IEC 60034-2-1 [1.40]. It is noted that the methods with this standard determine efficiency values more accurately than the methods previously used.
In order to promote a competitive motor market transformation, a new international standard IEC 60034-31 [1.41] was released in 2010 for the addition of the IE4 motor efficiency level. Since no sufficient market and technological information is available to allow IE4 standardization, this efficiency class is intended to be informative. It is expected that advanced technologies will be developed in the near future that can enable manufacturers to design motors for the IE4 class efficiency levels, while maintaining motor dimensions compatible with the existing motors having lower efficiency classes. The four electric motor efficiency classes, testing standards, and regulation over time are listed in Table 1.2.

A rated efficiency of a motor is a function of its rated output. The comparisons of the efficiencies for all four efficiency classes (IE1, IE2, IE3, and IE4) are presented in Figures 1.23 and 1.24 for 50 Hz and 60 Hz electric motors, respectively. Furthermore, the comparison of four efficiency classes for 50 Hz and 4-pole motors is given in Figure 1.25.

### 1.2.10 Motor Insulation

The maximum operating temperature of a motor depends on the selection of motor insulation. As the maximum temperature is determined, the maximum motor load, typically specified as the amount of power the motor can deliver on a continuous basis, can be also determined. Thus, motor insulation needs to be defined at the motor’s conceptual design stage.

According to the maximum allowable operating temperature that insulation systems can withstand, electric insulation can be categorized into several classes, characterizing the capability of the insulator to resist aging and failures due to overheating. During motor operation, an insulation material may gradually lose its insulating ability to perform the task. The lifetime of insulation materials depends on thermal, chemical, electrical, and mechanical factors. Among them, thermal and electrical stresses are most important.

<table>
<thead>
<tr>
<th>Efficiency Level</th>
<th>Efficiency Class Standard</th>
<th>Test Standard</th>
<th>Regulation over Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard efficiency</td>
<td>IE1</td>
<td>IEC 60034-2-1</td>
<td>China</td>
</tr>
<tr>
<td></td>
<td>IEC 60034-30</td>
<td>Medium uncertainty</td>
<td>Taiwan 2003</td>
</tr>
<tr>
<td>High efficiency</td>
<td>IE2</td>
<td>IEC 60034-2-1</td>
<td>Australia 2006</td>
</tr>
<tr>
<td></td>
<td>IEC 60034-30</td>
<td></td>
<td>Brazil 2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Canada 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>China 2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Europe 2011</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Korea 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Switzerland 2011</td>
</tr>
<tr>
<td>Premier efficiency</td>
<td>IE3</td>
<td>IEC 60034-2-1</td>
<td>Europe 2015–2017</td>
</tr>
<tr>
<td></td>
<td>IEC 60034-30</td>
<td>Low uncertainty</td>
<td>United States 2011</td>
</tr>
<tr>
<td>Super premier efficiency</td>
<td>IE4</td>
<td>IEC 60034-31</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE 1.23
Comparison of four efficiency classes for electric AC motors with 50 Hz.

FIGURE 1.24
Comparison of four efficiency classes for electric AC motors with 60 Hz.
In fact, dielectric strength of insulation is very sensitive to temperature aging. Average insulation lifetime decreases rapidly with the increase in motor internal temperatures. A generally accepted rule of thumb is that each 10°C rise above the rating temperature may reduce the motor lifetime by one-half.

There are generally five specialized insulation elements used in an electric motor, including turn-to-turn insulation between separate wires in each coil, phase-to-phase insulation between adjacent coils in different phase groups, phase-to-ground insulation between windings and the electrical ground, slot wedge to hold conductors firmly in the slot, and impregnation to bring all the other components together and fill in the air space.

Dielectric strength refers to the maximum electric field (in V/m in the SI system, and V/mil in English system, where 1 mil = 0.001 in.) that a material can withstand without breaking down and losing its insulating capabilities. The dielectric strength of a material depends on the specimen thickness, the electrode shape, the rate of the applied voltage increase, the shape of the voltage–time curve, and the medium surrounding the sample (e.g., air, gas, or liquid). It should be noted that in strong electric fields, Ohm’s law does not hold for insulation materials that have extremely high electric resistance. The current density increases almost exponentially with the electric field, and at a certain value, the current jumps to very high magnitudes at which a specimen of the material is destroyed [1.42].

Dielectric strength values of some solid insulation materials at room temperature and normal atmospheric pressure are presented in Table 1.3.

Based on an average 20,000 h lifetime, the maximum allowable temperature and insulation materials for each insulation class are listed in Table 1.4. The motor classification is based on the temperature rating of the lowest-rated component in the motor.

Thermal aging is an irreversible, permanent reduction of material properties, defined as deterioration. Many of the insulation failures can be attributed to the fact that the
### TABLE 1.3

Dielectric Strength of Some Solid Insulation Materials

<table>
<thead>
<tr>
<th>Insulation Material</th>
<th>Dielectric Strength (V/m × 10^6)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ceramics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Porcelain</td>
<td>35–160</td>
<td>[1.43]</td>
</tr>
<tr>
<td>• Titanates of Mg, Ca, Sr, Ba, and Pb</td>
<td>20–120</td>
<td>[1.44]</td>
</tr>
<tr>
<td><strong>Glasses</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Fused silica, SiO₂</td>
<td>470–670</td>
<td>[1.43]</td>
</tr>
<tr>
<td>• Alkali–silicate glass</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td><strong>Insulating films and tapes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Low-density polyethylene film</td>
<td>300</td>
<td>[1.45]</td>
</tr>
<tr>
<td>• Poly-ᵦ-xylylene film</td>
<td>410–590</td>
<td>[1.46]</td>
</tr>
<tr>
<td>• Aromatic polymer films</td>
<td></td>
<td>[1.47]</td>
</tr>
<tr>
<td>– Kapton H (DuPont)</td>
<td>389–430</td>
<td></td>
</tr>
<tr>
<td>– Ultem</td>
<td>437–565</td>
<td></td>
</tr>
<tr>
<td>– Hostaphan</td>
<td>338–447</td>
<td></td>
</tr>
<tr>
<td>– Amorphous Stabar K2000 (ICI film)</td>
<td>404–422</td>
<td></td>
</tr>
<tr>
<td>– Stabar S100 (ICI film)</td>
<td>353–452</td>
<td></td>
</tr>
<tr>
<td>• Polyetherimide film (26 μm)</td>
<td>486</td>
<td>[1.48]</td>
</tr>
<tr>
<td>• Parylene N/D (25 μm) film</td>
<td>275</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Cellulose acetate film</td>
<td>157</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Cellulose triacetate film</td>
<td>157</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Polytetrafluoroethylene film</td>
<td>87–173</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Fluorinated ethylene-propylene copolymer film</td>
<td>157–197</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Ethylene-tetrafluoroethylene film</td>
<td>197</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Ethylene-chlorotrifluoroethylene copolymer film</td>
<td>197</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Polychlorotrifluoroethylene film</td>
<td>197</td>
<td>[1.49]</td>
</tr>
<tr>
<td></td>
<td>118–153.5</td>
<td>[1.49]</td>
</tr>
<tr>
<td><strong>Micas</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Muscovite, ruby, natural</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>• Phlogopite, amber, natural</td>
<td>118</td>
<td>[1.49]</td>
</tr>
<tr>
<td>• Fluorophlogopite, synthetic</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td><strong>Potassium bromide, KBr, crystalline</strong></td>
<td>80</td>
<td>[1.43]</td>
</tr>
<tr>
<td><strong>Sodium chloride, NaCl, crystalline</strong></td>
<td>150</td>
<td>[1.43]</td>
</tr>
<tr>
<td><strong>Varnish</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Vacuum-pressure-impregnated baking-type solventless varnish</td>
<td>79.9</td>
<td></td>
</tr>
<tr>
<td>• Epoxy baking-type varnish</td>
<td>90.6</td>
<td></td>
</tr>
<tr>
<td>– Solventless, rigid, low viscosity, one part</td>
<td>82.7</td>
<td></td>
</tr>
<tr>
<td>– Solventless, semiflexible, one part</td>
<td>106.3</td>
<td>[1.49]</td>
</tr>
<tr>
<td>– Solventless, semirigid, chemical resistant</td>
<td>181.1</td>
<td></td>
</tr>
<tr>
<td>– Solvable, for hermetic electric motors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Polyurethane coating—clear conformal, fast cre</td>
<td>78.7</td>
<td></td>
</tr>
<tr>
<td>– Standard conditions</td>
<td>47.2</td>
<td></td>
</tr>
<tr>
<td>– Immersion conditions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
operation temperature exceeds the temperature limits of insulation materials. In fact, temperature has a strong impact on the lifetime of insulations. As the temperature rises above the normal operating temperature, the lifetime of insulation can be quickly shortened (Figure 1.26). This phenomenon is called thermal aging. As discussed by Bonnett and Soukup [1.52], the increase in temperature may have resulted from various causes, including the following: (1) voltage variation or unbalance (per Bonnett and Soukup, 3.5% voltage unbalance per phase will lead to an increase of winding temperature of 25% in the phase with the highest current), (2) frequent motor starts and stops, (3) improper motor cooling, (4) severe environmental conditions such as high ambient temperature, and (5) motor operation under overloading conditions.

In many motor manufacturers, the reference ambient temperature $T_a$ is assumed to be 40°C. The temperature rise of a motor is referred to as the difference between the measured temperature of the motor winding and the ambient temperature, that is, $\Delta T = T_w - T_a$. However, the standard method of measuring the winding temperature involves taking the ohmic resistance of the winding. This provides the average temperature of the whole winding, including the motor leads, end turns, and wires deep inside the stator slots. Therefore, to reflect the temperature difference within the winding, a so-called hot spot allowance must be added to adjust the allowable temperature rise. The hop spot allowance $T_{hs}$ is usually assumed to be 5°C–15°C, depending on the insulation class. For a specific insulation class, the allowable temperature rise of a motor is determined for preventing motor overheating under all loading conditions (no load, full load, locked rotor, etc.):

$$\Delta T = T_{\text{max}} - (T_a + T_{hs})$$  \hspace{1cm} (1.45)
1.2.11 Motor Operation Reliability

Motor operation reliability and testing are two key components for design optimization and safe operation of motors. Motor reliability is the measure of the chance that the motor can operate normally over a period of time without failure. In the motor industry, one of the useful parameters is the mean time between failures, defined as the reciprocal of the failure rate (identified as $t$).

Two failure modes dominate the life of motors: bearing failures and winding failures. In all motor failures, bearing failures account the majority. Winding failures generally occur in the early stage of motor running and are attributed to shorts and grounds resulted from assembly quality rather than the long-term insulation degradation. By utilizing more than 2000 actual failure cases of fractional horsepower motors in the existed data failure bank, Wilson and Smith [1.53] developed a mathematical reliability model for each failure mode by means of Weibull cumulative distribution function and regression technique for use in predicting overall motor life and failure rates.

1.3 Classifications of Electric Motors

Electric motors can be classified in a variety of ways according to their operating characteristics, such as the source of electric power, type of rotor winding, type of motion, control pattern, the magnetic flux orientation, structure topology, power rating, and the cooling methods. A brief classification of rotary electric motors is given in Figure 1.27.
FIGURE 1.27
The classification of rotary electric motors.

Rotary electric motor

AC

- Three phase
  - Synchronous
    - Reluctance
      - Hysteresis
    - Stepped
    - PM
    - Servo
  - Asynchronous
    - Switched reluctance
    - Variable reluctance
    - Synchronous reluctance
    - Surface mounted
    - Surface insert
    - Interior PM

- Single phase
  - Wound rotor
  - Squirrel cage

DC

- Brushless
  - Induction
  - Synchronous
    - Reluctance
    - PM
    - Servo
  - Hysteresis
  - Switched reluctance

- Brush
  - Shunt wound
  - Separately wound
  - Series wound
  - Compound wound
  - Direct drive
  - Servo
  - PM commutator

Powered with a DC supplier but converted into AC signals with inverter or other converting devices.
1.3.1 DC and AC Motors

DC motors are designed to run on DC power. This type of motors was invented much earlier than the type of AC motors. They are often used when high torque at low speed is required. The speed adjustments of DC motors can be as much as 20:1, and they can operate at 5%–7% of the motor's base speed (some can even operate at 0 rpm) [1.54]. There are a number of different types of DC motors:

- **Shunt wound motor**—In this motor, the rotor and stator windings are connected in parallel. Hence, the current in the rotor and stator windings are independent of one another. The characteristics of a shunt motor provide it very good speed regulation.

- **Separately excited motor**—In this motor, the rotor and stator winding are connected with different power suppliers. For a long time, it has been the most common configuration used in industrial applications for DC motors with electronic speed control. Due to their excellent controllability and simple operational performance, separately excited motors are extensively used in speed or position control systems.

- **Series motor**—As its name indicates, the rotor and stator windings in a series motor are connected in series. The torque is proportional to $I^2$ so it gives the highest torque per current ratio over all other DC wound field motors at economical costs. It is therefore used in starter motors of cars and some old generation elevator motors [1.55].

- **Compound motor**—As the combination of the series motor and the shunt motor, the motor has the torque characteristics of the series motor and the regulated speed characteristics of the shunt motor. A compound motor comprises an armature winding on the rotor and two field windings on the stator. The stator is connected to the rotor through a compound of shunt and series windings. Compound motors are often adopted to drive loads such as shears, presses, and reciprocating machines.

- **Brushed DC PM field motors**—Field windings are now replaced by PM materials and the winding has a series of commutator bars with carbon brushes arranged to provide mechanical commutation of the motor. Commutation is the switching of the current direction in the winding at the right timing to produce continuous torque vectors in one direction for continuous rotating speeds of the shaft.

- **Universal motors with brushes and commutators** have been designed to operate on either AC or DC power. For this type of motor, the stator's windings are connected in series with the rotor windings through a commutator. The advantages of universal motors are high starting torque, compact size, and ability to run at high operating speed. The negative aspects include the short lifetime caused by the commutator and brushes and high noise and vibration. Therefore, this type of motor is often used in applications where the motor only operates intermittently. Universal motors generally run at high speeds, making them suitable in home appliances (e.g., vacuum cleaners and food mixers) and home power tools (e.g., electric drills) where single-phase wall plug in power is abundant.

- **Brushless DC motor**—This special type of motors has been developed to overcome the limitations and drawbacks of brushed DC motors. Practically, brushless motors are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive commutate the motor. It usually requires sensors and electronic control system for controlling the
inverter output amplitude, waveform, and frequency. Though a number of brushless motors are available (e.g., induction, switched reluctance), typical brushless motors are made with PMs. With built-in PM, the motor does not need a separate excitation winding, resulting in reduced power losses and increased efficiency. The size of the PMDC motor is the smallest (high power density) among all other DC motors. Often, PMDC motors are served as servomotors.

Advantages of brushed DC motors include low initial cost, high reliability, and simple speed and torque control characteristics. Brushless DC motors have evolved from brush DC motors as power electronic devices and became available to provide electronic commutation in place of the mechanical commutation provided by brushes. Brushless motors have increased reliability, longer lifetime, higher efficiency, less maintenance, reduced noise, elimination of ionizing sparks from commutator, and overall reduction of electromagnetic interference.

Today, DC motors are still used in a wide range of applications, especially for those applications requiring precise speed control over a large range around the rated speed, such as steel mills, mines, and electric trains. However, DC motors usually require additional operational elements such as brushes and commutators that transfer electric power to motor armatures. However, commutators usually can cause power ripples and limit the rotor speed and brushes increase the frictional power lower and radiofrequency interference. Furthermore, as brushes wear and tear, carbon dust spreads throughout the motor, causing some operation and performance problems. As a consequence, the maintenance of the interface between the brush and commutator becomes critical for motor operation reliability. In addition, the use of brushed can enhance the motor acoustic noise.

AC motors are driven by AC power sources. By eliminating commutators and brushes, AC motors offer several advantages over DC motors, including increased operation reliability, longer lifetime, higher efficiency, less maintenance, reduced cost, shorter frame size, and simpler motor structure. AC motors are dominant in industrial motion control for cost/performance reasons. As the most common type, single-phase AC motors are mainly used for residential and commercial applications. Three-phase AC motors are especially suitable for high-power applications. In general, single-phase motors operate less efficiently than three-phase motors.

Brushless DC motors are similar to AC synchronous motors. The major difference is that the waveform used to drive AC motors is typically sinusoidal and could come directly from an AC source or could be using the pulse-width modulation (PWM) technique. Therefore, AC synchronous motors develop a sinusoidal back EMF, as compared to a rectangular or trapezoidal back EMF for brushless DC motors.

Motors used in hospital equipment or other patient-care facilities are required to comply with low noise level standards to endorse patient comfort and reduce anxiety. Brushless DC motors are ideal for noise-sensitive environments due to the lack of brushes, which emit audible noise during rotation [1.56].

The disadvantages of AC motors include difficulty of speed control, high control complexity, less torque density, inability for operating at low speeds, induced eddy current and hysteresis power losses in the stator and rotor cores, high cost, and poor positioning control.

### 1.3.2 Single-Phase and Three-Phase Motors

In most countries, household power is usually single phase due to the low cost of single-phase power distribution. A single-phase motor is run from an AC single-phase power
system. The most standard frequencies of single-phase power systems are either 50 or 60 Hz, although other frequencies may be also available. However, unlike three-phase motors, a single-phase motor is unable to produce the start torque itself; it must be started by some external means such as an auxiliary start winding or a start capacitor. Single-phase motors need some other forcing functions to set direction of rotation (DIR). The auxiliary start winding or start capacitor creates a simulated phase to set the DIR.

Three-phase power is a common form of electric power due to its inherent benefits in high-powered transmission and electric equipment operation. In a three-phase power system, ACs are carried by three circuit conductors with the same frequency and amplitude but different phases. As sinusoidal functions of time, the current at each conductor has shifted $120^\circ$ in phase from each other. Correspondingly, in a three-phase motor, there are also three windings (separated equally in space by $120^\circ$) per pole on stator to produce a rotating magnetic field.

Because of higher efficiencies and favorable torque–current characteristics versus single-phase motors, the three-phase AC motors dominate in almost all industries and consume more than half of all the electricity used in industry. In contrast, three-phase motors are more efficient and compact than single-phase motors of comparable power rating. Three-phase motors have generally lower vibrations and last longer than single-phase motors under the same conditions. As a matter of fact, the effectiveness and low cost of three-phase motors are major reasons for three-phase power to be extensively used in industry.

### 1.3.3 Induction and Permanent Magnet Motors

Depending upon the method of generation of the magnetic field in the rotor, an AC motor can be classified either a PM AC motor, where the magnetic field of the rotor is directly produced by PMs, or an IM, where the magnetic field of the rotor is produced though the induction effect onto the rotor bars/winding.

In an IM, the AC power supply is connected to the stator winding to generate a rotating magnetic field. Because of this rotating field, the rotor is powered by means of electromagnetic induction. The change in magnetic flux through the rotor induces AC in rotor windings and in turn creates its own magnetic field. The induced current in the rotor gives rise to magnetic forces, which cause the rotor to rotate in the direction defined by the stator rotating magnetic field. In actual operation, the rotor speed always lags the magnetic field speed, which is defined as the synchronous speed, allowing the rotor windings or conducting bars to cut magnetic lines of force and produce useful torque.

According to the rotor structure, IMs can be further divided into two subcategories: (1) squirrel cage motors in which the rotor is made of conductive aluminum/copper bars that are parallel (or have a small skew angle) to the rotor centerline and short-circuited by the end rings (Figure 1.28) and (2) wound rotor motors where windings are made on the rotors (Figure 1.29).

IMs are perhaps the simplest and most rugged motors, which have been extensively used in a variety of applications, from household appliances to heavy industrial equipment, due to their simple structures and low costs. In modern squirrel cage IMs, the conducting bars are formed in the skewed slots distributed axially along the rotor surface by casting. These conducting bars are connected at the ends of the rotor slots as the end rings to form the closed electric circuit.

For IMs, the stator operates with the power supply frequency $f$ ($f=60$ Hz in North America and $f=50$ Hz in most countries of the world) and the rotor winding contains
FIGURE 1.28
Conductive bars and end rings in a squirrel cage motor with closed slots.

FIGURE 1.29
Rotor winding in a wound IM.
current and voltage with slip frequency $f_{\text{slip}}$ or $sf$, where $f_{\text{slip}}$ is defined as the frequency corresponding to the slip speed $n_{\text{slip}} = (n_s - n_r)$.

A low rotor resistance will result in the current being controlled by the inductive component of the circuit, yielding a high out-of-phase current and a low torque.

PMMs use permanent magnets to generate the required magnetic field and thus separated excitation windings are no longer required. A permanently excited synchronous motor has a sinusoidal back EMF and therefore operates with a sinusoidal voltage. PMMs are designed to provide a wide operation speed and load range with high motor efficiency, usually in excess of 90% from less than 50% speed driving a typical pump or compressor load to a peak range in excess of 97% for high-speed applications [1.57]. The structure of a PMM is shown in Figure 1.30.

PMMs have numerous advantages over IMs. First, the built-in PMs in a PMM eliminate rotor windings that are required in an IM. Hence, it greatly reduces the rotor inertia and power losses and, consequently, increases operational reliability and improves dynamic load response. Second, since the stator current in a PMM is only for torque production and thus magnetizing current through the stator is no longer necessary, a PMM operates at a higher power factor and thus a higher efficiency over an IM for the same power output. Third, the application of rare-earth PMs makes PMMs with high power density and high torque-to-inertia ratio, which lead to fast dynamic response capability. As a matter of fact, rare-earth PMMs have the highest power density of any motor type. This feature is especially desirable for applications in which the motor size is a main consideration. Today, PMMs have become increasingly popular in various industrial and commercial sectors. They are especially ideal in high-accuracy, high-performance motion control applications, for instance, computer numerical control (CNC) machine tools, robots, embedded motion, engraving machines, packaging and printing machines, semiconductor fabrication facilities, medical equipment, and satellite servo systems.

**FIGURE 1.30**
The typical structure of a PMM. (Courtesy of Kollmorgen Corporation, Radford, VA.)
The comparison of motor efficiency and power factor between a 55 kW, 1500 rpm IM and a PMM under an identical operation condition and power rating is given in Figure 1.31 [1.58].

According to the mounting pattern of PMs, PMMs can be further divided as surface mounted, surface insert, core insert, and pole shoe. Surface-mounted PM (SPM) motors have dominated for decades. In recent years, some emerging markets and perhaps the sharp price rise of rare-earth magnets have boosted demand for IPM motors. With advantages such as high-speed performance, robust mechanical structure, low heat generation in rotor, and special designs that can support near-constant power over a broad range of speed, IPM motors provide an excellent solution for applications like traction motors, machine tools, or high-speed rotors.

In the surface-insert method, PMs are buried inside the rotor core. This method can offer some distinct advantages, for instance, the simple and robust rotor structure, high torque density, easy-to-achieve flux-weakening operation, and potentiality of fully sensorless operation [1.59].

Torque produced by an IPM motor is based on two different mechanisms [1.60]: one is the same as an SPM motor; PM torque is generated by the magnetic flux linkage between the PM rotor field and the electromagnetic field of the stator. Another is known as reluctance torque. PMs buried inside a rotor pole piece exhibit high reluctance directly along the magnetic axis due to the low permeability of the PMs and pole pieces between the magnetic poles or magnet barriers, creating inductance saliency and reluctance torque. Thus, IPM motor designs augment PM torque with reluctance torque. As a result, the magnets used in IPM motors can be thinner, achieving significant cost reductions.

**FIGURE 1.31**
Comparison of calculated motor efficiency and power factor between a 55 kW, 1500 rpm IM and a PMM under an identical operation condition.
1.3.4 Synchronous and Asynchronous Motors

A synchronous motor refers to a three-phase AC motor in which the rotor runs at the same speed of the rotating magnetic field of the stator. The synchronous speed $n_s$ can be expressed in different ways, depending on the unit it adopted:

$$n_s = \frac{f}{p} \text{ in rps (Hz)}$$  \hspace{1cm} (1.46a)

$$n_s = \frac{60f}{p} \text{ in rpm}$$  \hspace{1cm} (1.46b)

where

- $f$ is the frequency of the AC supply current in Hz
- $p$ is the number of magnetic pole pairs per phase

The synchronous speeds of 50 and 60 Hz machines are presented in Figure 1.32 for various magnetic pole pairs.

If $N$ denotes the number of magnetic poles per phase, then it gives that $N=2p$ and yields

$$n_s = \frac{120f}{N} \text{ in rpm}$$  \hspace{1cm} (1.47)

Therefore, synchronous speed can be altered by changing either the frequency applied to the motor or the number of magnetic poles. Some multispeed motors adopted external connections that enable to switch the stator poles, for example, from 4 to 6 poles. By using an adjustable frequency drive, motor speed can vary in a large speed range under a constant voltage.

![Figure 1.32](image-url)  
Synchronous speeds of 50 and 60 Hz machines under various pole numbers.
In the unit of radians per second (rad/s), the angular synchronous speed \( \omega_s \) is given as

\[
\omega_s = \frac{\pi n_s}{30} = \frac{2\pi f}{p} = \frac{4\pi f}{N}
\]  

(1.48)

In contrast, in an IM, the stator windings are wound around the rotor to produce a rotating magnetic field with a three-phase power supply. It is the varying magnetic field that induces currents in the rotor conductors/end rings (or rotor windings). Thus, the interaction between the magnetic fields of the stator and rotor causes a rotational motion of the rotor.

Because current in the rotor conductors/end rings is induced by the stator windings, the rotating speed of the rotor must lag the rotating speed of the stator’s magnetic field (i.e., the synchronous speed). This speed difference is called slip, which is defined as

\[
s = \frac{n_s - n_r}{n_s} = \frac{\omega_s - \omega_r}{\omega_s}
\]  

(1.49)

where

- \( n_s \) and \( n_r \) are the synchronous speed and rotor speed in rpm
- \( \omega_s \) and \( \omega_r \) are the angular synchronous speed and angular rotor speed in rad/s, respectively

Thus, the rotor rotating speed of an asynchronous motor becomes

\[
n_r = n_s (1 - s) \text{ in rpm}
\]  

(1.50a)

\[
\omega_r = \omega_s (1 - s) \text{ in rad/s}
\]  

(1.50b)

Slip increases with load. Usually, full-load slip ranges from less than 1%–3% for larger-power motors to 4%–6% for small-power motors.

Synchronous motors can be built with either salient pole rotor or nonsalient pole (cylindrical) rotors, depending on the customers’ specifications and applications. Generally, salient pole motors are typically found in high-power, low-speed applications. Motors with cylindrical rotors are typically found in high-power, high-speed applications such as spindle motors in machine tools.

### 1.3.5 Servo and Stepper Motors

There are two main types of motion control systems: closed loop and open loop. A closed-loop system applies a feedback system to verify whether or not the desired output has been reached. For instance, an encoder is commonly attached with a servomotor to measure the velocity and position of the servomotor for providing the information to the motion controller. Obviously, servomotor systems require the use of the closed-loop system. As a contrast, an open-loop system does not need any feedback for verifying the output. In practice, most step motor systems use open-loop system. The difference between the two control schemes is whether or not the use of feedback system (Figure 1.33).
An open motion control system usually consists of a motion controller, a feedback system, an electric motor, and a motor drive. The motion controller acts primarily as the brain of the motion control system. Its main function is to make sure the output of the system is as close as possible to the desired result. Based on the information from the feedback system (such as encoder, resolver, sensors), the motion controller sends the electronic signals to the motor drive to adjust motion path or trajectory. The feedback system is to obtain the motor motion information (e.g., displacement and speed), which are then converted into a set of digitized output signals and fed to the motion controller for making necessary adjustments. The motor drive takes the low-power electronic signal from the motion controller and converts it into high-power current/voltage to the motor, which executes the tasks from the drive as an actuator. All these components are integrated to form the complete motion control system to provide the desired movement for various applications.

The word *servo* originally comes from the Latin word *servus*, meaning slave or servant. NEMA [1.61] defined a servomotor as “an electric motor that employs feedback with the purpose of producing mechanical power to perform the desired motion of the servo mechanism.” Simply speaking, any control element that employs feedback is a servo.

Today, servomotors are increasingly being used in a variety of applications due to their high power density, high efficiency, and excellent dynamic performance as compared with other motor drive technologies. Servomotors operate with closed-loop control systems. The ability of the servomotor to adjust to differences between the motion profile and feedback signals depends greatly upon the types of control systems and servomotors. There are two types of servomotors: one is classical DC servomotor and another is AC servomotor. Generally, AC servomotors can handle higher current surges compared to DC servomotors. It is to be noted that in some references, AC servomotors are referred to as brushless DC motors, causing confusion to some readers. An AC servomotor or the so-called brushless DC motor is essentially a three-phase AC synchronous motor. It has a position transducer inside the motor to transmit motor shaft position to the drive amplifier for the purpose of controlling current commutation in the three phases of the motor windings.

**FIGURE 1.33**
Comparison of two control schemes: (a) the open control loop and (b) the closed control loop.
Stepper motors are special motors used in motion control systems. This type of motor has high torque at low speeds, high reliability, low cost, and simple rugged construction that operates in almost any environment. Typical applications include printers, image scanners, CNC machines, and volumetric pumps. Unlike common AC and DC motors rotating continuously, a stepper motor moves in fixed angular increments, called the step angles. In a stepper motor, a full revolution is divided into a large number of discrete steps. In fact, a stepper motor is an actuator that converts electrical pulse signals into angular displacements. Once the stepper motor receives an electrical pulse signal, it moves a fixed step angle in a predefined direction. Thus, by controlling the pulse number, the angular displacement (i.e., the motor positioning) can be controlled precisely. By altering the pulse frequency, the accurate control of the motor rotating speed and acceleration can be achieved. It is important to note that in this control mechanism, no feedback systems are required. This allows the stepper motor to operate in an open-loop system, making the motion control easier and less expensive. In addition, stepper motors can operate at a set speed regardless of load as long as the applied load is less than the limited torque rating.

As an open-loop control system, the stepper motor requires only the input of the current state. The number of steps per revolution varies by model and manufacturer. Stepper motors were introduced in the early of 1960s as an economical replacement to closed-loop DC servo systems. Unlike conventional motors that rotate continuously, stepper motors rotate in fixed angular increments. One revolution of a stepper motor involves taking a number of steps, depending on the number of rotor teeth, motor construction, and type of drive scheme used in the motor control.

Stepper motor technology does have some disadvantages. The most critical drawback is the loss of synchronization and torque if a large load exceeds the motor's capacity. A high-inertia load can cause the rotor to slip, or not advance when the step pulse is given. Consequently, the user typically selects a stepper motor's capability with 2:1 factors of safety (FS) to torque to minimize or eliminate loss of synchronization. Stepper motors also tend to run hot because phase current is independent of the load. In some applications, if the motor needs to be overdriven by the load, it may be undesirable to feel the poles of the stepper motor as the rotor is being pulled by the load [1.62].

Today, stepper motors are available in many topologies and step sizes for various industrial and commercial applications due to their advantages of low cost, high reliability, no cumulative error, high torque at low speeds, simple and rugged construction, and excellent response to start-up, stopping, and reverse operation.

There are basically three types of stepper motors: PM, variable reluctance, and hybrid [1.63]. The PMM has relative low torque and low speed with large step angles. Its simple construction and low cost make it an ideal choice for nonindustrial applications. The variable reluctance motor (VRM) usually has three-phase stator windings. It can achieve large torque outputs. However, due to their large vibrations and high noise emissions, VRMs are gradually out of the main industrial market. The hybrid stepper motor combines the best characteristics of the variable reluctance and PMMs by constructing multistor poles and PMs inside the rotor. Therefore, the hybrid stepper motor is the most widely used stepper motor today. The comparison of three types of stepper motors is listed in Table 1.5.

A cutaway diagram of hybrid stepper motors is demonstrated in Figure 1.34. The stator coils are wound on stator poles. The rotor is a cylindrical PM, magnetized along the axis with radial soft iron teeth. Thus, one pole of the rotor may align with the stator in distinct positions.

The polarity of rotor laminations is shown in Figure 1.35. Unlike conventional motors, the magnet in a stepper motor is magnetized axially rather than radially. As shown in
TABLE 1.5
Comparison of Three Types of Stepper Motors

<table>
<thead>
<tr>
<th>Stepper Motor Type</th>
<th>Phase</th>
<th>Step Angle</th>
<th>Torque</th>
<th>Vibration and Noise</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent magnet</td>
<td>2 or 4</td>
<td>7.5° or 15°</td>
<td>Low</td>
<td>Low vibration at low frequencies, low noise</td>
<td>High efficiency, low current, low heat generation</td>
</tr>
<tr>
<td>Variable reluctance</td>
<td>3</td>
<td>1.5°</td>
<td>High</td>
<td>Large</td>
<td>Out of main industrial market</td>
</tr>
<tr>
<td>Hybrid</td>
<td>2</td>
<td>1.8°</td>
<td>High</td>
<td>Low</td>
<td>With the most wide applications</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.72°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 1.34
Structures of hybrid stepper motors, which combines features of the PM stepper and the variable reluctance stepper motors.

Figure 1.35, two axially spaced sections each formed with radially projecting and angularly spaced teeth. In addition, the teeth on the north end of the rotor are displaced by a half of a pole pitch from the teeth on the south end. Both of these two features make stepper motors unique from other motors.

For standard reluctance stepper motors (e.g., without PM), the rotors look similar to the aforementioned rotor except there is no PM and the magnetic field is not permanently present in the rotor lamination. The coils in the stator create a magnetic field in the stator that attracts or repels the soft iron rotor laminations into position. Then the coil current is reversed to reverse the coil magnetic field and keeps the rotation moving. A stepper motor drive is required to switch the currents.
1.3.6 Gear Drive and Direct Drive Motors

There are several motor driving patterns in motion control applications: (1) gear drive, (2) direct drive, (3) tangential drive (e.g., belt, chain), (4) ball/lead screw drive, and (5) worm drive.

Gear drive is a conventional mechanism in connecting electric motors to external mechanical loads. The shaft of a motor is attached to one end of the gearbox and, through the internal configuration of gears of the gearbox, provides a given output torque and speed determined by the gear ratio. In such a way, a motor is coupled with a transmission device (e.g., gearbox) to reduce the rotating speed and increase the output torque. The most important design parameter of gearboxes is the gear ratio $\gamma_g$, which is defined as the ratio of the input speed to the output speed. In a gear drive system, the ratio of the load torque $T_l$ (the output torque) to the motor torque $T_m$ (the input torque) is determined by the gear ratio $\gamma_g$ and the gearbox efficiency $\eta_{gb}$:

$$\frac{T_l}{T_m} = \gamma_g \eta_{gb}$$

(1.51)

Gearboxes are available in many different types, sizes, gear ratios, efficiencies, and backlash characteristics. They can be generally categorized into several different types: parallel shaft gearbox (e.g., spur and helical gearbox), perpendicular shaft gearbox (e.g., bevel gearbox), planetary gearbox, and worm gearbox, just to name a few. For the type of parallel shaft gearbox, according to the number of shafts, gearboxes can be further classified as single-stage (two shafts), dual-stage (three shafts), and multistage (more than three shafts) gearboxes. Usually, this type of gearboxes takes more space than other gearbox types.
Planetary gearboxes are the most commonly used gearboxes in the motion control market due to their high torsional rigidity, high torque, high efficiency, low inertia, and low backlash.

However, there are some disadvantages in using gearboxes. The main problem is backlash introduced by gearboxes. Backlash is the gap between the teeth of two adjacent gears. Thus, the rotational backlash of a gearbox is the accumulated backlash from all paired gears. It can be measured as the free rotational angle at the gearbox output shaft when the input shaft is locked, or vice versa. In precise motion control applications involving frequent load reversals (e.g., CNC machines, elevators, wind pitch control systems), backlash plays a crucial role to determine the repetitive positioning accuracy. For this type of applications, gearboxes must be made with low, strictly controlled backlash and high stiffness. For demonstration purpose, the theoretical backlash of gearbox and torsional stiffness are shown in Figure 1.36.

The use of separated motor and gearbox may greatly increase the system volume and lower the torque density and system reliability. To solve these problems, some motor manufacturers have designed motors with built-in gearboxes for achieving the solution of high torque capacity, smooth operation, minimal maintenance, and high-efficiency motors in compact sizes, as shown in Figure 1.37.

DDR motors are designed to directly drive an external loaded machine. They can be housed or frameless component sets of a PM field assembly and wound stator. The frameless part set can be built into a machine as embedded motion onto the user's shaft, housing, and bearing assembly and offers the most compact form factors. By eliminating the need for additional mechanical transmission devices, it allows improved motor reliability, efficiency, dynamic performance, torque density, motion accuracy, and disturbance response. This also leads to large mass savings in the mechanical structure and enables further cost reductions. There are other advantages such as better load inertia matching, ease of control, low noise emission, and streamlined machine design.

![Figure 1.36](image)

Theoretical backlash of a gearbox and stiffness curve.
Introduction to Electric Motors

Typical DDR motors are shown in Figure 1.38, which offer many high-performance features and zero maintenance in a precision servo solution. Among them, the cartridge DDR motor, developed by Kollmorgen in 2005, is the first in the motor industry to combine the space-saving and performance advantages of frameless DDR technology. The cartridge DDR motors are supported by customers’ bearings, thus providing up to 50% more torque density than comparably sized conventional servomotors and the ability to remove the motor without disassembling the machine. By making direct drive benefits available to simple mechanisms, this type of motors has been successfully used in many applications such as packaging, printing, medical equipment, converting, and others.

For a DDR motor, torque is proportional to rotor diameter squared. Thus, in order to increase motor torque, DDR motors are typically designed with high diameter-to-length ratios, that is, large diameters and short axial lengths. In addition, a DDR motor can simultaneously have both a very large OD and ID. This implies that the DDR motor looks more like a thin ring. In fact, the large OD and ID help develop the large motor torque. This thin-ring shape may be particularly suitable for some applications requiring large diameters and short lengths such as computerized tomography (CT) scanners, magnetic resonance imaging (MRI) scanners, and wind turbines. As an example, a DDR motor for a telescope drive has a diameter of 2.5 m and a length of less than 50 mm. This motor can produce a continuous torque exceeding 10,000 N-m [1.64]. In large machine tool applications, DDR diameters of 1 m or so are commonly encountered.

Frameless DDR motors do not contain housings, bearings, or feedback devices, as shown in Figure 1.39. This implies that a frameless DDR motor must be integrated into the user’s machine. To help integrate the motor, motor manufacturers often provide a reusable assembly tool called bridge to maintain the alignment of the rotor and stator during assembly.

The design of DDR motors is mainly influenced by its rotating speed, torque, and power. The achievable power of a motor is approximately proportional to the square of the air gap diameter and to the axial length of the motor at the air gap. This indicates that with a doubling of the air gap diameter, the motor power can increase four times. As a matter of fact, direct motors with low rotating speeds usually have a large diameter and a short length.
FIGURE 1.38
Various DDR motors. (Courtesy of Kollmorgen Corporation, Radford, VA.)

FIGURE 1.39
Frameless DDR motors. (Courtesy of Kollmorgen Corporation, Radford, VA.)
Comparing with conventional servo systems, the advantages of direct drive systems include the following:

- It significantly increases system efficiency by eliminating inefficient gearboxes.
- Because the gearbox in a motor system is a primary noise source, the elimination of the gearbox greatly reduces the noise emission from the motor.
- Motor reliability increases due to the reduction in the number of rotating parts.
- The positioning inaccuracy from transmission compliance no longer existed.
- Lower inertia enables fast and accurate positioning.
- A direct drive servomotor is capable of precise revolution control with high resolutions.
- Without speed reduction devices, mechanical backlash, hysteresis, and elasticity in gear transmission systems are eliminated.
- There is no need for gearbox lubrication and it simplifies maintenance.

However, direct drive motors require more precise control systems. Since the direct drive motors need special design, their individual costs are much higher than other servomotors, but system costs utilizing them can be lower than the total installed cost.

1.3.7 Brush and Brushless Motors

Brush motors have a long history of applications since the first electric motor was invented in the late nineteenth century. For a classical DC motor, an electrical power source is connected to the rotor winding through a commutator and brushes. A commutator usually consists of a set of contact bars attached to the rotating shaft of a motor. As the stator windings are sequentially energized to generate a rotating magnetic field, the rotor aligns itself with the magnetic field of the stator. A number of stationary brushes come into contact with corresponding the contact bars of the commutator for reversing the flow of current in the rotor winding. In order to reduce the contact electric resistance at the contacting surface, brushes are pressed against the commutator and thus result in some friction between the brushes and commutator. In addition, at high rotating speeds, brushes become increasingly difficult to maintain reliably in contact with the commutator. Brushes may bounce off from the commutator surface to produce sparks and consequently break the circuit in a very short period of time. Continuous sparking can cause overheat, erode, or even melt the commutator. For this reason, brush motors are restricted to relative low speeds to avoid brushes excessively bouncing and sparking.

To overcome these drawbacks, brushless motors have been developed to replace brushed motors in some motion control applications. Brushless DC motors typically operate with PM rotors, offering distinct mechanical and electrical advantages over conventional systems. Attachment of PMs on rotor and elimination of rotor coil windings allow significant reductions in rotor inertia and increase in motor acceleration and efficiency. Winding heat can be dissipated directly from the stator into the environment and rotor heating is much lower than that in a brush motor. Generally, comparing to brush motors, brushless motors offer higher operation reliability, higher dynamic accuracy, higher efficiency, less product variation, and smaller size but require complex and expensive electronic control systems.

With the widespread use of brushless AC motors in industrial, commercial, and military applications, brushes are gradually exiting the electrical machine market.
1.3.8 Reluctance Motors

Reluctance motors are special motors that use salient pole rotors but without windings and PM on the rotors. There are several types of reluctance motors, with different construction and slightly different functions [1.65]:

- Switched reluctance motor (SRM)—By eliminating windings and PMs from the rotor, this type of motor has inherent advantages over some DC and AC motors, such as simple structure, structure robustness, low cost, and operation in high temperatures. SRMs have been designed mainly for the applications in high-power, high-efficiency, variable speed drives, enabling to deliver a wide range of torque. This type of motor requires the closed-loop position control.

- VRM—This type of motor is an evolution of the stepper motor but with less salient poles. The motors are generally designed for use in low-power, open-loop position and speed control systems where efficiency is not of prime importance. In fact, there are similarities between switched and VRMs such as the operating principles, mechanical structures, performing characteristics, and power losses. Both of the types are similar to the brushless PMMs except that the rotors are made from laminated soft magnetic materials.

- Synchronous reluctance motor—This type of motor is similar to synchronous AC motors. The rotor has salient poles but the stator has smooth, distributed poles, whereas both the switched and variable motors have salient poles for both the rotor and stator.

SRMs can be traced back to the invention of Robert Davidson in 1938 [1.66]. However, this type of motors did not find widespread use until the late 1970s due to the difficulty in controlling the machine. For an SRM, there are no windings or PMs on the rotor. When the stator windings are powered, the rotor’s magnetic reluctance produces a force that attempts to align the rotor with the exited stator poles. The coils in the adjacent slots are powered successively so that the rotor can rotate continuously. This operation principle is based on the difference in magnetic reluctance for magnetic field lines between aligned and unaligned rotor position when a stator coil is excited; the rotor experiences a force that will pull the rotor to the aligned position [1.67].

Due to the elimination of magnets and rotor windings, SRMs offer several performance, efficiency, and cost advantages. In an SRM, torque is produced by the tendency of its movable part to move to a position of least reluctance. The SRM has salient poles on both the rotor and the stator, but only the stator poles carry windings. When the stator windings are energized, they create a magnetic field that pulls the nearest pole on the rotor toward it. Consequently, the performance of SRMs is largely a function of the power electronics that control the sequencing of pole energizations. Besides, the SRMs have characteristically high power-to-weight ratios and are well suited for vehicle applications [1.68].

SRMs have been found to offer important advantages over conventional motors in many industrial and commercial applications. In recent years, SRMs have been receiving increasing attention because they can provide similar performance to brushless DC motors without using expensive rare-earth magnets. In addition, their robust construction and efficiency over a wide speed range make them well suited to a variety of applications including hybrid and electric vehicles. However, the main drawbacks are its high-torque ripple and consequently high audible noise. As shown in Figure 1.40, the stator of an SRM is similar to a brushless DC motor but the rotor has no magnets or windings attached.
1.3.9 Radial-Flux and Axial-Flux Motors

The configuration of the electromagnetic field in a motor determines the motor’s geometry and structural topology. Electric motors in which the magnetic flux travels in the radial direction are classified as radial-flux (RF) motors. This type of motors is cylindrical in shape, and the rotor is typically located inside a stator but can also be placed outside the stator in some special applications, sometimes referred to as inside out motors or outer rotating rotor motors. As a contrast, motors in which the magnetic flux travels in the axial direction are classified as axial-flux (AF) motors. This type of motors usually has multiple disk- or pancake-shaped rotors and stators. A typical brushless AF motor is demonstrated in Figure 1.41, showing a stator–rotor–stator structural topology. AF motors offer low axial...
length and are common in automotive radiator cooling fan applications, table top medical or lab devices, and specialized elevator machines to name but a few. The structure of a DC brush AF motor is shown in Figure 1.42. As can be seen from the figure, the armature is constructed from several layers of copper conductors in a unique flat-disk configuration. Because it adopts ironless design, the thin, low-inertia armature design leads to exceptional torque-to-inertia ratios. The ironless armature enables the motors to deliver more torque over their entire speed range. In fact, the torque is almost constant from 0 to 3000 rpm, which is not attainable with conventional ironcore motor designs. In addition, this type of motors can accelerate from 0 to 3000 rpm in only 60° of rotation [1.69].

1.3.10 Rotary and Linear Motors

According to the motion pattern of motor, an electric motor can be classified as either rotary or linear motor. As indicated in their names, the rotor in a rotary motor always rotates with respect to its rotating axis and the rotor in a linear motor moves linearly along the flat stator. Actually, a linear motor has the motion of a rotary motor if it was laid out in a flat state.

Linear motors are typically used in the applications that require linear or reciprocating motions (Figure 1.43). A famous example is the high-speed maglev train that was built in 2004 at Shanghai, China, and has been in normal commercial operation thereafter. Similar to rotating motors, linear motors can be grouped as induction or PM linear motors. When very fast linear acceleration or high linear forces are required, linear motors are often employed. A disadvantage is the mechanical structure to support them is more expensive than rotary motor structures.
1.3.11 Open and Enclosed Motors

An open motor refers to the motor that has ventilating openings that permit passage of external cooling air to get in the motor for flowing over and around the windings. With the openings on the motor housing, it makes possible for the external objects such as dusts and moisture to enter into the motor, causing motor damage even failure. Therefore, this type of motors cannot work under harsh environments.

An enclosed motor refers to the motor that is completely enclosed to prevent the free exchange of air between inside and outside of the motor housing. In such a configuration, heat is usually dissipated relying on conduction from the heat source (i.e., stator windings) to the motor housing and then from the housing to the environment by convection. This cooling mode is applicable only to small motors with relative low heat loads. For high-powered motors, a build-in cooling system such as a liquid cooling system or using heat pipes is necessary. This type of motors usually has high International Protection Rating or Ingress Protection Rating (IP) values and thus can be used in harsh and dangerous environments.

1.3.12 Motor Classification according to Power Rating

According to the motor nominal power, electric motors can be briefly divided into five categories:

- Micromotors are electric motors with rated output power of 0.05 hp (<37 W) or less. Micromotors have been used across a wide range of commercial and industrial applications for light duty, especially in microelectronics, computer, and precision instrument industries.
• Small motors are larger than 0.05 hp but less than 1 hp (37–746 W). Their applications focus primarily on power hand tools, appliances, medical devices, small fans, optical devices, electrical cars, precise motion control systems, and other small machinery.

• Medium motors are considered to be in the range of 1–100 hp (746 W–74.6 kW). The majority of medium motors are used in various industrial applications such as industrial fans, pumps, motion-control systems, machine tools, and vehicles.

• Large motors occupy the power range of 100–1000 hp (74.6 kW–746 kW). They are normally designed for use in medium-duty applications as in elevators, large vehicles, industrial blowers/fans, printing machines, package machines, air compressors, and other industrial large machines.

• Extra large motors range from 1000 to 10,000 hp (746 kW–7.46 MW), which are usually used in heavy-duty applications, such as large rolling mills, large machine tools, high-speed trains, skyway elevators, ship propulsion, and mining machinery.

• Ultra large motors are considered to be larger than 10,000 hp (>746 MW). NASA used a motor that is rated 135,000 hp for a wind tunnel. In addition, the industry’s largest players such as GE, Siemens, TECO-Westinghouse, ABB, and Toshiba have developed their own ultra large motors.

It is worth to note that the range for each motor category shown earlier has not been clearly defined by international, national, or professional standards yet.

1.4 Motor Design and Operation Parameters

In designing, selecting, and repairing electric motors, it often involves a number of constants that reveal the relationships of torque, current, speed, voltage, power loss, and other operating characteristics. Among these constants, the back EMF constant and torque constant are the two most important constants for evaluating motor performance.

1.4.1 Back EMF Constant, $K_e$

The induced voltage in motor conductors under a rotating magnetic field is defined as the back EMF $V_e$ and is directly proportional to the angular velocity of the motor. Thus, the proportionality constant, referred to back EMF constant, is defined as the ratio of back EMF to motor rotational speed, in the unit of V/(rad/s) or V/rpm (in some applications, V/krpm):

$$K_e = \frac{V_e}{\omega} \quad (1.52)$$

Thus, $K_e$ is a measure of how many volts per rpm the motor would produce if driven as a generator. It can be also used to determine how fast a motor will run with a given voltage applied to it.
1.4.2 Torque Constant, \( K_t \)

\( K_t \) is called torque constant (N-m/A) or torque sensitivity, which is defined as the torque \( T \) (in N-m) generated by a motor to the motor input current \( I \) (in A), that is,

\[
K_t = \frac{T}{I}
\]  

(1.53)

For a sinusoidal commutated motor, the root-mean-square (rms) current \( i_{rms} \) should be used to replace \( I \) in the aforementioned equation, where \( i_{rms} \) is related to the peak AC current \( i_p \) as

\[
i_{rms} = \frac{i_p}{\sqrt{2}}
\]  

(1.54)

Figure 1.44 presents the block diagram of conventional circuit for estimating motor torque constant. This conventional engineering method assumes that when the motor is accelerated, the motor torque constant is proportional to a position change as the output of the motor, regardless of the input current of the motor. However, motor torque constant actually depends on the input current during acceleration of the motor. Hence, the conventional method cannot provide the accurate result for motor torque constant. Based on a new block diagram shown in Figure 1.45, a new method was proposed to calculate motor torque constant by a multiplicity of measured current and speed values [1.70]:

\[
K_t = \frac{\sum_{k=1}^{n} i(k-1)[\nu(k) - \nu(k-1)]}{\sum_{k=1}^{n} i(k-1)^2}
\]  

(1.55)

where

\( i(k) \) and \( \nu(k) \), respectively, indicate the current and the speed of the motor at a sampling time \( k \)

\( n \) indicates a natural number greater than 1

---

**FIGURE 1.44**

The block diagram of conventional circuit for estimating motor torque constant.
1.4.3 Velocity Constant, $K_v$

$K_v$ is the motor velocity constant, measured in rpm or rad/s per volt. In fact, $K_v$ is the reciprocal of $K_e$. For brushless motors, $K_v$ is the ratio of the motor's unloaded rpm or rad/s to the peak voltage. This parameter is used for selecting the winding in the motor.

It can be shown that if the torque constant $K_t$ is in N-m/A and the back EMF constant $K_e$ in V/(rad/s), then,

$$K_t = K_e \frac{1}{K_v} \quad (1.56)$$

1.4.4 Motor Constant, $K_m$

$K_m$ is the motor constant, defined as the torque constant $K_t$ divided by the square root of the resistive power loss $P_r$:

$$K_m = \frac{K_t}{\sqrt{P_r}} \quad (1.57)$$

- For DC motors,
  $$P_r = I^2R_{DC} \quad (1.58a)$$

- For three-phase AC motors,
  $$P_r = i_{rms}^2R_{AC} = \frac{3i_{rms}^2R_{AC}}{2} \quad (1.58b)$$

where $R_{DC}$ and $R_{AC}$ are the winding resistances for DC and AC motors, respectively. Substituting (1.58a) into (1.57), it yields

$$K_m = \frac{K_t}{I\sqrt{R_{DC}}} = \frac{T}{I^2\sqrt{R_{DC}}} \quad (1.59)$$
Since $P_m - P_{out} = \sum P_{loss} > F R_{DC}$, it follows that

$$\sqrt{P_m - P_{out}} > I \sqrt{R_{DC}}$$

(1.60)

Therefore, the minimum torque constant is obtained as

$$K_{m,\text{min}} = \frac{T}{\sqrt{P_m - P_{out}}}$$

(1.61)

Similarly, substituting $P_r$ for the corrected 3-phase AC motor and thus obtaining another $K_m$ equation as

$$K_m = \frac{K_I}{1.225 \sqrt{R_{AC}}}$$

(1.62)

In fact, $K_m$ represents the ability of a motor to convert electrical power to mechanical power. A motor with a higher value of $K_m$ can generate torque more efficiently. $K_m$ is winding independent and is used as a rating comparison factor in selecting the motor size in various motor applications. In some references, $K_m$ is also called motor size constant.

### 1.4.5 Mechanical Time Constant, $\tau_m$

In design and analysis of servomotors, it often deals with two time constants: mechanical time constant $\tau_m$ and electrical time constant $\tau_e$. A servomotor’s dynamic motion response is controlled by these two time constants. Usually, $\tau_m$ and $\tau_e$ are listed in the servomotor specifications. However, it should be cautioned that these two time constants in the specifications are for the motor alone with no load inertia connected to the motor shaft. It is important to understand the impact of actual load conditions on the time constants [1.71].

The mechanical time constant $\tau_m$ (in unit of second $s$) is usually defined as the ratio of motor moment of inertia to the damping factor with a zero-impedance power source:

$$\tau_m = \frac{R J_m}{K_I K_c}$$

(1.63)

where

- $R$ is the motor winding resistance
- $J_m$ is the motor moment of inertia

To take into account the impact of load on $\tau_m$, the previously mentioned definition may be modified as

$$\tau_m = \frac{R_i J_i}{K_I K_c}$$

(1.64)

where

- $R_i$ is the total motor winding resistance of all phases plus the external circuit resistance and the total inertia
- $J_i$ is the sum of the motor inertia and the reflected inertia from the load to the motor shaft
According to NEMA [1.61], the mechanical time constant refers to the time taken by an unloaded motor to reach \((1 - 1/e)\) (where \(1 - 1/e = 63.2\%\)) of its maximum rated speed in a no-load condition. \(\tau_m\) can be measured by applying a constant voltage to the motor, then measuring the velocity, and determining the time it takes to reach 63.2% of maximum rated speed.

One important factor to affect the mechanical time constant is temperature. During a normal operation process, the motor temperature rises from the ambient time (usually 40°C) to its normal operation temperature that is below the allowable maximum value. The electric resistance of the winding changes accordingly as

\[
R(T) = R(T_o)[1 + \alpha(T - T_o)]
\]

(1.65)

where \(\alpha\) is temperature coefficient of resistance (°C\(^{-1}\) or K\(^{-1}\)).

Similarly, for PMMs, the back EMF constant \(K_e\) and torque constant \(K_t\) are also affected by temperature. Both \(K_e\) and \(K_t\) have the same functional dependence on the motor’s air gap magnetic flux density that is produced by the motor’s magnets. All PMMs are subject to both reversible and irreversible demagnetization. It has been reported [1.72] that within the temperature range of −60°C to 200°C, all four types of PMs (aluminum–nickel–cobalt [alnico], SmCo, NdFeB, and ferrite/ceramic magnets) exhibit linear, reversible thermal reduction in field strength such that the amount of magnetic flux density produced by each magnet decreases linearly with increasing magnet temperature. Hence, the expression for the reversible decrease in both \(K_e(T)\) and \(K_t(T)\) with increasing magnet temperature is given as

\[
K_e(T) = K_e(T_o)[1 - \alpha(T - T_o)]
\]

(1.66a)

\[
K_t(T) = K_t(T_o)[1 - \alpha(T - T_o)]
\]

(1.66b)

where temperature coefficient of resistance \(\alpha\) takes different values according to the different types of PM:

- \(\alpha\) (Alnico) = 0.0001/°C
- \(\alpha\) (SmCo) = 0.00035/°C
- \(\alpha\) (NdFeB) = 0.001/°C
- \(\alpha\) (Ferrite) = 0.002/°C

Thus, a 100°C rise in magnet temperature causes a reversible decrease in \(K_e\) and \(K_t\) as −1% for alnico, −3.5% for SmCo, −10% for NdFeB, and −20% for ferrite or ceramic magnets. This indicates that the motor operation temperature has the strongest impact on ferrite magnets.

By taking into account both load and temperature, the mechanical time constant becomes

\[
\tau_m(T) = \frac{R_i(T)J_L}{K_t(T)K_e(T)}
\]

(1.67)

Taking the ambient temperature of 40°C (104°F), the normalized mechanical time constant ratio, \(\tau_m(T) / \tau_m(40°C)\), for each type of PMs is plotted in Figure 1.46 as a function of
temperature. The increase in the mechanical time constant ratio is resulted from the combined effects of increasing electrical resistance and thermal demagnetization. It can be seen from the figure that the largest increase occurs in ferrite magnets with the mechanical time constant ratio increasing by a factor of 2.45 at 155°C. At the same temperature, it increases by a factor of 1.85, 1.57, and 1.49 for NdFeB, SmCo, and alnico magnets, respectively. These results have confirmed that the operation temperature has a strong impact on servomotor’s dynamic motion response. Therefore, ignoring the temperature effect can lead to erroneous predictions of the servomotor’s dynamic motion response to the applied voltage command. Rare-earth and ferrite/ceramic magnets have increased in magnetic flux at cold temperatures. Rare-earth magnets have improved resistance to demagnetization at cold temperatures, whereas ferrite/ceramic magnets have an increase in demagnetization risk at low temperatures.

1.4.6 Electrical Time Constant, \( \tau_e \)

According to NEMA [1.61], the electrical time constant of a servomotor is the time required for the current to reach \((1 - 1/e)\) (i.e., 63.2%) of its final value after a zero source impedance, and the stepped input voltage is applied to the motor that maintained in the locked rotor or stalled condition (i.e., \( \omega = 0 \)). A small electrical time constant indicates the high dynamic response of a servomotor.

Mathematically, the electrical time constant \( \tau_e \) is defined as the ratio of armature inductance \( L \) to its winding electric resistance \( R \):

\[
\tau_e = \frac{L}{R} \tag{1.68}
\]
Similarly, by taking into account the load and temperature effect, the equation becomes

\[
\tau_e(T) = \frac{L}{R_e(T)} \tag{1.69}
\]

where \( R_e(T) \) is the total resistance, including the resistance of all phase windings and the external circuit resistance, at the temperature \( T \). This equation indicates that with the increasing temperature, electrical time constant \( \tau_e \) decreases due to the increase in \( R_e(T) \).

### 1.4.7 Thermal Time Constant, \( \tau_{th} \)

The thermal time constant \( \tau_{th} \) is an indicator of the heat capacity of a motor, showing how fast or how slow the generated heat can be built up in the motor and can be effectively dissipated to the environment. In another words, it is a measure of how long it takes a motor to reach thermal equilibrium.

The thermal time constant \( \tau_{th} \) can be expressed as

\[
\tau_{th} = \frac{\rho c_p V_e}{hA_s} \tag{1.70}
\]

where

- \( \rho \) is the density
- \( c_p \) is the specific heat
- \( V_e \) is the effective motor volume (this is because a motor is not a solid)
- \( h \) is the convective heat transfer coefficient
- \( A_s \) is the motor outer surface area

This equation indicates that larger mass \( m \) \((m = \rho V_e)\) and specific heat \( c_p \) lead to larger \( \tau_{th} \), that is, larger heat storage capability and slower changes in temperature. Higher heat transfer coefficient \( h \) and larger motor outer surface area \( A_s \) help dissipate the generated heat quickly from the motor to the ambient, leading to smaller \( \tau_{th} \), that is, faster changes in temperature. Obviously, a lower value of thermal time constant is highly desired.

The motor thermal time constant may be used to estimate the temperature rise of a motor. The motor temperature rise \( \Delta T \) can be predicted as [1.73]

\[
\Delta T = T - T_a = P_{loss} R_{th} + (T_i + T_a - P_{loss} R_{th}) e^{-t/\tau_{th}} \tag{1.71}
\]

where

- \( T_a \) is the ambient temperature
- \( T_i \) is the motor initial temperature at the start of operation
- \( P_{loss} \) is the motor total power losses that must be dissipated from the motor
- \( R_{th} \) is the overall motor-to-ambient thermal resistance
- \( t \) is the motor operation time

If \( \Delta T \) is specified, the aforementioned equation can be used to determine how long of the motor could reach the specified value of temperature rise.
Mathematically, as $t$ approaches infinity (i.e., $e^{-t/\tau_{th}}$ approaches zero), the system attains thermal stability and the motor temperature reaches its final temperature $T_f$. Hence, the temperature rise $\Delta T$ becomes

$$\Delta T = T - T_a = P_{loss}K_{th}. \quad (1.72)$$

The variation of the temperature ratio $T/T_f$ with respect to motor operation time is plotted in Figure 1.47. At $t = 0$, the power is supplied to the motor and the motor temperature starts to rise exponentially until it reaches its final temperature at the thermal equilibrium. According to the engineering definition, thermal time constant is the time required to reach 63.2% of the final temperature.

It is worth to note that in practice, it is found that the thermal time constant of motor is not constant. It varies correspondingly to the change in heat load rates. For example, motors running in intermittent operation will have a shorter time constant than a motor running up to temperature in a continuous load operation. This is due to the definition of $\tau_{th}$ that assumes no internal heat generation and uniform heat distribution. Both are not purely true in motor operation.

### 1.4.8 Viscous Damping, $K_{vd}$

In general, damping can be divided into three types: viscous damping, coulomb or dry-friction damping, and hysteretic or structural damping. From the standpoint of physics, viscous damping is the dissipation of energy as occurred in liquid or air between moving parts. An example of viscous damping is ball bearing lubrication. It results in lower torque delivered at the output shaft to the torque developed at the rotor. Viscous damping in a single-degree-of-freedom torsional system is referred to as torsional viscous damping $K_{vd,\tau}$.
which is directly proportional to the damping torque $T_d$ and inversely proportional to the angular velocity $\omega$ and is always opposite to the direction of motion, that is,

$$K_{vd,t} = \frac{T_d}{\omega} \quad (1.73)$$

The unit of viscous damping is N-m/rpm or N-m/(rad/s).

For reciprocating or linear motion systems, viscous damping $K_{vd,r}$ is defined as the ratio of the damping force $F_d$ over the velocity $\dot{x}(t)$ with the unit of N-s/m:

$$K_{vd,r} = \frac{F_d}{\dot{x}(t)} \quad (1.74)$$

Another example of viscous damping is iron losses in a motor that are functions of frequency, circulating currents and iron mass.

### 1.5 Sizing Equations

The determination of appropriate motor size is an essential task in motor design. An oversized motor can provide itself a higher safety factor in stress and structural firmness but waste energy and can potentially create performance problems with the driven equipment, especially in turbomachinery such as fans or pumps. In some circumstances, an oversized motor may compromise the reliability of both the components and the entire system.

Empirical sizing equations are very useful for motor engineers to preliminarily determine the motor design at the early stage of motor design. Various sizing equations have been developed by different researchers and designers in the history of motor development. A set of sizing equations was proposed by Honsinger [1.74] for induction machines. This method focuses on the optimal electrical loading and the machine internal geometry for a given power level:

$$\frac{P}{n_s} = \xi_s D_{6,s}^3 L_e \quad (1.75)$$

$$\frac{P}{n_s} = \xi_s D_{r,s}^2 L_e \quad (1.76)$$

Based on these two sizing equations, the $D^{2.5}L_e$ sizing equations can be derived as

$$\frac{P}{n_s} = \xi_s' D_{6,s}^{2.5} L_e \quad (1.77)$$
\[
\frac{P_o}{n_s} = \xi_s D_{s,o}^{2.5} L_e
\]

(1.78)

where
- \(D_{s,o}\) and \(D_{r,o}\) are the OD of stator and rotor, respectively
- \(P_o\) is the output power
- \(n_s\) is the rotor rotating speed
- \(L_e\) is the effective stack length and \(\xi_s\) and \(\xi_r\) are coefficients for stator and rotor, respectively

These coefficients contain the information regarding motor structure.

However, traditional sizing equations are based on the premise that the excitation of the electrical machine is provided by a sinusoidal voltage source to produce a sinusoidal EMF. In order to eliminate the deficiencies of traditional sizing equations, scientists at University of Wisconsin [1.75–1.77] have developed a general-purpose sizing equation that could take into account different waveforms of back EMF and machine characteristics. A particular effort has been made to express the sizing equation that characterizes the output power \(P_o\) as a function of overall volume of the machine. This sizing equation is easily adjustable for different motor topologies, such as RF, AF, and transverse-flux (TF) motors. The general-purpose sizing equation takes the form of

\[
P_o = \frac{1}{1 + K_\phi} \frac{m \pi}{m_1} \frac{1}{m_1} \frac{K_{s,r} K_p \eta B_{g,s} A f}{p} \frac{\lambda^2 d_{s,o}^2 L_e}{d_{g}}
\]

(1.79)

where
- \(K_\phi = A_r / A_s\) is the ratio of electrical loading on rotor and stator
- \(A = A_r + A_s\) is the total electrical loading
- \(m\) is the number of phases of the motor
- \(m_1\) is the number of phases of each stator (if there is more than one stator, each stator has the same \(m_1\))
- \(K_s\) is the EMF factor
- \(K_i\) is the current waveform factor, defined as the peak phase current \(I_p\) to the \(rms\) value of the phase current \(I_{rms}\)
- \(K_p\) is termed the electrical power waveform factor
- \(\eta\) is the motor efficiency
- \(f\) is the frequency
- \(p\) is the motor pole pairs
- \(\lambda\) is the ratio of the air gap surface diameter to the stator OD (\(\lambda = d_g / d_{s,o}\))

The application of this general-purpose sizing equation can provide motor engineers with a useful tool in designing new high power density motors.

### 1.6 Motor Design Process and Considerations

The design of electric motor is a complex task, involving multidisciplines such as electromagnetics, mechanics, thermal science, material science, vibrations, acoustics,
rotordynamics, electronics, tribology, control theory, and mathematics. The design process of electric motors involves continuous iterations between electromagnetic, thermal, structural, rotordynamic, and systematic designs based on a variety of theoretical analyses, numerical simulations, and lab tests. To achieve an optimum design, all design parameters and criteria must be considered comprehensively.

There are two basic approaches in motor design: a subsystem/component approach and a system approach. Traditionally, a common engineering approach is to break down the system into subsystems or components (e.g., stator, rotor, feedback, cooling, coupling), design and optimize these subsystems, and then assemble them as a whole system. This is more likely the conventional bottom-up design strategy in engineering design. In the subsystem/component approach, the design of each subsystem/component is essentially independent of each other and all the work carry out in parallel. Thus, one of the benefits of this approach is its short design time with simplified problem. However, this approach ignores the interactions among different subsystems/components. This leads to a possible result that even if each subsystem/component performs well, the system as a whole may not perform well. This is because the sum of the functioning of the individual subsystem/component is quite often not equal to the functioning of the whole.

A system approach focuses on overall system performance and creates a technical solution that satisfies the functional requirements for the system. This is the result of the synthetic mode of thinking applied to physical problems. This approach takes account of the intrinsic connections and interactions among different subsystems/components. In this approach, the design engineers evaluate the entire system to determine how end-use requirements can be provided most effectively and efficiently. The system approach is actually based on a top-down design strategy, in which the requirements are always satisfied at every step of the design process.

In modern motor designs, engineers often involve some degree of compromise and trade-offs among various competing requirements and design features such as motor efficiency, operation reliability, torque density, IP rating, cooling, noise, and cost-effectiveness, to name a few. Decisions on trade-offs involve systematic comparisons of all benefits and costs for achieving a satisfactory overall design.

It is worth to note that the two design approaches are not always absolutely opposite. Under some circumstances, engineering designs may gainfully employ both methodologies [1.78].

### 1.6.1 Design Process

Good design of electric motor involves many engineering aspects upon which the success of the design work depends, including customer’s specifications, motor operation condition, material selection, system integration, technical analysis, and manufacturing process, as demonstrated in Figure 1.48. In finding the best design solution, engineers must make trade-offs among many factors that determine the final design and cost of the motor. In addition, identifying and understanding the design constraints and limitations are critical to the success of the motor design.

The general design flow chart of electric motor is presented in Figure 1.49. The design process starts with the careful reviewing of customer’s specifications and requirements, especially the requirements of motor operation and performance. Based on these information, the motor type and topology can be determined, such as PMM or IM, synchronous or asynchronous motor, and RF or AF motor. Then, the main motor design parameters are primarily set by using empirical equations. The overall sizing of the machine is of
great importance in terms of performance, structural integrity, cost, and weight. The major motor dimensions are determined via sizing equations available in the literature.

In the design of modern electric motors, none of technical design is isolated from the other designs. As a matter of fact, all designs in different fields have strongly influenced each other. Hence, these design processes are neither in series nor in parallel, rather, they form a crossover network. During this design stage, engineers/designers must communicate frequently to exchange their design concepts, innovative ideas, experience, and other useful information, especially the modifications that could impact on other designs. The design iterations between different design processes continue to carry out until the initial design is fully implemented.

Electromagnetic design is the core part of the motor design for determining motor key operating and performing characteristics. The electromagnetic design is highly dependent on the motor structure and rotordynamics analyses performed on the rotor. Recently, with the increasing demands for high-efficiency and high-reliability motors, one of the trends in novel motor development is to integrate the electromagnetic structure and mechanical transmission structure into a functional system for not only simplifying the motor structure but also increasing torque density, motor efficiency, and operation reliability.
Mechanical Design of Electric Motors

Figure 1.49
The flowchart of motor design.
The calculated power losses from electromagnetic design are passed into thermal analysis. With the fast development of computational technologies in last several decades, it becomes more popular today for thermal analysis to be executed by means of advanced computational fluid dynamics (CFD) software package. In the current CFD market, many powerful commercial software packages are available, either for general-purpose or specific applications, to solve heat transfer and fluid dynamics problems. CFD methods are used to provide detailed information of motor cooling such as temperature distribution, velocity field, pressure drop, and thermal interaction between solid surfaces and fluid flows in electric motors and to confirm and refine the preliminary designs. However, performing a CFD analysis still remains a challenging task and requires highly skilled engineers due to the complexities involved, such as the complexity of highly nonlinear partial differential equations, CFD model meshing, large amount demanding of computational resources, determination of models and parameter of turbulent flows, convergence of simulation, and complexity of inputs and related tasks. Extensive design iterations exist between the thermal, mechanical, and other design processes for achieving the optimized motor design.

Mechanical design consists of a number of design components:

- Fatigue analysis—As a material is subject to cyclic loads, a fatigue crack nucleus may be initiated on a microscopically small scale, and then the crack grows to a macroscopic size, finally causing material failure suddenly at a stress level below the material ultimate tensile strength or even yield tensile strength. During normal operation, some motor components are subject to alternative loads. One example is the motor shaft that is subject to gravitational force from the rotor core and drag force from a load machine (e.g., using belt or gear driving). When the rotor rotates, the shaft experiences cyclic loads creating a compression-expansion cycle for every revolution.

- Mechanical stress/strain analysis—The performance of mechanical stress/strain analysis is to determine whether the motor structure or components can withstand various loads without failure. The analysis allows for design optimization to achieve the best performance of electric motors. Due to the increasing complexity of modern motors, the stress/strain analysis today is mostly carried out using 3D finite element models. Recently, 3D finite element models have been used to perform thermo-mechanical analyses for providing more complete and accurate simulation results.

- Torsional analysis—When a motor is in normal operation, it may be subject to torsional vibration due to various causes. In analytically determining the torsional response, it requires to calculate the torsional resonance frequencies of the motor. To do this requires the torsional stiffness and mass inertia of both the motor and the load system, as addressed previously.

- Buckling analysis—Bucking is a phenomenon that a structural member subjected to compressive stress suddenly fails due to the loss of its stability. The actual compressive stress of the structural member at the point of failure is much lower than the ultimate strength that the material can withstand. For instance, some motors have a number of ventilation ducts within the lamination core (either stator or rotor or both). These ventilation ducts are constructed by I-beams or II-beams that function like spacers. It is highly desired to perform bucking analysis to avoid the instability failure of beams.

- Determination of manufacturing process for motor components—Each motor part can be fabricated by many different manufacturing processes. The selection
of manufacturing process is based on many factors, including cost-effectiveness, productivity, process cycle time, availability, motor part geometry, requirements for part strengths, vibration and dampness, surface finishing, material properties, porosity/void, and environment friendliness. As an example, for a large volume of motor endbells, the most suitable manufacturing method is die casting.

- Determinations of geometric dimension and tolerance (GD&T)—The purpose of GD&T is defined as describing the geometric requirements for part and assembly geometry. Proper applications of GD&T can ensure allowable part and assembly geometry defined on the drawings leads to right size, shape, form, location, orientation, and location, define the proper assembly of mating parts, and enable assembled motors to function as intended. Mechanical engineers are responsible to provide the information for drafters and manufacturing engineers for the fabrication of motor components and the layout of motor assembly. Based on the information, 3D solid models can be generated to explicitly describe nominal geometries and their allowable variations at both the component level and system level.

- Setting up an appropriate fitness between mechanically mating components—Improper fitness between mating parts may greatly reduce the motor lifetime or lead to motor failure. For example, a loose fitting between a shaft and a bearing can cause the relative movement between the two components, resulting in a fast wear of the shaft and thus high heat generation due to the friction. In addition, an improper fitness may cause motor vibration.

- Selection of motor bearings—It has been reported that more than a half of motor failures can be attributed to the failure of bearings. Among them, improper selection of bearings is one of the major causes, usually dominated by wrong grease or lubrication selection.

- Selection of materials of motor components—Material selection in the motor industry is an artful balance between material performance, motor reliability, manufacturing process, and total cost. Apparently, material selection can heavily influence the motor performance and lifetime. None of the materials is perfect to satisfy all requirements. It is the responsibilities of engineers to make trade-offs between various design factors, for example, material performance and cost, and strength and durability.

- Determination of mechanical, electric, and electromagnetic power losses—The mechanical losses in a motor usually consist of friction losses and windage losses. The electric losses (also referred to as copper losses) represent all the resistive losses in motor windings and cables and are usually the main loss component in electric motors. The electromagnetic losses (i.e., iron losses), including eddy current and hysteresis losses in motor cores and other components, are often obtained through electromagnetic analysis conducted by electrical engineers. All the information is requested by thermal engineers for performing CFD or numerical heat transfer analysis.

Design optimization is the top goal of motor design. When the preliminary design is complete, the engineers need to examine whether the predetermined optimum objectives of the design have been reached. For different applications, these optimum objectives can be different, namely, the maximum peak torque, the highest torque density ratio, the most efficient cooling, and the total weight. If the design does not satisfy certain requirements,
the design engineers need to review their designs to identify the design gap and do the design iteration again until all optimum objectives are gained.

The next step is to build a prototype motor for validating the motor design as a whole unit. This is the critical step for the success of products. No matter how perfect the results achieved from engineering analyses are, prototype motor testing is an essential and necessary step to validate the conceptual design and ensure normal motor operation. Only after a series of successful tests, the motor can start mass production.

1.6.2 Design Integration

An electric motor usually consists of dozens to even thousands of components. In order to increase motor operation reliability, reduce the manufacturing cost, and simplify the assembly process, it is desired to integrate some of the components together in one self-contained package, including (1) motor-transmission device (e.g., gearbox, belt, chain) integration, (2) mechanical–electromagnetic system integration, and (3) motor control (e.g., feedback, drive).

As one of the most important constituents in an automated electric driving system, an electronic drive is used to deliver a usable form of power to control the performance of a servomotor for an end user. As presented in Figure 1.50, the integrated motor drive assembly system includes a motor, a fan, and a drive unit. One remarkable advantage of such integrated assembly systems is their compactness in size and ease of installation into a small industrial or other application. Generally, the drive is disposed on the motor or arranged in an integral housing with the motor. Both the motor and drive are shared with the same cooling fan [1.79].

![Diagram of Motor Drive Assembly System](image_url)

**FIGURE 1.50**
Integration of electric motor, drive, and fan as one unit (U.S. Patent 7,362,017) [1.79]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)
A growing trend in motor control is the integrated system that combines motor, feedbacks, and controller in one self-contained package. By integrating the controller with the motor, the possibility of mismatch is eliminated. Based on the integrated modular motor drive concept, an integrated traction drive has been developed recently. The integration of motor and drive offers a number of attractive features such as reduced drive volume and the elimination of power transmission cables. Correspondingly, it reduces radiated electromagnetic interference and voltage transient due to power transmission over long cable distances [1.80]. Furthermore, the integration of motor and drive can offer fault-tolerant features not possible with conventional drives [1.81,1.82]. On the caution side, significant thermal management and analysis are required to protect the electronic drive and motor combination.

1.6.3 Mechatronics

Mechatronics is the confluence of classical engineering disciplines with mechanical, electrical, and electromagnetic engineering, sensor technology, drive and actuator technology, control theory, and computer science. In recent years, one of the design trends in the electric machine industry is to design intelligent mechatronics products. Mechatronics is not just a new design strategy but also a new way of doing business to gain competitive advantage in the global market. As a result, it has been extensively used to design improved products and processes [1.83].

In fact, the mechatronic design approach that involved multidisciplinary is expected to become a key technology to gain a competitive advantage in the era of modern manufacturing. The development of mechatronics will therefore be crucial to the continued competitiveness of national economies.

The magnetic hard disk drive (HDD) is believed to be one of the most successful examples of modern mechatronics systems. In a state-of-the-art HDD servo system, a high-speed servomotor, a read/write head, a data storage disk, and other components are designed as one unit. The precision position control of HDD enables the tolerance to be less than one micrometer while operating at high speed [1.84]. As the mechatronics technology advances, new application areas of motor mechatronics can be developed in promising directions, such as mobile robots and medical devices.

1.7 Motor Failure Modes

There are a number of different approaches to assess motor failure modes. Generally, there are three primary failure modes identified from motor root cause analyses. The most important failure mode is electrical-related failure, caused by the breakdown of motor winding insulations, overloading condition, winding short circuit, and other issues. In a typical case, the breakdown of insulation material is attributed to exceeding of the temperature limit of windings. An overloading condition can cause the winding current exceeding its limit to damage coils. The second failure mode is magnetic failure, which usually resulted from the thermal demagnetization of PM (for PMMs). The thermal demagnetization of PM may be attributed to high motor operation temperature, shock, vibration, or strong magnetic field generated by a stator. The third failure mode is mechanical failure of motor structure and components. In this failure mode, bearing failures are encountered frequently. Another common failure mode is loose/broken rotor bars. Usually, most
mechanical failures result from slow processes such as mechanical wear and gradual degradation of material properties. During the process, the defective parts continue to display characteristic signs until they completely fail. This is different from most electronic component failures that happen suddenly and without warning.

Statistics have shown that despite the reliability and simplicity of construction of IMs, annual motor failure rate is conservatively estimated at 3%–5% per year, and in extreme cases, up to 12%, as in the pulp and paper industry [1.85]. The downtime in a factory due to motor failure may lead to a high cost, even exceeding the cost of motor replacement. In some instances, a motor failure may cause the entire production line to stop and thus interrupt the production process.

Based on the data collected from 1141 motors, those larger than 200 hp and less than 15 years in service, IEEE published a long report in three parts [1.86–1.88] to address motor failure modes according to the root causes of failure. In this report, Part I presented general results based on categories of motor types. Part 2 combined various categories and addressed some questions resulting from Part 1. Part 3 of the survey results was to address new questions and comments and to add more specific analyses of areas not yet explored previously.

A similar investigation of motor failure modes has been conducted by Electric Power Research Institute (EPRI) [1.89]. Though the approach of EPRI is different from IEEE (EPRI focused on failed motor components), their results are consistent. The integration of these two surveys was made by Venkataraman et al. [1.85], as presented in Table 1.6.

### Table 1.6

Comparison of Failure Modes for Large-Size Motor

<table>
<thead>
<tr>
<th>IEEE Survey</th>
<th>EPRI Survey</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Failure Contribution</strong></td>
<td><strong>Failure Contribution</strong></td>
</tr>
<tr>
<td>Persistent overload</td>
<td>Stator ground insulation</td>
</tr>
<tr>
<td>4.2</td>
<td>23</td>
</tr>
<tr>
<td>Normal deterioration</td>
<td>Turn insulation</td>
</tr>
<tr>
<td>26.4</td>
<td>3</td>
</tr>
<tr>
<td>Bracing</td>
<td>Core</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Cage</td>
<td></td>
</tr>
<tr>
<td>Cage</td>
<td></td>
</tr>
<tr>
<td>Electrical-related total</td>
<td>Electrical-related total</td>
</tr>
<tr>
<td>30.6</td>
<td>33.3</td>
</tr>
<tr>
<td>High vibration</td>
<td>Sleeve bearings</td>
</tr>
<tr>
<td>15.5</td>
<td>16</td>
</tr>
<tr>
<td>Poor lubrication</td>
<td>Antifriction bearings</td>
</tr>
<tr>
<td>15.2</td>
<td>8</td>
</tr>
<tr>
<td>Thrust bearings</td>
<td>Rotor shaft</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Rotor core</td>
<td></td>
</tr>
<tr>
<td>Mechanical-related total</td>
<td>Mechanical-related total</td>
</tr>
<tr>
<td>30.7</td>
<td>31.35</td>
</tr>
<tr>
<td>High ambient temperature</td>
<td>Bearing seals</td>
</tr>
<tr>
<td>3.0</td>
<td>6</td>
</tr>
<tr>
<td>Abnormal moisture</td>
<td>Oil leakage</td>
</tr>
<tr>
<td>5.8</td>
<td>3</td>
</tr>
<tr>
<td>Abnormal voltage</td>
<td>Frame</td>
</tr>
<tr>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Abnormal frequency</td>
<td>Wedges</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Abrasive chemicals</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Poor ventilation cooling</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>Other reasons</td>
<td>Other components</td>
</tr>
<tr>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>Environmental reasons and other reasons total</td>
<td>Maintenance-related and other parts total</td>
</tr>
<tr>
<td>38.7</td>
<td>35.35</td>
</tr>
</tbody>
</table>

Data from IEEE and EPRI motor reliability surveys.
From the table, it can be seen that the most common reasons of the motor failures are bearing failures and failures related to the stator insulation. High vibration can lead to mechanical failures. Furthermore, many failures are related directly or indirectly to high operation temperature.

### 1.8 IP Code

Electric motors are designed to withstand various harsh environments such as flammable and explosive environments, high ambient pressure or vacuum, extreme temperatures, and high shock loads and vibrations. In some cases, they may operate in space or under deep water.

The IP code is an international standard for electric devices. It applies to the classification of degrees of protection provided by enclosures for electrical equipment against the insertion or intrusion of solid and liquid objects, external influences, or conditions such as dust, moisture, water, icing, corrosive solvents, and mechanical impacts. The IP code consists of two digits and optional letters. The indications of digits and optional letters are shown in Tables 1.7 and 1.8, respectively [1.90].

#### TABLE 1.7
Indications of IP Digits

<table>
<thead>
<tr>
<th>IP</th>
<th>Protection of Person</th>
<th>Protection of Equipment</th>
<th>IP</th>
<th>Protection of Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No protection</td>
<td>No protection</td>
<td>0</td>
<td>No protection</td>
</tr>
<tr>
<td>1</td>
<td>Protected against contact with large areas of the human body (back of hand)</td>
<td>Protected against objects over 50 mm in diameter</td>
<td>1</td>
<td>Protected against vertically falling drops of water, e.g., condensation</td>
</tr>
<tr>
<td>2</td>
<td>Protected against contact with fingers</td>
<td>Protected against solid objects over 12 mm in diameter</td>
<td>2</td>
<td>Protected against direct sprays of water up to 15° from vertical direction</td>
</tr>
<tr>
<td>3</td>
<td>Protected against tools and wires over 2.5 mm in diameter</td>
<td>Protected against solid objects over 2.5 mm in diameter</td>
<td>3</td>
<td>Protected against sprays to 60° from vertical direction</td>
</tr>
<tr>
<td>4</td>
<td>Protected against tools and wires over 1 mm in diameter</td>
<td>Protected against solid objects over 1 mm in diameter</td>
<td>4</td>
<td>Protected against water sprayed from all directions (limited ingress permitted)</td>
</tr>
<tr>
<td>5</td>
<td>Protected against tools and wires over 2.5 mm in diameter</td>
<td>Protected against dust (limited ingress, no harmful deposit)</td>
<td>5</td>
<td>Protected against low-pressure jets of water from all directions (limited ingress permitted)</td>
</tr>
<tr>
<td>6</td>
<td>Protected against tools and wires over 2.5 mm in diameter</td>
<td>Totally protected against dust</td>
<td>6</td>
<td>Protected against strong jets of water</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>7</td>
<td>Protected against the effects of immersion between 15 cm and 1 m</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>8</td>
<td>Protected against long periods of immersion under pressure</td>
</tr>
<tr>
<td>9K</td>
<td></td>
<td></td>
<td>9K</td>
<td>Protected against ingress of high-temperature (steam) and/or high-pressure water</td>
</tr>
</tbody>
</table>
### Table 1.8

Indications of Optional Letters in IP

<table>
<thead>
<tr>
<th>First Letter (Optional)</th>
<th>Protected against Access to Hazardous Parts with</th>
<th>Second Letter (Optional)</th>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Back of hand</td>
<td>H</td>
<td>High-voltage device</td>
</tr>
<tr>
<td>B</td>
<td>Finger</td>
<td>M</td>
<td>Device moving during water test</td>
</tr>
<tr>
<td>C</td>
<td>Tool</td>
<td>S</td>
<td>Device standing still during water test</td>
</tr>
<tr>
<td>D</td>
<td>Wire</td>
<td>W</td>
<td>Weather condition</td>
</tr>
</tbody>
</table>

### Table 1.9

Typical IP Codes Used for Different Motor Applications

<table>
<thead>
<tr>
<th>IP Classification</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP00</td>
<td>Open motor</td>
</tr>
<tr>
<td>IP12</td>
<td>Open drip-proof motor [1.91]</td>
</tr>
<tr>
<td></td>
<td>Drip-proof motor [1.91]</td>
</tr>
<tr>
<td>IP13</td>
<td>Splash-proof motor [1.91]</td>
</tr>
<tr>
<td>IP21</td>
<td>Elevator motor</td>
</tr>
<tr>
<td>IP23, IP24</td>
<td>Weather protected motor [1.91]</td>
</tr>
<tr>
<td>IP42</td>
<td>Commercial refrigeration application</td>
</tr>
<tr>
<td>IP44</td>
<td>Totally enclosed fan-cooled motor [1.91]</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed pipe-ventilated motor [1.92]</td>
</tr>
<tr>
<td>IP54</td>
<td>Regular for commercial applications (fans, blowers)</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed force-ventilated motor [1.91]</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed air-to-air-cooled motor [1.92]</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed air-over motor [1.91]</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed air-to-water-cooled motor [1.91]</td>
</tr>
<tr>
<td></td>
<td>Totally enclosed water-cooled motor [1.92]</td>
</tr>
<tr>
<td>IP55</td>
<td>Waterproof motor [1.92]</td>
</tr>
<tr>
<td>IP65</td>
<td>Motor used in hybrid vehicles</td>
</tr>
<tr>
<td></td>
<td>Elevator motor</td>
</tr>
<tr>
<td></td>
<td>High-speed spindle servomotor</td>
</tr>
<tr>
<td></td>
<td>Some direct drive motor</td>
</tr>
<tr>
<td>IP67</td>
<td>Motor used under severe operation conditions (e.g., pitch and yaw control motors in wind turbines, driving motors in chemical reactors and in machine tools)</td>
</tr>
<tr>
<td></td>
<td>Motor used outdoor under harsh environments</td>
</tr>
<tr>
<td></td>
<td>Motor used in aerospace and defense applications (military vehicle, submarine, satellite, etc.)</td>
</tr>
<tr>
<td></td>
<td>Motor used in food processing, beverage, and pharmaceutical applications</td>
</tr>
<tr>
<td>IP69K</td>
<td>Motor operating under ultra-harsh or aggressive environments (e.g., autoclaving, high-pressure spray, and frequent washdown with caustic chemicals)</td>
</tr>
<tr>
<td></td>
<td>Motor used in deep water such as in propelling systems</td>
</tr>
<tr>
<td></td>
<td>Liquid immersion pumps</td>
</tr>
</tbody>
</table>
The IP code has a strong impact on the motor design. With the IP defined, a number of design factors, such as motor construction, insulation, sealing method, coating, cooling technique, and component material, must be specifically determined to satisfy the requirements and regulations of the IP code.

As a reference, common IP codes used in electric motors in practice are summarized in Table 1.9.

References


