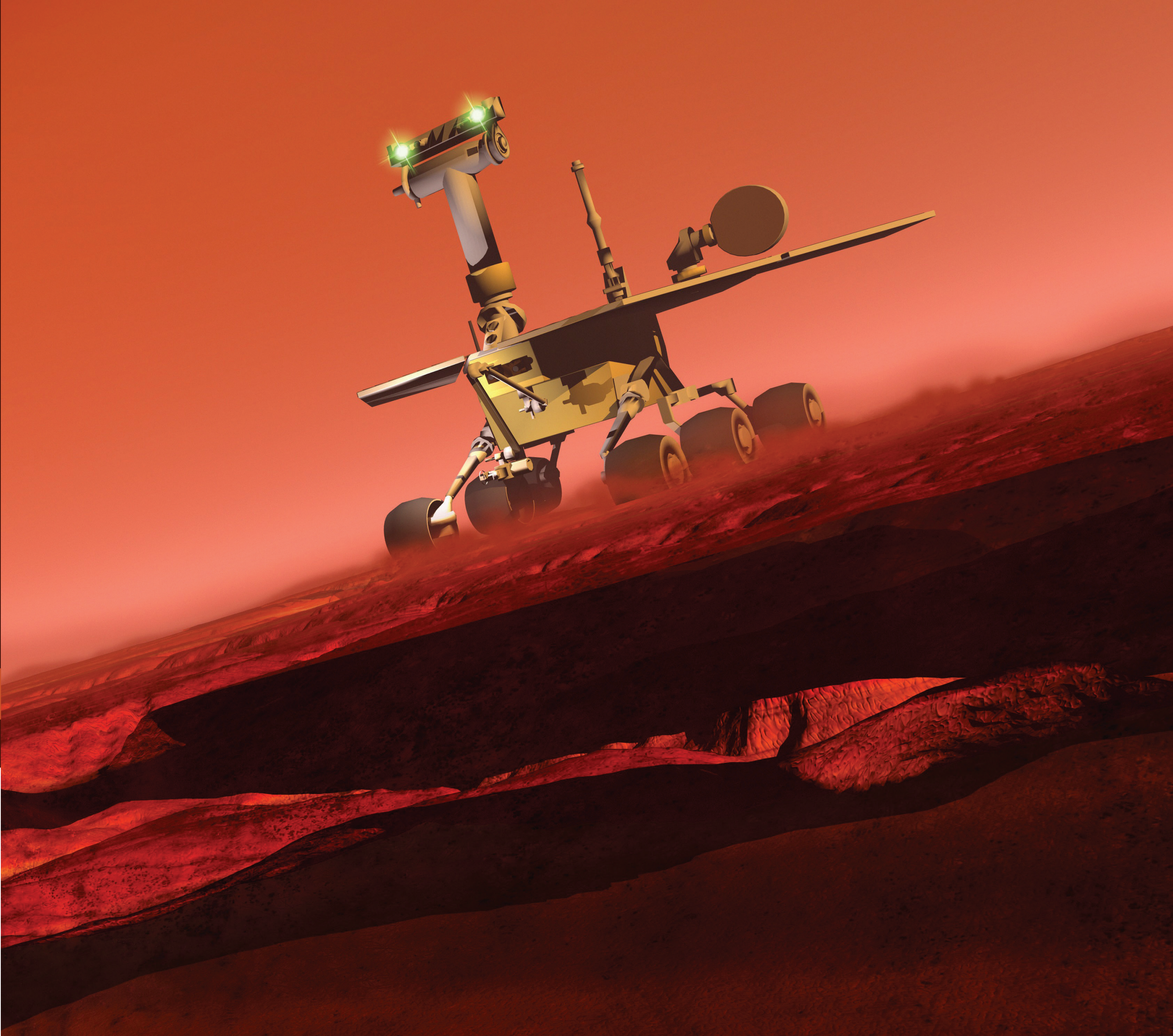
SECOND EDITION

Fundamentals of ELECTRIC DRIVES

MOHAMED A. EL-SHARKAWI



Fundamentals of Electric Drives

Second Edition

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Dedicated to my family and my students

Preface

A modern electric drive system consists of a motor, an electric converter, and a controller that are integrated to perform a mechanical maneuver for a given load. Because the torque/volume ratio of modern electric drive systems is continually increasing, hydraulic drives are no longer the only option used for industrial applications. In addition to their use in industrial automation, modern electric drives have other widespread applications, ranging from robots to automobiles to aircraft. Recent advances in electric drive design have resulted in low-cost, lightweight, reliable motors. Advances in power electronics have led to a level of performance that was not possible a few years ago; induction motors, for example, were never used in variable-speed applications until the development of variable frequency and rapid switching. Due to advances in power electronics, several new designs of electric motors are now available, such as brushless and stepper motors.

Modern electric drive systems are used increasingly in such high-performance applications as robotics, guided manipulations, transportation, renewable energy, and actuation. In these applications, controlling the rotor speed is only one of several goals; the full range includes controlling the starting, speed, braking, and holding of the electric drive systems. The exploration of these control functions forms the core of this text.

Purpose and Features

This book is designed to be used as a teaching text for a one-semester course on the fundamentals of electric drives. Readers are expected to be familiar with the basic circuit theories and the fundamentals of electronics, as well as with three-phase analysis and basic electric machinery.

In this book, I cover the basic components of electric drive systems, including mechanical loads, motors, power electronics, converters, and gears and belts. Each component is first discussed separately; various components are then combined in a discussion of the complete drive system. If instructors use this book in the first course on the subject, they will not need to use additional material because this book is self-contained.

The focus of this book is on the fundamentals of electric drive systems. The general types of electric loads and their dependence on speed are explained early in the book, and load characteristics are considered throughout. To help the reader understand why a particular motor is selected for a particular application, I present and highlight the differences and similarities of electric motors.

Power converters are discussed in some detail, with ample mathematical analysis. Early in the book, I present several solid-state switching devices and specific characteristics of each; this comparison of solid-state devices allows the reader to understand their features, characteristics, and limitations. Triggering, synchronization, modulation, isolation, and protection of power electronic devices are also discussed in detail.

Converters are divided into several groups: ac/dc, ac/ac, dc/ac, and dc/dc. Several circuits are given for these converters and are analyzed in detail to help readers understand their performance. Detailed analyses of the electrical waveforms of power-converter circuits demonstrate the concepts of power and torque in a harmonic environment.

After readers become familiar with electric machines and power converters, they can comprehend the integration of these two major components that creates an electric drive system. This book includes detailed explanations of the various methods for speed control and braking. Well-known applications appear throughout the book in order to demonstrate the theories and techniques. Discussions of the merits, complexities, and drawbacks of the various drive techniques help readers form opinions from the perspective of a design engineer.

Examples and Problems

In each chapter, examples and problems simulate several aspects of drive performance. The problems address key design and performance issues and are therefore more than mere mathematical exercises.

New Features

- Improved focus on the basic principles of power electronic devices, including both synchronization and isolation circuits.
- New sections on brushless motors have been added to Chapters 5 and 6.
- Additional analysis of static Scherbius drives.
- New coverage of wind energy systems operating in regenerative braking.
- Applications to electric vehicle, robotic, and electric tractions are provided throughout.
- New sections on regenerative, dynamic, and concurrent braking of BLDC motors.
- New examples and exercises have been added throughout the book.

Supplements

An Instructor's Solutions Manual and Lecture Note PowerPoint slides are available for this book on Cengage Learning's secure, password-protected Instructor Resource Center. The Instructor Resource Center can be accessed at https://login.cengage.com.

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Contents

Fundamentals of Electric Drives

Elements of Electric Drive Systems

The study of electric drive systems involves controlling electric motors in the steady state and in dynamic operations, taking into account the characteristics of mechanical loads and the behaviors of power electronic converters.

In the not-so-distant past, designing a versatile drive system with broad performance was a difficult task that required bulky, inefficient, and expensive equipment. The speed of an electric motor was controlled by such restrictive methods as resistance insertion, use of autotransformers, or complex multimachine systems. Motor selection for a given application was limited to the available type of power source. For instance, dc motors were used with direct current sources, and induction motors were driven by ac sources.

To alleviate the problem of matching up the motor and the power source and to provide some form of speed control, a common and elaborate scheme such as that shown in Figure 1.1 was commonly used. Because its terminal voltage is relatively easy to adjust, the dc motor was regularly selected for applications requiring speed control. Given the status of the available technology, controlling the speeds of alternating-current machines was much more difficult.

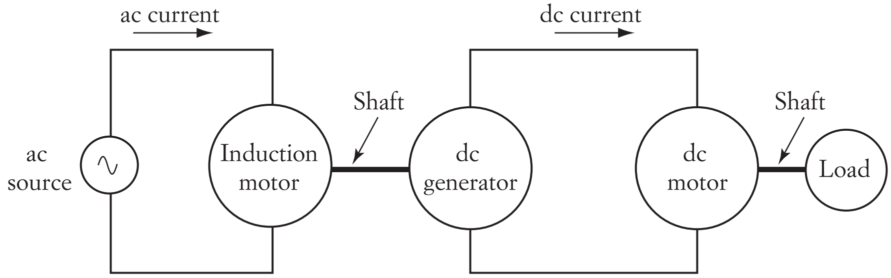


FIGURE 1.1 Multimachine system for speed control

The system in Figure 1.1 consists of three electromechanical machines: an ac motor, a dc generator, and a dc motor. The ac motor (induction), which drives a dc generator, is powered by a single- or multiphase ac source. The speed of the induction motor is fairly constant. The output of the dc generator is fed to the dc motor. The output voltage of the dc generator is adjusted by controlling its excitation current. Adjusting the field current of the generator controls the terminal voltage of the dc motor. Hence, the speed of the dc motor is controlled accordingly.

The system described here is expensive, inefficient, and complex, and it requires frequent maintenance. However, because of the limited technology available during the first half of the 20th century, this system was the leading option for speed control. In fact, a number of these systems are still in service; for example, old elevators may still use this system today.

In recent decades, however, enormous strides have been made in the areas of power electronics, digital electronics, and microprocessors. With the advances in power electronic devices, cheaper, more efficient, and versatile options for speed control are now available.

Continuous improvements in solid-state technologies are yielding even more reliable and better-performance devices, as well as new types of solid-state switches. Solid-state devices can now handle larger amounts of current and voltage at higher efficiencies and speeds. Additionally, the prices of these devices are continually dropping.

Among the important developments in solid-state power electronics technology is the integrated module. Solid-state switches can now be found in various configurations, such as H-bridge or six-pack modules. Complete driving circuits are now a part of very sophisticated and elegant designs. Most designs now have built-in options for speed control and overcurrent protection. Previously, building such modules took several months.

With the development of power electronic devices and circuits, virtually any type of power source can now be used with any type of electric motor. Speed control can now be achieved by using a single converter. In fact, the older, inefficient drive systems currently being used in some industrial applications are now being replaced with solid-state drives. This retrofitting process is estimated to be a multi-billion-dollar business in the United States alone.

With modern solid-state power technology, motors can be used in more precise applications, such as position control of robots and airplane actuation. Hydraulic and pneumatic systems are now being replaced by electric drives.

1.1 Historical Background

Due to the lack of technology, electric drives historically were designed to provide crude power without consideration of performance. Advances in industrial manufacturing led to a need for more sophisticated drives, which stimulated the development of modern systems. The drive systems have various forms:

1. *Line shaft drives.* This is the oldest form of an electric drive system. (An example is shown in Figure 1.2.) The system consists of a single electric motor that drives equipment through a common line shaft or belt. This system is inflexible because

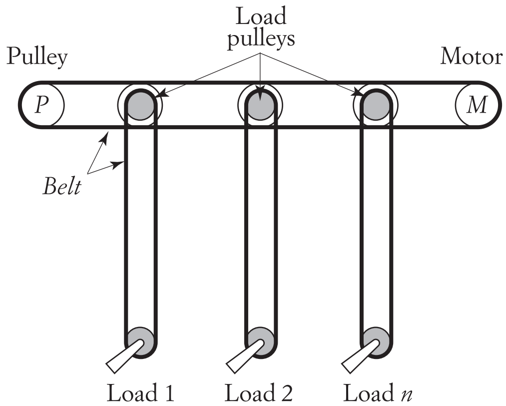


FIGURE 1.2 Single-motor, multiple-load drive system

the line shaft continuously rotates regardless of the number of pieces of equipment in operation. This system is presented here for historical reasons but is rarely used.

2. *Single-motor, single-load drives.* This is the most common form of electric drive. In this system, a single motor is dedicated to a single load. (Examples are shown in Figure 1.3.) Applications include household equipment and appliances

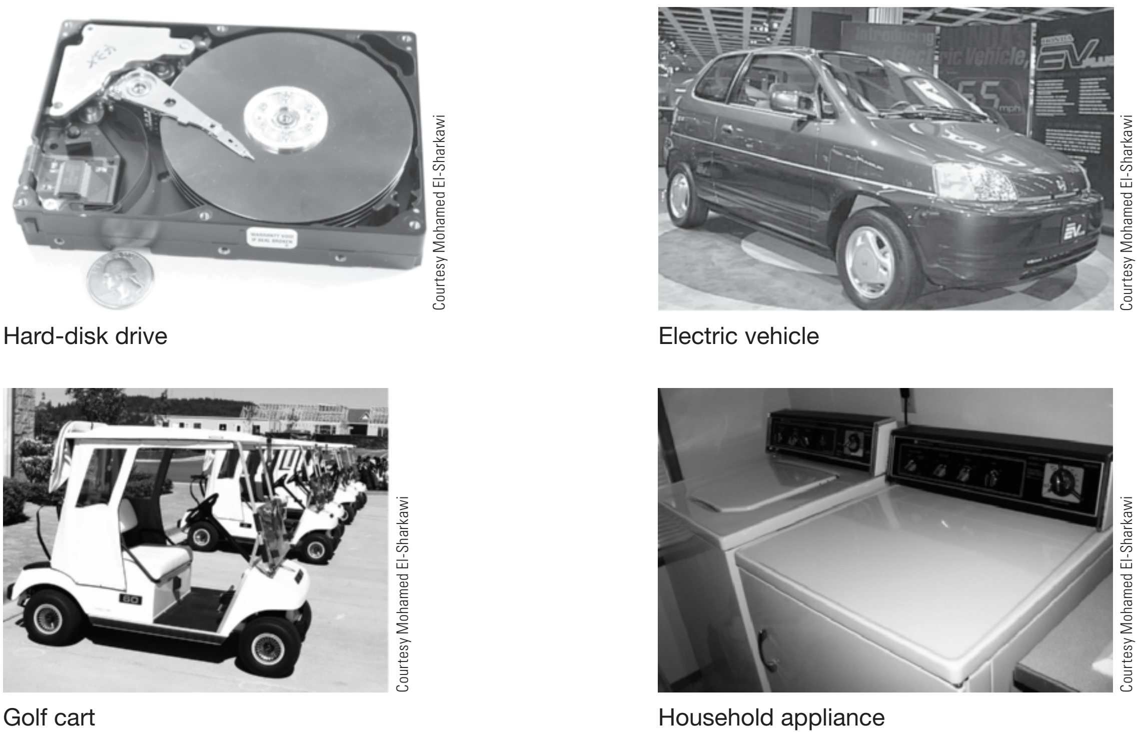
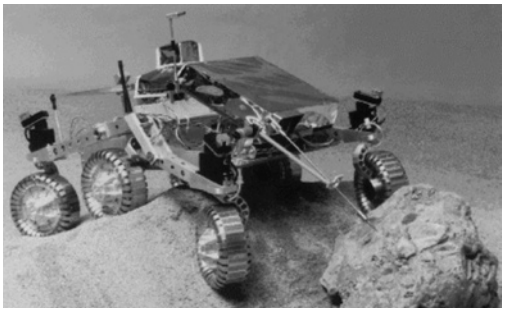


FIGURE 1.3 Single-motor, single-load drive systems

such as electric saws, drills, disk drives, fans, washers, dryers, and blenders. The computer hard disk drive in the figure employs high-performance drives for the rotation of the disk. The head actuation of the hard-disk drive is controlled by a separate system.

The traction of most electric cars is a single-motor drive system. The motor replaces the internal combustion engine of conventional vehicles.

3. *Multimotor drives.* In this type of system, several motors are used to drive a single mechanical load. This form is usually used in complex drive functions such as assembly lines, paper-making machines, and robotics. (Figure 1.4 shows several examples of this type of load.) Airplane actuation is done electrically in most military and several commercial airplane models. Each flap of the airplane is controlled separately by redundant drive systems. Compared to the commonly used hydraulic

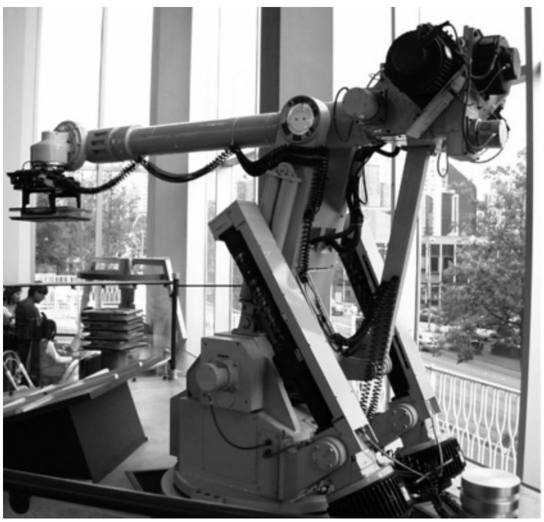


NASA

Mars rover

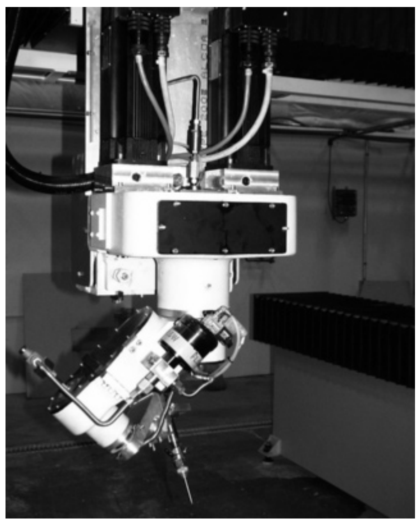
U.S. Air Force

Airplane actuation system



Courtesy Mohamed El-Sharkawi

Robot arm



Courtesy Mohamed El-Sharkawi

Industrial manipulator

FIGURE 1.4 Multiple-motor, single-load drive systems actuator, electric actuation (sometimes known as fly-by-wire) is much lighter and faster, involves lower maintenance, and does not require the heating of any hydraulic fluid. It is therefore a more popular method in aviation.

The rover used by NASA for Mars exploration is a six-wheeled vehicle of a rocker bogie design to negotiate obstacles. Vehicle navigation is accomplished through control of its drive and steering motors. The energy source of the vehicle is solar—several solar panels capture solar energy and store it in a battery pack.

The industrial manipulator or the robot arm can employ as many motors as the process requires. The manipulator shown in Figure 1.4 is used for waterjet cutting. The end effector of the manipulator or the robot arm must be accurately controlled to achieve the desired precision.

1.2 Basic Components of an Electric Drive System

A modern electric drive system has five main functional blocks (shown in Figure 1.5): a mechanical load, a motor, a converter, a power source, and a controller. The power source provides the energy the drive system needs. The converter interfaces the motor with the power source and provides the motor with adjustable voltage, current, and/or frequency. The controller supervises the operation of the entire system to enhance overall system performance and stability.

Often, design engineers do not select the mechanical loads or power sources. Rather, the mechanical loads are determined by the nature of the industrial operation, and the power source is determined by what is available at the site. However, designers usually can select the other three components of the drive systems (electric motor, converter, and controller).

The basic criterion in selecting an electric motor for a given drive application is that it meet the power level and performance required by the load during steady-state and dynamic operations. Certain characteristics of the mechanical loads may require a special type of motor. For example, in the applications for which a high starting torque is needed, a dc series motor might be a better choice than an induction motor.

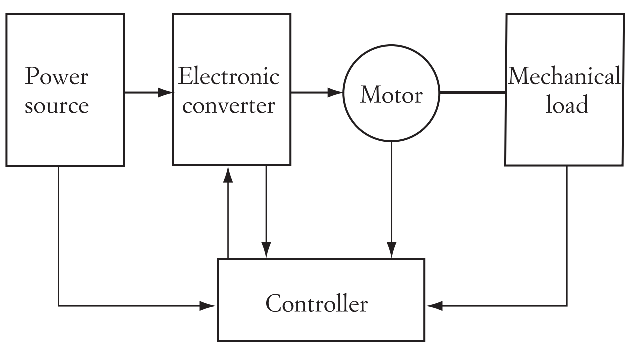


FIGURE 1.5 Functional blocks of an electric drive system

In constant-speed applications, synchronous motors might be more suitable than induction or dc motors.

Environmental factors may also determine the motor type. For example, in food processing, chemical industries, and aviation, where the environment must be clean and free from arcs, dc motors cannot be used unless they are encapsulated. This is because of the electric discharge that is generated between the motor's brushes and its commutator segments. In those cases, the squirrel cage induction motor or other brushless machines are probably the better options.

The cost of the electric motor is another important factor. In general, dc motors and newer types of brushless motors are the most expensive machines, whereas squirrel cage induction motors are among the cheapest.

The function of a converter, as its name implies, is to convert the electric waveform of the power source to a waveform that the motor can use. For example, if the power source is an ac type and the motor is a dc machine, the converter transforms the ac waveform to dc. In addition, the converter adjusts the voltage (or current) to desired values. The controller can also be designed to perform a wide range of functions to improve system stability, efficiency, and performance. In addition, it can be used to protect the converter, the motor, or both against excessive current or voltage.

1.2.1 Mechanical Loads

Mechanical loads exhibit wide variations of speed-torque characteristics. Load torques are generally speed dependent and can be represented by an empirical formula such as

$$T = CT_r\left(\frac{n}{n_r}\right)^k \tag{1.1}$$

where C is a proportionality constant, T_r is the load torque at the rated speed n_r, n is the operating speed, and k is an exponential coefficient representing the torque dependency on speed. Figure 1.6 shows typical characteristics of various mechanical loads.

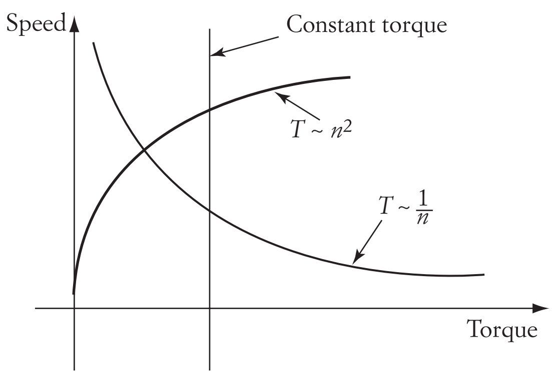


FIGURE 1.6

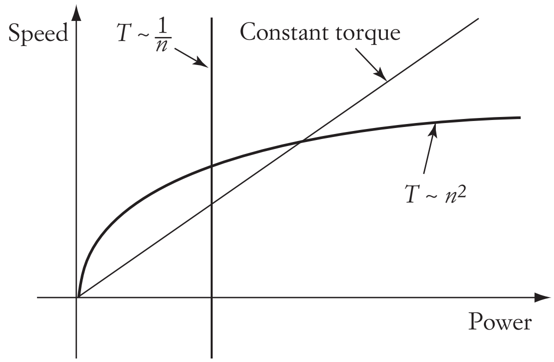


FIGURE 1.7 Typical speed-power characteristics of mechanical loads

The mechanical power of the load is given by Equation (1.2), where ω is the angular speed in rad/s, and n is the speed in r/min (or rpm). Figure 1.7 shows the mechanical power characteristics that correspond to the loads shown in Figure 1.6.

$$P = T\omega; \qquad \omega = 2\pi \frac{n}{60} \tag{1.2}$$

Figure 1.8 shows several types of mechanical loads that are commonly used in households. In general, the load characteristics can be grouped into one or more of the following types:

1. *Torque independent of speed.* The characteristics of this type of mechanical load are represented by Equation (1.1) when k is set equal to zero and C equals 1. While torque is independent of speed, the power that the load consumes is linearly dependent on speed. There are many examples of this type of load, such as hoists or the pumping of water or gas against constant pressure.
2. *Torque linearly dependent on speed.* The torque is linearly proportional to speed when $k = 1$, and the mechanical power is proportional to the square of the speed.

Fan: $k = 2$ Electric drill: $k = -1$

FIGURE 1.8 Types of common mechanical loads

This is an uncommon type of load characteristic and is usually observed in a complex form of load. An example would be a motor driving a dc generator connected to a fixed-resistance load, for which the field of the generator is constant.

3. *Torque proportional to the square of speed.* The torque-speed characteristic is parabolic when $k = 2$. Examples of this type of load are fans, centrifugal pumps, and propellers. The load power requirement is proportional to the cube of the speed and may be excessive at high speeds.

4. *Torque inversely proportional to speed.* In this case, $k = -1$. Examples of this type include milling and boring machines. This load usually requires a large torque at starting and at low speeds. The power consumption of such a load is independent of speed. This is why the motor of an electric saw does not always get damaged (due to overcurrent) when the saw disk is blocked.

Some loads may have a combination of the characteristics listed. For example, the friction torque exhibits a complex form of speed torque that varies according to the operating speed. At low speeds, the friction torque is almost inversely proportional to the speed due to the magnitude of the static and coulomb frictions. At high speeds, it is almost linearly proportional to the speed due to the viscous friction.

1.2.2 Electric Motors

Electric motors exhibit wide variations of speed-torque characteristics, some of which are shown in Figure 1.9. Synchronous or reluctance motors exhibit a constant-speed characteristic similar to that shown by curve I. At steady-state conditions, these motors operate at constant speed regardless of the value of the load torque. Curve II shows a dc shunt or a separately excited motor, where the speed is slightly reduced when the load torque increases. Direct current series motors exhibit the characteristic shown in curve III; the speed is high at light loading conditions and low at heavy loading. Induction motors have a somewhat complex speed characteristic similar to the one given by curve IV; during steady state, they operate at the linear portion of the speed-torque characteristic, which resembles the characteristic of a dc shunt or a separately excited motor. The maximum developed torque of induction motors is limited to T_{max}.

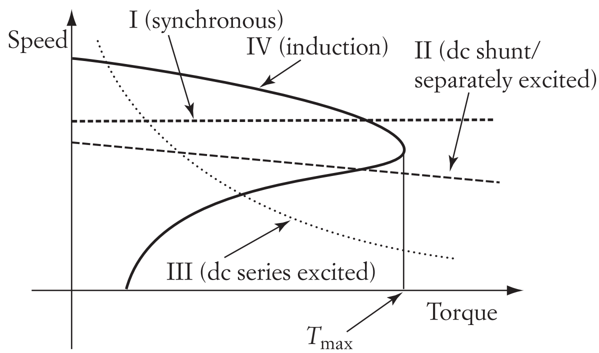


FIGURE 1.9

In electric drive applications, electric motors should be selected to match the intended performance of the loads. For example, in constant-speed applications, the synchronous motor is probably the best option. Other motors, such as induction or dc, can also be used in constant-speed applications, provided that feedback circuits are used to compensate for the change in speed when the load torque changes.

1.2.3 Power Sources

Two major types of power sources are used in industrial applications: alternating current (ac) and direct current (dc). Alternating current sources are common in industrial installations and residences. These sources can either be single-phase or multiphase systems. Single-phase power sources are common in residences, where the demand for electric power is limited. Multiphase power sources are used in high power consumption applications. The most common type of power source in the United States is the three-phase, 60-Hz power source. In Europe, most of the Middle East, Africa, and Asia, the frequency is 50 Hz.

Extensive industrial installations usually have more than one type of power source at different voltages and frequencies. Commercial airplanes, for example, may have a 400-Hz ac source in addition to a 270-volt dc source.

1.2.4 Converters

The main function of a converter is to transform the waveform of a power source to that required by an electric motor in order to achieve the desired performance. Most converters provide adjustable voltage, current, and/or frequency to control the speed, torque, or power of the motor. Figure 1.10 shows the four basic types of converters.

1. *dc to ac.* The dc waveform of the power source is converted to a single- or multiphase ac waveform. The output frequency, current, and/or voltage can be adjusted according to the application. This type of converter is suitable for ac motors, such as induction or synchronous motors.
2. *dc to dc.* This type is also known as a “chopper.” The constant-input dc waveform is converted to a dc waveform with variable magnitude. The typical application of this converter is in dc motor drives.
3. *ac to dc.* The ac waveform is converted to dc with adjustable magnitude. The input could be a single- or multiphase source. This type of converter is used in dc drives.
4. *ac to ac.* This converter is also called inverter. Indeterminate input waveform is typically ac with fixed magnitude and frequency. The output is an ac with variable frequency, magnitude, or both. The conversion can be done directly or through a dc link. The dc link system consists of two converters connected in cascade; the first is an ac/dc, and the second is a dc/ac. Typical applications of the dc link converter are ac motors.

In addition to electric drives, dc link converters are also used in such applications as the uninterruptable power supply (UPS). Figure 1.11 shows the basic components of a UPS. The dc link between the two converters has a rechargeable battery. In normal operation, the input current i_{in} is converted to a dc current I_{dc_1}