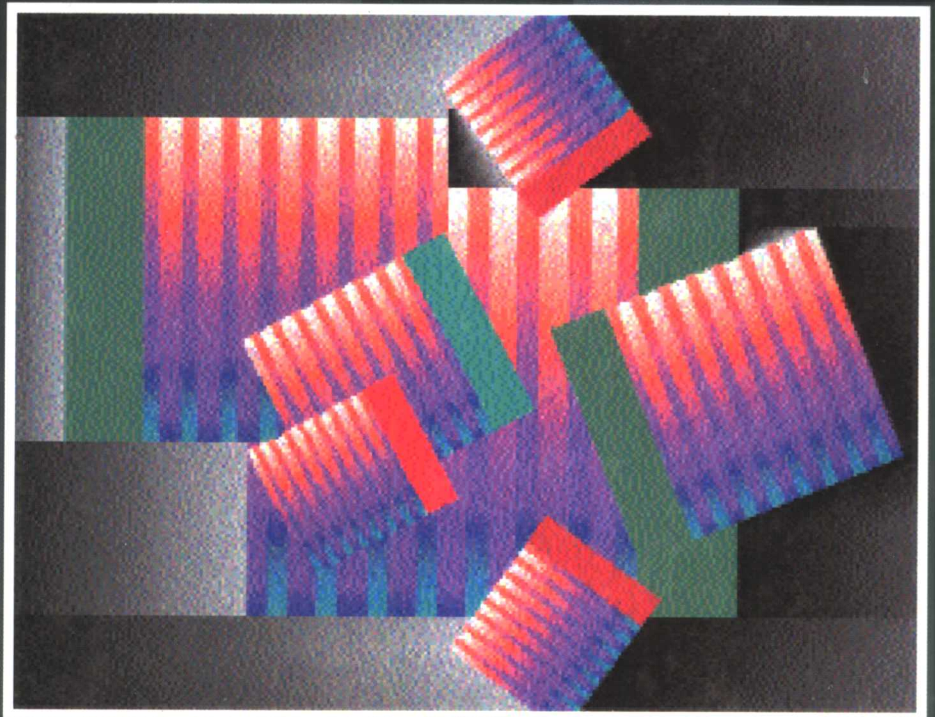
Electrical Power and Controls



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ELECTRICAL POWER AND CONTROLS

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PREFACE

Over the past decade or so, communications, electronics, and power have converged to provide more efficient manufacturing processes for various types of industry. Many motors are installed with electronic drives; programmable logic controllers are finding widespread application; and communications networks at the device, control, and information levels are used to monitor many industrial processes. Engineers and technologists will require a broad background in all of these areas.

Unfortunately, the time available in a typical curriculum is fixed, and in some cases the number of hours required for a degree has decreased. Thus, like many electric power instructors, we have been confronted by pressures to eliminate the required power course from our electrical engineering technology curriculum in favor of something that is "more worthwhile" in the view of many of our colleagues. The challenge was for us to show the value of our course for the majority of our graduates. Thus, we found it necessary to move away from a course that dealt almost exclusively with electric machines and transformer theory to one that includes the principles of operation and application of motors, motor controls, power quality, power electronics, motor circuit design, programmable logic controllers, and other topics that a typical graduate might encounter in the workplace.

As we developed our course, it became evident that there was no particular text that covered all of the topics that we wanted to include. Thus, we began writing our own text. Although this text was developed to support a one-semester sophomore course in electrical engineering technology, we have included more material than could be covered in a single semester. This allows greater flexibility in designing a course using this text. This text uses primarily algebra and trigonometry for calculations and derivations; however, some calculus (primarily integrals) is used, particularly for Faraday's law. In general, the calculus can be skipped by those who have not taken an introductory calculus course. Throughout the book, we have made extensive use of figures and photos to reinforce the text discussion. We believe this is particularly important for today's traditional college students who are much more visually oriented and less inclined to read lengthy discussions. Recognizing the reluctance of students to read, in addition to problems, we have included review questions at the end of the chapters. This has a twofold benefit. First, it forces the student to read the material and, second, allows the incorporation of written assignments, which is emphasized by accreditation agencies and industry.

ORGANIZATION OF THE TEXT

Although physics is a prerequisite course, we have found that our students often do not remember the concepts of force, torque, energy, and power and the relations between them. Thus, Chapter 1 presents a review of these basics, which allows us to introduce examples related to the electric power industry, such as pumped-water storage. Introducing the concept of energy storage in electric fields (capacitors) and magnetic fields (inductors) prepares the student for the discussion of reactive power in Chapter 2. Chapter 1 also introduces the electric power system and discusses some current events, such as deregulation and the projected decline of nuclear generation. We typically cover Chapter 1 in one to two lectures.

Chapter 2 provides a review of basic electric power calculations, including a review of phasors and single-phase and three-phase electric power. The concepts of real, reactive, and apparent AC power are presented as they are used throughout the text. Because our students have seen this material before, we cover the material quickly in two lectures.

Due to the widespread use of electronics in the commercial and industrial workplace, the issue of power quality has become extremely important. Every individual who uses electronic equipment contributes to the power-quality problem. Thus, we believe that every electrical engineer and technologist should be aware of the problems caused by the equipment they or others use. Chapter 3 introduces the concept of power quality using the CBEMA-ITIC curve. This curve includes not only steady-state phenomena but also transients. Thus, we have included a discussion of transient-voltage surge suppressors that can benefit every individual who wishes to provide protection for a personal computer, whether at home or in the workplace. We have also included a discussion of uninterruptible power supplies, as the advertising for these devices is often short on facts and long on claims. The heart of Chapter 3, however, is the discussion of harmonics in the power system. The concept of harmonics is introduced here and is continued in later chapters when transformers, induction motors, and variable-speed drives are discussed.

Since one of our goals is for students to understand the operation of transformers and motors, some background in magnetic properties and materials is required. Chapter 4 introduces the concepts of flux, flux density, permeability, magnetic field intensity, reluctance, ferromagnetic materials, and losses due to hysteresis and eddy currents in magnetic materials. The emphasis is not to provide enough information for the students to become machine designers, but rather to give enough background so they can understand the operating principles of the devices.

Chapter 5 introduces the first component of the power system—the transformer. The ideal transformer is introduced first and then the underlying assumptions are removed to produce an equivalent circuit for the transformer. Single-phase transformers are examined in detail, followed by a discussion of transformer bandwidth for electronics circuits, K-factor-rated (harmonics-rated) transformers, autotransformers, instrument transformers, and three-phase transformers. After the development of the transformer model, the topics are essentially independent, so the instructor can skip over sections that are not of interest.

Because some instructors prefer to present AC machines before DC, and others prefer the opposite, Chapter 6 develops the basic concepts of motor and generator operation for both types of machines. Chapter 6 can be followed by Chapter 7, "The Induction Motor," Chapter 10, "The Synchronous Machine," or Chapter 11, "The DC Machine," depending on the desires of the instructor or reader. Because we believe that most students will encounter AC machines in the workplace, we present the AC machine first. The basic components of the synchronous machine are presented and the rotating magnetic field in the three-phase stator winding is developed prior to the discussion of the induction motor. Following the AC machine, the DC machine is presented in a similar manner.

Chapter 7 presents the polyphase induction motor. It emphasizes practical, application-oriented material, beginning with construction features and nameplate information and concluding with wiring diagrams and reduced-voltage starting. The equivalent circuit for the induction motor is developed for those who feel it is important; however, we typically skip over that section and use the equivalent circuit primarily to discuss the losses in the induction motor. Following the calculation of motor efficiency, the requirements of the National Energy Policy Act (NEPACT) of 1992 for induction motors are discussed. Throughout the chapter, NEMA standards and requirements are discussed.

Chapter 8 presents several types of single-phase induction motors and the universal motor. The primary emphasis is on understanding the differences in construction and performance of the various machines rather than on mathematical analysis. Speed control of the shaded-pole induction motor by varying the number of turns in the stator winding is discussed.

Power electronics is an increasingly important topic due to the widespread use of variable-speed drives in industry. Chapter 9 begins with a discussion of a variety of solid-state power switches, including various types of diodes and transistors. This material is provided for completeness and to allow the practicing engineer/technologist to compare different technologies. Depending on the preferences of the instructor or reader, that material could be omitted. Following the discussion of switching technologies, the variable-frequency AC motor drive is discussed with primary emphasis on the induction motor. The chapter concludes with discussions of stepper motors and brushless DC motors, which are becoming increasingly important.

The synchronous machine is presented in detail in Chapter 10. Following a description of the construction features, the synchronous generator is discussed first followed by the synchronous motor. Both round-rotor and salient-pole machines are discussed, although the primary emphasis is on the round-rotor case. Phasor diagrams are used extensively to illustrate the operation of the synchronous machine.

Chapter 11 concludes the discussion of electric machines with the DC machine. The chapter begins with a discussion of the operation and construction of the DC machine, followed by a detailed discussion of commutation. Generator and motor operation of the various types of DC machines (series, shunt, compound) are presented, and the chapter concludes with a discussion of the efficiency of DC machines.

Motors must be started and stopped and that is normally done with a control system. Chapter 12 presents the basics of control systems. A variety of control devices—relays, switches, pilot devices, motor starters, contactors, etc.—are discussed, followed by some basic considerations of ladder diagrams. Reduced-voltage starters and reversible starters for AC machines are presented, followed by starters for DC motors.

Following the presentation of motor starters and overload sensors in Chapter 12, Chapter 13 presents the fundamentals of power circuit design. The use of *National Electric Code* tables is emphasized in the design of motor circuits and voltage drop calculations.

Programmable logic controllers (PLCs) are being used for a wide variety of applications in the commercial, industrial, and institutional markets. As an example of how widespread they have become, our university has begun installing micro-PLCs in classrooms to control lighting levels via dimming ballasts on the fluorescent lights. As a result, we have devoted two weeks of the semester to PLCs. Chapter 14 provides some background on what a PLC is and what it is used for, a review of binary and octal arithmetic calculations, and a discussion of the scanning cycle. The Allen-Bradley PLC 5 is used as an example for discussing the programming commands, addressing schemes, and memory structure of PLCs. Much of the material would be similar for other PLCs and could be supplemented by PLC-specific information, such as addressing techniques.

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T. L. Skvarenina and W. E. DeWitt

CONTENTS

CHAPTER 1

Fundamentals of Energy and the Power System

■ INTRODUCTION

In this chapter we will examine the power system to understand how the electric utility industry operates in the United States. We will see that the power system is highly interconnected and operates at a number of different standard voltages. However, before we look at the power system and its components, we need to review some of the concepts of force, energy, work, and power because the power system converts energy from various forms into electricity. We begin by considering the gravitational force.

■ OBJECTIVES

After studying this chapter you should be able to:

- Define and calculate force, energy, power, and torque and convert units between the SI and British systems.
- List the parts of the power system.
- List typical voltages found in the various parts of the power system.
- Describe the interconnections between electric utilities in the United States and explain the purpose of those interconnections.
- List three reasons why the power system uses AC instead of DC.
- Define the term *nonutility generator* (NUG) and explain the importance of NUGs in today's electric marketplace.

■ GRAVITATIONAL FORCE

Any two masses will have an attraction between them, as shown in Figure 1–1. This phenomenon is called *gravity* and results in a force between the two objects given by

$$f = k\frac{m_1 m_2}{r^2} \qquad (1\text{–}1)$$

where

f = the force attracting the two masses

r = the distance between centers of mass

m_1 and m_2 = masses

k = universal gravitational constant

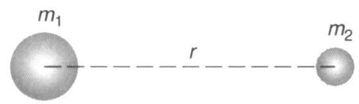

Figure 1–1
Gravitational attraction of two masses.

If SI (MKS) units are used, f is in newtons (N), r is in meters (m), and m_1 and m_2 are in kilograms (kg). Then k has the numerical value

$$k = 6.67 \times 10^{-11} \frac{\text{N}\cdot\text{m}^2}{\text{kg}^2}$$

Clearly, at least one of the masses has to be very large for the gravitational force between two masses to be significant.

The form of gravity we are most familiar with, of course, is the gravity of the earth. In Figure 1–2, the earth is now m_1; mass m_2 is at the surface of the earth, so the separation between mass centers is approximately the radius of the earth (if the earth is considered to be a point mass). By substituting the mass of the earth and earth's radius into equation 1–1, we obtain the gravitational constant of earth:

$$f = m_2 g \qquad (1\text{–}2)$$

where

$$g = 9.81 \frac{\text{N}}{\text{kg}} = 9.81 \frac{m}{\text{s}^2}$$

In fact, the earth is not perfectly spherical, so the radius varies somewhat with position on the earth.

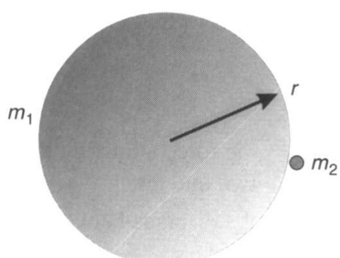

Figure 1–2
Gravitational attraction of the earth.

Thus, the gravitational constant also varies, but the variation in gravity is relatively small. The force of gravity is directed radially toward the center of the earth. Force and the gravitational constant are vectors since they have magnitude and direction.

■ ENERGY

Energy is defined as the capacity of a system to do work. Energy may be kinetic—a truck traveling down the highway has kinetic energy—or it may be potential—a pond of water on top of a hill has potential energy. Potential energy is is very important because it can be stored for use when needed. The pond of water could be drained through a turbine at the bottom of the hill, which in turn could drive a generator to produce electricity. The kinetic energy of the truck, on the other hand, is generally not as useful; although, in the case of an electrically driven truck, one might recharge the batteries as the vehicle decelerated. Energy exists in many forms and can be changed from one form to another. Forms of energy include heat, light, sound, mechanical, electric field, magnetic field, and chemical.

The name used to represent energy is different in each system of units. Examples include calories, ergs in the CGS system, joules in the SI (or MKS) system, British thermal units (Btu) or ft lb in the English system, and even oil barrel equivalents. The most common unit that will be used in this text is the joule, abbreviated J, or its multiples—kilojoule (1 kJ $= 10^3$ J) and megajoule (1 MJ $= 10^6$ J). The megajoule is a commonly encountered quantity, and it is enlightening to consider several examples. One MJ is approximately the kinetic energy of a 5000 lb truck traveling 60 miles per hour. It is also the energy required to boil away a quart of room-temperature water, and it is the energy contained in 0.5 lb of high explosive. A unit that most people encounter is the kilowatt hour (kwh) because electric utilities bill for kwh usage. A kwh represents one kw being used for one hour and is equivalent to 3.6 MJ. Finally, the United States

Department of Energy tracks energy usage with a unit called the *quad*. One quad is one-quadrillion (10^{15}) Btu. All of the energy used in the United States during a year amounts to about 100 quads. Table 1–1 shows some physical equivalents of given amounts of energy. Table 1–4, at the end of the chapter, contains some unit conversions.

Much of the emphasis in this book will be on the conversion of energy because electricity is something we typically convert to some other form of energy to do something useful. For example, to move a mass in the opposite direction of the gravitational force, we must expend energy. When we climb stairs, we know the more flights we climb, the more tired we become. Essentially, we are expending energy to move the mass of our body away from the center of the earth. However, we are actually storing the energy in the form of potential energy. For example, if you climbed a ladder up to a platform to bungee jump, you would expend energy climbing the ladder. By virtue of being 25 or 30 meters in the air, you would have stored potential energy. When you jumped off the platform, the potential energy would be converted to kinetic energy as your altitude decreased and your velocity increased. Once the bungee cord was fully extended (but not yet stretched), you would reach your maximum velocity, most of your potential energy having been converted to kinetic energy. As the bungee begins to stretch, you would begin to slow down. You would lose kinetic energy, but some of it would be stored as potential energy in the bungee cord. When the bungee is stretched to its maximum length, you would stop and reverse direction, converting the potential energy of the cord back to kinetic energy of your body. Of course, there are losses in the bungee cord, so it would heat up from the stretching and eventually you would come to rest.

TABLE 1–1 SOME ENERGY EQUIVALENTS

Energy unit	Equivalent
1 Btu	1 match tip
1 million Btu	90 lb of coal 8 gallons of gasoline 11 gallons of propane
1 quad (10^{15} Btu)	45 million tons of coal 10^9 cu ft of natural gas 170 million barrels of oil About one day of world energy use
1000 kwh of electricity	0.588 barrels of crude oil 310 lb of coal 3300 cu ft of natural gas

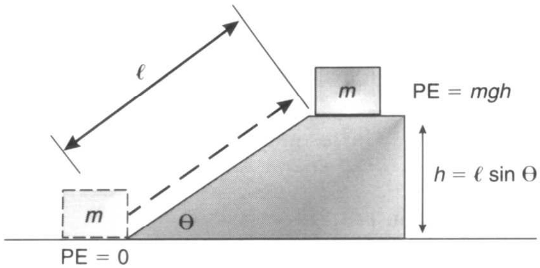

Figure 1–3
Potential energy of a mass at an elevation.

An important thing to remember about potential energy is that the amount of energy stored by moving a mass to a higher altitude is independent of how the mass got to its position. Figure 1–3 shows a mass at the top of a ramp. The mass was moved up the ramp to an altitude h by traveling a distance ℓ. Neglecting friction between the mass and the ramp, the energy required to move the mass is

$$w = mgh = mg(\ell \sin \theta) \tag{1–3}$$

Equation 1–3 also gives the potential energy of the mass at the top of the ramp. The energy could be recovered by allowing the mass to slide back down or by pushing it off the end. From equation 1–3, we can conclude that energy is the product of force and distance.

Knowing how much potential energy is stored can allow us to actually calculate how much energy must be provided by a system, as in the following example.

Example 1–1

An elevator motor in the Sears Tower in Chicago is required to lift a load of 4000 kg to an altitude of 300 m. How much energy must the motor provide (neglecting any losses in the hoist mechanism)?

Solution

From equation 1–3,

$$w = 4000 \text{ kg} \times 9.81 \frac{\text{N}}{\text{kg}} \times 300 \text{ m}$$

$$w = 11{,}772{,}000 \text{ N·m} = 11.77 \text{ MJ}$$

Potential energy

One characteristic of the electric power system, as we will see, is that it must deliver electric energy to the customers when they want it, in essentially any quantity they want. Because electricity is a form of energy that cannot be stored very easily, the generators in the power system must produce the energy at the time it is being used. This has important implications for the power system; it must be sized to handle the maximum load even though that load may only appear for short periods of time, a few days a year. In order to make more efficient use of the power system generators, it is possible to convert electrical energy to some other form and store it for later reconversion to electricity. One example of this is a battery. When we charge a battery, we are storing chemical energy that can later be used to create electrical energy. It is also possible to use the concepts of potential energy.

Figure 1–4 shows a simplified version of a pumped-storage facility. Here, water is transferred between two reservoirs at different altitudes. During the daytime, when electrical energy demand is high, the water from the upper reservoir is allowed to run down the pipe. It gains kinetic energy as it does so, which is used to turn a turbine that drives a synchronous machine to generate electricity. During the night, when electrical demand is lower, the synchronous machine is run as a motor. It then pumps the water back to the top so that it stores potential energy. One utility in Michigan operates a pumped-storage facility with six generators, each rated at 388,000 kVA (kilovolt-amperes). In 1996, there was approximately 20 GW of pumped-storage generation capability in the United States. The effect of using pumped storage is to level the demand for electricity. Consider how much energy could be stored in a pumped-storage facility.

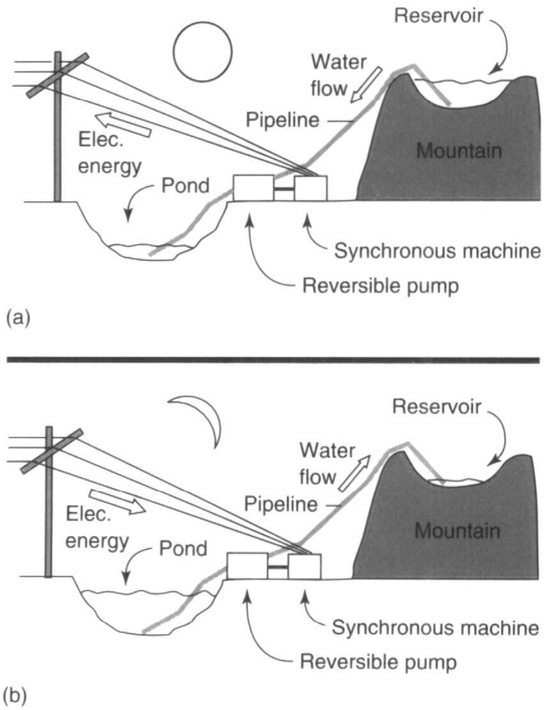

Figure 1–4

Pumped storage of energy to generate electricity.

a. Water drives the generator during the day.
b. Electricity is used to pump the water to a higher elevation during the night.

Example 1–2

How much energy could be stored in a pumped-storage facility if the reservoirs are separated by 400 m in altitude and each is 1.0 km square and 5.0 m deep? (Note: 1.0 cc of water has a mass of 1.0 g and 1.0 m^3 of water has a mass of 1000 kg.)

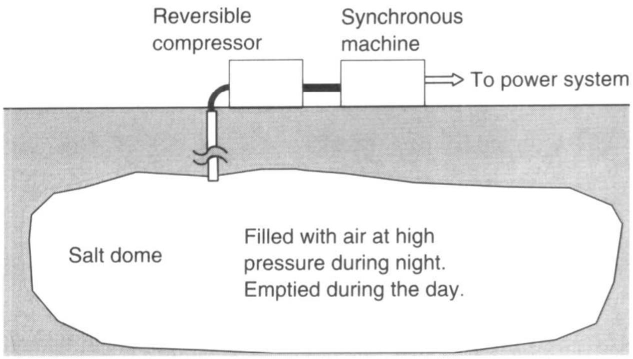

Figure 1–5
Example of storing energy to generate electricity by storing compressed air in an unused salt mine.

Solution
The total amount of water to be pumped is

$$5 \text{ m} \times 1000 \text{ m} \times 1000 \text{ m} = 5(10)^6 \text{ m}^3 = 5(10)^9 \text{ kg}$$

From equation 1–3:

$$w = mgh = 5(10)^9 \text{ kg} \times 9.82 \text{ m/s}^2 \times 400 \text{ m}$$
$$w = 19.64 \text{ TJ } (1 \text{ terajoule} = 10^{12} \text{ J})$$

Recalling that 1.0 kwh = 3.6 MJ, the gross total stored energy is $5.46(10)^6$ kwh.

Another method of storing potential energy for later use is shown in Figure 1–5. Here, air is pumped at night into an underground cavern to a high pressure. Then, during the day, the compressed air is used to drive the generator to create electrical energy. A utility in Alabama uses an empty salt mine (salt dome) to store the compressed air.

Kinetic energy

Any body in motion possesses kinetic energy. As shown in Figure 1–6, motion can be translational or rotational. The kinetic energy stored in a moving mass is given by the following two equations:

$$E = \frac{1}{2}mv^2 \qquad (1\text{–}4)$$

$$E = \frac{1}{2}I\omega^2 \qquad (1\text{–}5)$$

Equation 1–4 applies to a body with translational motion; equation 1–5 applies to a rotating body. In equation 1–4, m is the mass of the object and v is its velocity. In equation 1–5, I is the moment of inertia and ω is its angular velocity in radians per second.

Rotational kinetic energy is particularly important when studying the dynamic operation of power systems. To deliver more power to the system loads, the input power to the generator prime movers must be increased. However, when customers change the load, the power into the generators cannot change instantaneously. Instead, the

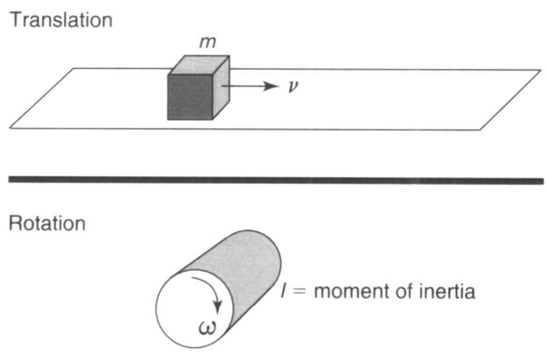

Figure 1–6
Translational and rotational motion.

energy stored in the rotors of the generators provides the instantaneous changes called for by the customers' loads. When the customers demand more power, the rotors of the generators slow down a small amount, thus reducing the stored kinetic energy. That change in kinetic energy is converted to electricity to meet the increased load. Eventually, the control system reacts, releasing more steam or water into the turbines driving the generators, which then return to their normal speed. The opposite happens when loads are removed from the system. A similar example is the use of a flywheel to store energy to keep a motor running during a power transient. The amount of energy stored in the rotor of one machine may not be extremely large, but when all the machines in the system are accounted for, there is a large amount of kinetic energy. Consider an example.

Example 1–3

A 345,000 kVA synchronous machine is used for power factor correction and has a rotor that is 2 m in diameter and 8 m long. Assume the rotor is solid steel, with a density of 7.65 g/cm^3, and calculate the kinetic energy of the rotor if the machine runs at 600 RPM.

Solution

The machine runs at 600 revolutions per minute or 10 revolutions per second. Solving for the angular velocity,

$$\omega = 2\pi(10)\ \text{rad/s} = 62.83\ \text{rad/s}$$

The moment of inertia of a cylinder is

$$I = \frac{1}{2}mr^2$$

where r is the radius. Thus, we need the mass of the rotor:

$$m = \rho V$$

or density times volume,

$$V = \pi r^2 \ell = \pi(1\ \text{m})^2(8\ \text{m}) = 25.13\ \text{m}^3 = 25.13(10^6)\ \text{cm}^3$$

The mass of the rotor is thus

$$m = [25.13(10^6)\ \text{cm}^3](7.65\ \text{g/cm}^3) = 192.3(10^6)\ \text{g}$$

or, converting to kg,

$$m = 192{,}300\ \text{kg}$$

Thus the moment of inertia is

$$I = [0.5(192{,}300)\ \text{kg}](1\ \text{m})^2 = 96{,}150\ \text{kg}\cdot\text{m}^2$$

Finally, the stored energy is given by equation 1–5: $w = 0.5I\omega^2$.

$$w = 0.5(96{,}150\ \text{kg}\cdot\text{m}^2)(62.83\ \text{rad/s})^2 = 379.6\ \text{MJ}$$

In reality, the rotor is not solid steel. It has copper coils and insulation, which have a lower density. Thus this number is probably somewhat high.

Energy stored in electric and magnetic fields

Energy can also be stored in electric and magnetic fields. This is very important when we consider AC power systems, because the energy that is stored in those fields impacts the current drawn from the source, as will be seen in Chapter 2.

Electric field energy

Figure 1–7 shows a parallel-plate capacitor, consisting of two conducting plates separated by a dielectric medium. If a DC voltage is applied to the

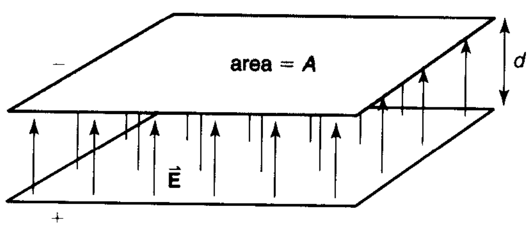

Figure 1–7
Parallel-plate capacitor and its electric field.

plates, then charge builds up on the surfaces of the two plates. The charges are represented by the + and − signs. As a result of the separation of the charges, there is an electric field between the plates, indicated by $\vec{\mathbf{E}}$. The electric field is a vector quantity, having magnitude and direction. In this case, the electric field goes from the positive plate to the negative plate. If the area of the plates is large compared to the separation between them, then the capacitance is given by

$$C = \frac{\epsilon A}{d} \tag{1-6}$$

where ϵ is the permittivity of the material between the parallel plates, A is the area of the plates, and d is the separation between the plates.

The energy stored in the electric field of a capacitor is given by

$$w_{\text{elec}} = \frac{1}{2}CV^2 \tag{1-7}$$

where V is the voltage between the plates of the capacitor. Clearly, to increase the stored energy one would either make the capacitance larger or the voltage larger. Because electric fields do not store a lot of energy for a given volume, magnetic fields are used in almost all energy conversion devices.

Magnetic field energy

Figure 1–8(a) shows a wire coil carrying a current. As a result of the current, a magnetic field is formed (this phenomenon is discussed in Chapter 4). The lines of magnetic flux exit one end of the coil, wrap around, and reenter the other end. Suppose, instead, the coil is a toroid, as shown in Figure 1–8(b). If the turns of the coil are close together and the dimensions of the coil cross section are small compared to the average radius of the toroid, the magnetic flux will be confined to the interior of the toroid, and the inductance of the toroidal coil is given by

$$L = \frac{\mu_0 N^2 A}{2\pi r} \tag{1-8}$$

where μ_0 is the permeability of free space, N is the number of turns in the coil, A is the cross-sectional area of the coil, and r is the average radius of the toroid. Obviously, one could make the inductance larger by increasing the number of turns or by increasing the size of the toroid (since the area could grow faster than the radius). The energy stored in an inductor is given by

$$w_{\text{mag}} = \frac{1}{2}LI^2 \tag{1-9}$$

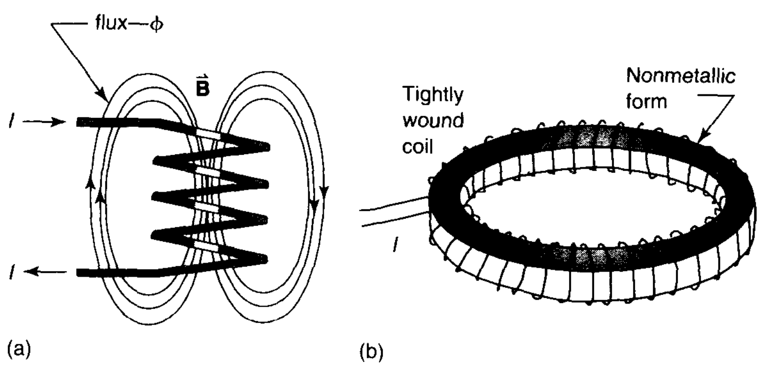

Figure 1–8
a. A loosely wound coil and the magnetic field resulting from the coil current.
b. A tightly wound, toroidal coil in which the magnetic field is confined to the interior of the coil.