Electromechanics AND Electric Machines

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SECOND EDITION

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Electromechanics and Electric Machines

To my uncle, Professor Majnoon Gorakhpuri, who through his own immeasurable literary contributions, profoundly influenced me. With deepest regards and affection,
S. A. Nasar

To Jean for her love and understanding,
L. E. Unnewehr

PREFACE TO THE FIRST EDITION

The purpose of this book is to develop the fundamental principles of electromechanics and electric machines and to guide the reader in the efficient applications of the governing principles of electromechanical devices that make up our modern technological society. It is unnecessary to recount the widespread use of both static and dynamic machines in this society, for they are a part of every aspect of our daily lives, from the starting of our cars, through operating numerous household appliances and providing most of the mechanical work in industry, to supplying an important energy conversion process in the production of electrical energy. These electromechanical devices also perform a significant role as actuators and transducers in control systems of all types, such as converting position or velocity to an electric signal as timing devices and as components in instrument and display systems. In short, electromechanical devices are a part of many of the systems with which engineers and technologists from many disciplines are concerned today, so that a knowledge of the basic concepts of torque, force, induced voltage, and electromagnetic fields that describe these devices is essential.

As the title of this book implies, several areas of background study are important for its understanding. The principal subject matter in which the reader should be prepared are electric circuit theory and basic mechanics. A course background in these subjects equivalent to an engineering college junior-level is recommended. Magnetic circuit theory, which is derived both from electromagnetic field theory and from analogies to static electric circuit theory, is also important. A review of magnetic circuit theory is supplied in Chapter 2 for those readers who are unfamiliar with the concepts and terms used in this theory.

With an emphasis upon fundamental concepts and principles, the aim of this book is to provide an understanding of many types of problems involving electromechanical devices. As noted above, the most frequent contact with an electromechanical device by today's engineer is as a component in a system. The differential equations and equivalent circuits for representing many types of devices and machines in systems models are developed for use in systems analysis, performance prediction, and so forth. Guidance on handling the nonlinearities associated with most machines and techniques for linear approximations are also given, and the theory and application of machines as control devices is presented.

The design of the common types of rotating machines and transformers—induction motors, many types of dc commutator motors, and appliance motors, and so forth—has become a mature science as a result of the outstanding developments in rotating machine theory during the first half of the twentieth century. Much of this design is now handled by routine computer design programs based upon this theory, and the typical reader of this book is not likely to need this highly specialized field of knowledge. However, there is a growing interest in many of the nonstandard configurations of rotating, linear, and static electromechanical devices as a result of recent aerospace activities, renewed interest in electric transportation, and the development of more sophisticated control systems. The design and analysis of these nonstandard devices generally require a return to basic principles, for which this book is suitable.

Finally, there are two significant emphases of the milieu in which this book was written that have contributed to its approach: economics and energy conservation. Both are vital in the proper application of electromechanical devices, and they are closely interrelated. There is potential for reducing the energy consumption of many systems by increasing the efficiency (or reducing the losses) of the electromechanical devices in the system. This may be accomplished by increasing the size of the device in some cases, by improving the devices cooling system, by using different materials in the device such as higher quality magnetic materials or bearings, or, in some cases, by employing an entirely different device that will perform the required function. All these alternatives will generally necessitate additional cost in the device and perhaps in other components of the total system. The usable lifetime and reliability of the device will also influence its overall cost. In the design and application of most electromechanical devices, there are many trade-offs available that permit choices between efficiency and cost. As the need to conserve the world's energy and materials resources becomes more urgent, the engineer must be cognizant of these choices. This book attempts to point out these trade-offs wherever possible. In some cases, problems at the end of the chapters are used for this purpose.

To briefly review the contents of the book, Chapter 1 presents a general introduction. The ac and dc operations of magnetic circuits, as well as magnetic circuits with permanent magnets, are considered in sufficient detail in Chapter 2. In a one-semester course, selected sections in this chapter may be skipped by the instructor. Transformers are discussed in Chapter 3, of which the first four sections can be covered in a one-semester course. Chapter 4, which deals with incremental motion electromechanical systems, such as transducers, provides the foundation for the formulation of the energy conversion process and its dynamics. Descriptive details and steady-state characteristics of dc machines are presented in Chapter 5. It is not recommended that the entire chapter be covered in a first course—much of the descriptive material may be given as reading assignments, followed by class discussions. The pertinent topics must be judiciously chosen by the instructor. Chapters 6 and 7 deal with induction and synchronous machines. These chapters are fairly short and, except for Sections 6.1, 7.5, and 7.6, the remainder of the two chapters are recommended for a first course. Solid-state control of electric motors is given in Chapter 8, which is fairly extensive. The choice of topics for presentation in a first course is left to the instructor. Chapter 9 outlines the general theory of electric machine dynamics. Although this chapter is not recommended for a first course, students should be made aware of its contents by at least scanning it.

Standard International (SI) units are used throughout the book. However, where other units are in common usage, these are also given. Unit conversion, wire table, and certain computer applications are included in the appendixes.

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Chapter 1
Introduction

This book is about the principles of electromechanics and their application in the design and analysis of electric motors, generators, transformers, and other electromechanical devices. The subject matter contained here encompasses a wide variety of disciplines, from advanced mathematics and computer science to many phases of electrical and mechanical engineering to the physical and material sciences. The devices and systems to which the principles of electromechanics are applied are likewise diverse in size, type of construction, materials used in construction, rotational speed and electrical frequency, and ultimate application.

The importance of electromechanical devices in almost every aspect of life does not need to be emphasized. The number of electric motors in the average U.S. residence today is probably a minimum of 10 and can easily exceed 50. There are at least 5 rotating electric machines on even the most spartan compact automobile, and this number is increasing steadily as emission and fuel economy systems are added. In an aircraft there are many more. Electromechanical devices are involved in every industrial and manufacturing process of a technological society. Many rotating machines have been on the moon and play an important role in most aerospace systems. More people travel by means of electrical propulsion each day—in elevators and horizontal people movers—than by any other mode of propulsion. The recent electrical blackouts in several major U.S. cities are a reminder of the almost total dependence of activity in urban areas on electric machines.

This book, therefore, deals with a vast and significant topic. An understanding of the principles of electromechanics is important for all who wish to extend the usefulness of electrical technology in order to ameliorate the problems of energy, pollution, and poverty that presently face humanity. Readers should keep sight of the long-range potential usefulness of electromechanical devices and electric machines while using this book.

From the brief listing of the applications of electric machines in the preceding paragraph, it is obvious that many portions of this industry are mature and are meeting the needs of society with relatively little need for research or advanced development. For example, the motor used in the garbage disposal of a modern home is probably designed by a relatively simple computer program and manufactured in a totally automated process. The hundreds of millions of clock motors manufactured each year also are almost totally standardized in design and manufacture. The same can be said of many types of industrial motors.

This is only a part of the picture, however, as one looks at the state of electromechanical development today. Even this apparently placid, static state-of-the-art in the manufacture of conventional motors may be changing drastically in the near future. In a recent effort to improve the efficiency of small induction motors used in homes, offices, businesses, and industrial plants, it was estimated by the Federal Energy Administration that 1 to 2 million barrels of oil per day could be saved in the United States by improving the efficiency of these motors by 20%.[1] This particular effort makes use of changes in capacitor size and winding connections in single-phase induction motors.

Efforts are also continually being made to improve efficiency of such motors by means of improved materials and design, while keeping in mind the availability of materials, the adverse environmental effects in the manufacture and use of materials (especially insulation materials), and the energy cost of manufacturing these materials. For example, aluminum has many desirable electrical characteristics for electromechanical applications and is one of the most abundant metals on the earth, but it is very costly in terms of energy use to process from raw materials.

Besides the changes in the manufacture and operation of conventional machines that are beginning to occur because of the need for energy and for environmental reasons, there are many exciting applications for new machine configurations, unusual operation of old configurations, sophisticated electronic control of all types of machines, and improved understanding of theory and design techniques to achieve more economical and energy-efficient machine designs. Many of the newer applications involve a new look at some old machines, such as redesigning commutator motors or operating a conventional squirrel-cage induction motor from a transistor inverter in order to develop an economically competitive electric car. Others involve the design of totally new motor configurations, such as the brushless dc motors being developed for aerospace, automotive, and industrial applications.

Electronic control of electric machines has been in use almost from the dawn of the electronic era, beginning with the relatively crude mercury-arc, rectifier-controlled motors. However, with the advent and present-day rapid development of solid-state power devices, integrated circuits, and low-cost computer modules, the range, quality, and precision of motor control has become practically unlimited.

The integration of electromechanical devices and electronic circuits has only just begun. The environment has always offered challenges to the design and operation of electric machines. For example, effective and reliable electrical insulation was one of the most difficult problems for early machine designers. Recently, rotating machines and other electromechanical devices have had to be developed for certain environment, including various types of nuclear radiation for nuclear power generating plants and for several space vehicles. Extremes of reliability in these environments have also been required in the space applications. Finally, as new sources of energy come into economic viability, electromechanical energy converters will be needed with characteristics to match energy sources such as solar converters, windmills, various nuclear configurations, coal-to-oil conversion processes, hydrogen systems, and so forth.

In this chapter, besides introducing the exciting possibilities for advanced development of electromechanical devices, we will discuss some of the basic concepts common to most electromechanical devices, review the methods of analysis that will be presented in subsequent chapters, and introduce the major classifications of rotating machines.

One book cannot do justice to the many topics mentioned thus far. This book will present the fundamentals of electromechanical devices. Some design guides and "rules of thumb" useful in analysis are given, but there is much more involved than can be related in these few pages. Therefore we trust that full use will be made by readers of the references given with each chapter. Of course, there is much material beyond these references, and we hope that this book will stimulate further investigation into this "beyond."

1.1 TYPES OF ROTATING MACHINES

There are four principal classes of rotating machines: dc commutator, induction, synchronous, and polyphase commutator machines. There are several other types of machines that do not fit conveniently into any of these classifications; they include stepper motors, which are, in general, synchronous machines operated in a digital manner; torque motors, which are either dc commutator or brushless synchronous machines operated in the torque (zero or low-speed) mode; homopolar machines, which are a variation of the Faraday disc generator principle and are used to supply low-voltage, high-current for plating loads;[2] and electrostatic machines, which fall into a different category of theory and practice from the electromagnetic machines to be discussed in this book.[3]

1. **DC Commutator Machines.** These are commonly referred to as just "dc machines" and are distinguished by the mechanical switching device known as the commutator. They are widely used in traction and industrial applications and are discussed in Chapter 5.
2. **Induction Machines.** The induction motor is the so-called "workhorse" of industry, but it is also the principal appliance motor in homes and offices. It is simple, rugged, durable, and long-lived, which accounts for its widespread acceptability in almost all aspects of technology. It can be operated as a generator and is so used in various aerospace and hydroelectric applications. Induction motors, because of their simple rotor structure, can operate at very high speeds. Figure 1.1 pictures an aerospace induction motor that operates at speeds near 64,000 rpm when driven from a source of 3200 Hz (see Chapter 6).
3. **Synchronous Machines.** The synchronous machine is probably the most diversified machine configuration, and it is often difficult to recognize the many variations that this class of machines can take on. The term *synchronous* refers to the relationship between the speed and frequency in this class of machine, which is given by (see Chapter 7).

$$\text{rpm} = 120\frac{f}{p} \tag{1.1}$$

where

$$\text{rpm} = \text{machine speed in revolutions per minute}$$

$$f = \text{frequency of applied source in hertz}$$

$$p = \text{number of poles on the machine}$$

A synchronous machine operates only at a synchronous speed; induction machines, often called *asynchronous* machines, operate at speeds somewhat below synchronous speeds. A wide variety of synchronous machines are in use today.

(a) **Conventional.** This is the standard synchronous machine (discussed in Chapter 7) which requires a dc source of excitation in its rotor. It is the machine used in most central-station electrical generating plants (as a generator) and in many motor applications for pumps, compressors, and so forth. A cutaway of a central-station generator is shown in Figure 1.2.

(b) **Reluctance.** This is a conventional machine without the dc field excitation; it is discussed in Chapters 4 and 7. It is one of the simplest machine configurations and has recently been used in applications conventionally supplied by induction motors. In very small power ratings, it is used for electric clocks, timers, and recording applications.