ELECTRIC MACHINES and DRIVES

Principles, Control, Modeling, and Simulation



Shaahin Filizadeh

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To Leila, *the thoughtful one,*

and

Rodmehr, *the playful one,*

for their love and support;

and

to my parents for their encouragement.



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Preface

Electric machines play crucial, yet often quiet and unnoticed, roles in our modern lives. The electricity that we have come to expect as an indispensable commodity is generated using electric generators. A large number of modern conveniences we enjoy are powered by electric motors of different forms and sizes. It is hard to imagine a world without electric machines and what they do to make our lives easier.

For a long period of time, the study of electric machines was a major portion of electrical engineering programs. In the past two or three decades, however, this subject was given less than its fair share of attention, while subjects such as digital and computer systems filled up large portions of curricula in many universities.

In recent years, electric machines have been used in radically new and exciting applications and in large scales, for example, in renewable energy generation schemes and electric and hybrid vehicles. These new developments and advances in power electronics and control systems have given electric machines a much deserved new life. This book aims to engage the student in the subject of electric machines and drives by laying a strong foundation rooted in physical principles of operation of these systems.

Overview of Chapters

The book comprises nine chapters and three appendices. The first two chapters are devoted to the underlying physical principles of electric machines. The laws of induction and interaction are described and their fundamental roles in electric machines are demonstrated through numerous examples. Chapter 3 is devoted to dc machines. Principles of their operation are described followed by a simple dynamic model that is then used to develop speed and torque control strategies. Chapters 4 through 6 are devoted to induction machines. Modeling, steady state–based drives, and high-performance drives are presented with particular attention to the underlying physics of the machine. Chapter 7 deals with modeling and high-performance control of permanent magnet synchronous machines. Chapter 8 presents elements of power electronics used in electric drive systems. Computer simulation is an indispensable tool in the study of modern electric machine and drive systems. They have evolved well beyond traditional analysis tools; computer tools are now increasingly used as tools for design

as well. Chapter 9 deals with simulation-based optimal design of electric motor drive systems.

The material in Appendix A on numerical simulation of dynamical systems is important. It allows the student to develop their own simulation code of electric machines and experiment with their computer models.

Computer Tools and Techniques

Throughout this book, a host of computer tools and techniques have been used. Three main computer programs have been used for this purpose:

1. Numerical simulations of simple cases have been directly coded using the integration method in Appendix A. These simulations are developed in MATLAB®.
2. Analysis of winding waveforms, inductances, and related calculations are done in Mathcad.
3. Simulations of electric machines with their power electronic drive circuits are done in the PSCAD/EMTDC transient simulation program. This is a widely used commercial program with a host of modeling and simulation capabilities, which prove to be particularly suited for high-power electronic drive systems.

These simulation cases are available through the publisher. The PSCAD/EMTDC simulation program has a student version that can be downloaded free of charge from www.pscad.com. Additional support material including chapter slides and a solutions manual are also available to the instructors through the publisher.

How to Teach from This Book

The material in this book can be taught, with minor variations, in one semester to a senior undergraduate or a graduate class. Depending on the background of the students and whether or not they have been exposed to power electronic circuits prior to taking this course, the instructor may drop Chapter 8 or supplement it with additional material (e.g., on dc–dc converters). Chapter 9 can be dropped if it is felt that its focus does not fit the theme of a particular course outline.

It is strongly recommended that simulation tools be incorporated in teaching of the material in the book. The supplied simulation cases can be used as

a base and can be supplemented through simulation assignments and small projects.

A great deal of learning in this book occurs in the end-of-chapter problems. They are designed to pick up on the points presented in chapters and develop them further or introduce additional aspects.

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I am grateful to my beloved wife Leila and my dear son Rodmehr for their immense understanding, support, and encouragement during this undertaking. It would have been impossible without their presence and I am deeply thankful to both of them. Thank you!



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1

Physics of Electric Machines

1.1 Introduction

Electric machines are devices used for energy conversion, mostly between mechanical and electrical forms. An electric motor is a machine that converts the electrical energy given to it as input to mechanical energy output; a generator does the reverse by producing electrical energy from mechanical energy input. Study of electric machines, therefore, requires knowledge and understanding of the principles of energy conversion.

Electric machines come in a wide variety of forms and sizes and are used in markedly different ways and applications. Consider, on the one hand, a small electric motor that rotates and precisely positions a compact disk in a CD drive and, on the other hand, a massive generator in a power plant that is driven by a turbine and generates large amounts of electricity. Despite such apparent differences in scale and application, all electric machines operate on the same underlying principles and share a simple backbone, which is a magnetic medium that links the electrical and mechanical ends of a machine.

Apart from its function of facilitating generation and directing magnetic flux to link machine windings, an electromagnetic medium also enables and facilitates the conversion and flow of energy between the two ends of a rotating electric machine, that is, its electrical and mechanical ends. Proper study of a rotating electric machine will therefore entail consideration of its magnetic structure and its role in the process of energy conversion. Although the study of electromagnetic systems is often associated with vector calculus of Maxwell's equations, it is indeed possible to describe and understand the behavior of electric machines in simple terms without recourse to complicated mathematics.

The intention of this chapter is to establish a foundation for understanding the operation of rotating electric machines using simple laws of physics. We use mathematics only as a facilitator and avoid it if the phenomenon at hand can be described equally well using words, figures, and qualitative description and judgment. Modeling and detailed analysis of electric machines requires mathematics, which is presented later (see Chapters 3 and 4, for example). At the end of this chapter, we revisit the linking function of

a magnetic circuit and also present some leads into numerical simulation of a nonlinear magnetic circuit.

1.2 Laws of Induction and Interaction: A Qualitative View

We stated that all electric machines use an electro-magnetic medium for linking their mechanical and electrical ends. There is a good reason for this, and it is rooted in two interesting phenomena that are observed when a magnetic field and a conductor interact with each other.

Consider the following simple situation (see Figure 1.1) in which a rectangular coil (a conductor) is placed in a uniform magnetic field. The two sides of the coil are housed in two slots on a cylindrical rotor. Figure 1.1 shows only a cross-sectional view of the two sides of the coil that are perpendicular to the page. We recall from physics that change of magnetic flux passing through a given surface causes induction of voltage. So let us assume that an external prime mover rotates the rotor on which the coil is assembled in the direction shown. Evidently, the flux passing through the affective area of the coil exposed to the magnetic field will vary with time, and hence, voltage will be induced across the two ends of the coil marked as 1 and 2 in Figure 1.1.

At this preliminary point, we are not concerned about determining an expression for the voltage, but rather we are establishing the fact that rotation of a coil in a magnetic field causes change of flux and thereby induction

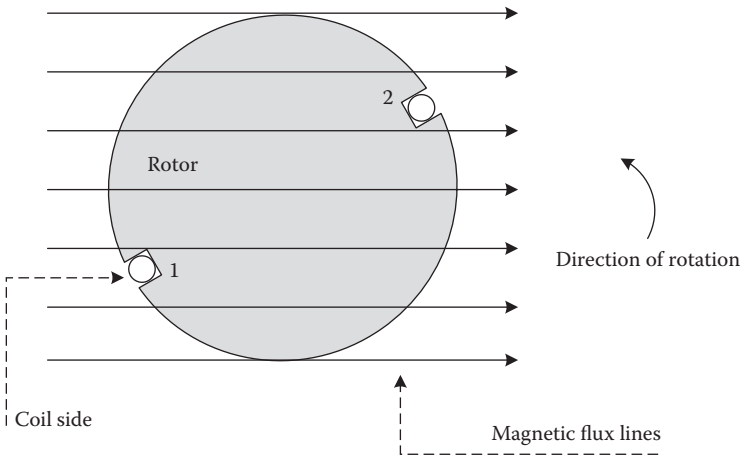

FIGURE 1.1
A rotating conducting coil in a magnetic field.

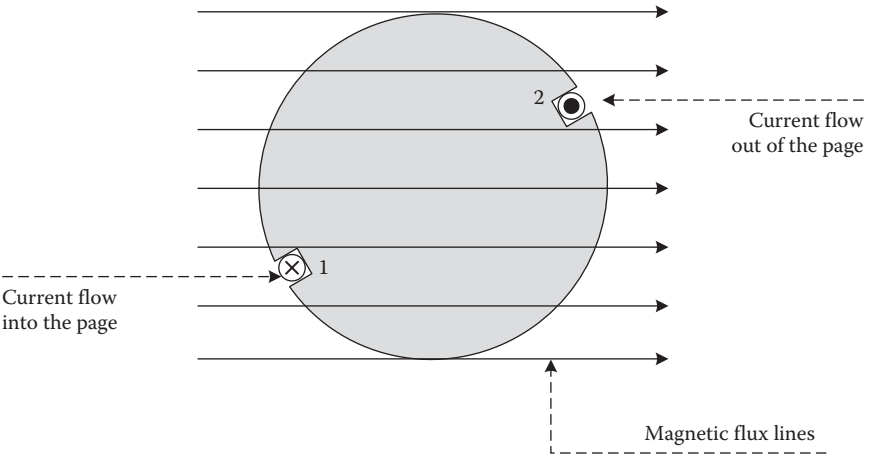

FIGURE 1.2
A current-carrying coil in a magnetic field.

of voltage. This is what we will refer to as *Faraday's law of induction*. This law is the basic principle of operation of an electric generator, a device in which mechanical energy is supplied to rotate a set of conducting coils in a magnetic field, thereby inducing a voltage in them.

The same setup can be used to explain how an electric motor works. Consider the situation shown in Figure 1.2 in which an external voltage source is connected across the terminals 1 and 2 of the coil, causing an electric current to pass through the coil (at the moment shown, the current flows out of the page from conductor 2 and into the page through conductor 1).

Presence of current-carrying conductors in a magnetic field leads to exertion of some force on the conductors. We will show in Section 1.4 that forces exerted on two conductors contribute to the creation of a mechanical torque that causes the coil (and thereby the housing rotor) to rotate. A mathematical expression for the torque produced and whether or not it leads to continuous rotation are not of concern at the moment. This *law of interaction* that explains the generation of force and torque on current-carrying conductors in a magnetic field forms the basic principle of operation of an electric motor.

Note that the two primitive generator and motor setups shown in Figures 1.1 and 1.2 contain exactly identical components. This is a profound observation with important practical implications. Based on this observation, it is possible to state that a given electric machine can, in principle, operate as both a generator and a motor depending on whether the energy flow is from its mechanical end to its electrical end or vice versa. Practical machines have more sophisticated structures that allow them to perform energy conversion with high performance and great efficiency; nonetheless, their basic principles of operation stay the same.

1.3 Induction and Interaction: A Closer Look

In this section, we consider some simple cases where the laws of induction and interaction are applied. The cases represent simplified, yet realistic, situations underlying the operation of electric machines. Where necessary and instructive, we also use mathematics to describe the phenomena at hand.

1.3.1 Induction of Voltage in a Coil

Consider the simple case depicted in Figure 1.3a. The figure shows the stator of an electric machine housing a coil (1-1′) made up of N turns of conducting wire and placed in two slots 180° apart. The rotor of the machine is designed such that it creates a magnetic field with a sinusoidal distribution in the space, given as follows:

$$\boldsymbol{B}_{\mathrm{R}}(\phi) = B_{\mathrm{m}} \cos(\phi - \theta_{\mathrm{r}})\hat{\boldsymbol{r}} \tag{1.1}$$

This expression specifies the flux density vector in the empty space between the stator and the rotor, which is known as the air gap. As seen in Figure 1.3a, the flux density has a radial orientation and varies sinusoidally in the space. Such a distribution of flux density is achieved either through proper arrangement of windings or by permanent magnets (PMs) on the rotor; the discussion that follows, however, is independent of how such a distribution is achieved. As shown in Figure 1.3, the rotor axis is assumed to be aligned with the positive peak of the rotor's magnetic field. The position of the rotor is denoted by θ_r, which measures the location of the rotor axis relative to the horizontal reference axis. If the length of the air gap is small enough, it can be assumed that the magnitude of flux density is essentially constant radially anywhere along the same radius in the air gap.

If the rotor is rotated, varying levels of magnetic flux will pass through the surface created by the sides of coil 1-1′ and confined between the coil's two ends (surface **1** in Figure 1.3b). According to Faraday's law of induction, variation of the flux linkage will induce a voltage in the coil. We now calculate the flux and subsequently the induced voltage in the coil.

Note that what we need to calculate is the flux that passes through the rectangular surface denoted as **1** in Figure 1.3b; however, the expression for flux density in Equation 1.1 is valid only in the air gap and we do not have an expression for the flux density passing through the rectangular surface **1**. To calculate the flux passing through surface **1**, we note that it must be equal to the flux that leaves the semicylindrical surface **2** (taken to be in the air gap of the machine where we do have an expression for flux density). This is due to Gauss's law, which rules out the existence of a single magnetic pole. In other words, the net magnetic flux that enters and leaves a closed volume must be equal to zero. Note that the radial orientation of flux density implies that the