

Preface

This book is intended to be an exposition of the modeling and control of electric machines, specifically, the direct current (DC) machine and the alternating current (AC) machines consisting of the induction motor, the permanent magnet (PM) synchronous motor, and the brushless DC motor. The particular emphasis here is on techniques used for high-performance applications, that is, applications that require both rapid and precise control of position, speed, and/or torque. Traditionally, DC motors were reserved for high-performance applications (positioning systems, rolling mills, traction drives, etc.) because of their relative ease of control compared to AC machines. However, with the advances in control methods, computing capability, and power electronics, AC motors continue to replace DC motors in high-performance applications. The intent here is to carefully derive the mathematical models of the AC machines and show how these mathematical models are used to design control algorithms that achieve high performance.

Electric machines are a particularly fascinating application of basic electricity and magnetism. The presentation here relies heavily on these basic concepts from Physics to develop the models of the motors. Specifically, Faraday's law ($\xi = -d\phi/dt$, where $\phi = \int_S \vec{B} \cdot d\vec{S}$), the magnetic force law ($\vec{F} = i\vec{\ell} \times \vec{B}$ or $\vec{F} = q\vec{v} \times \vec{B}$), Gauss's law ($\oint \vec{B} \cdot d\vec{S} = 0$), Ampère's law ($\oint \vec{H} \cdot d\vec{\ell} = i_{\text{free}}$), the relationship between $\vec{B}$ and $\vec{H}$, properties of magnetic materials, and so on are reviewed in detail and used extensively to derive the currently accepted nonlinear differential equation models of the various AC motors. The author made his best attempt to make the modeling assumptions as clear as possible and to consistently show that the magnetic and electric fields satisfy Maxwell's equations (as, of course, they must). The classical approach to teaching electric machinery is to present their equivalent circuit models and to analyze these circuit models ad nauseam. Further, the use of the basic Physics of electricity and magnetism to explain their operation is minimized if not omitted. However, the equivalent circuit is a result of assuming constant-speed operation of the machine and computing the sinusoidal steady-state solution of the nonlinear differential equation model of the machine. Here, the emphasis is on explaining how the machines work using fundamental concepts from electricity and magnetism, and on the derivation of their nonlinear differential equation models. The derivation of the corresponding equivalent circuit assuming steady-state conditions is then straightforward.

Electric machines also provide fascinating examples to illustrate con-

cepts from electromagnetic field theory (in contrast to electricity and magnetism). In particular, the way the electric and magnetic fields change as one goes between reference frames that are in relative motion are vividly illustrated using AC machines. For this reason, optional sections are included to show how the electric and magnetic fields change as one goes between a coordinate system attached to the stator to a coordinate system that rotates with the rotating magnetic field produced by the stator currents or a frame attached to the rotor. Also given in an optional section is the derivation of the axial electric and azimuthal magnetic fields in the air gap.

This is also a book on the control of electric machines based on their differential equation models. With the notable exception of the sinusoidal steady-state analysis of the induction motor in Chapter 7, very little attention is given to the classical equivalent circuits as these models are valid only in steady state. Rather, the differential equation models are used as the basis to develop the notions of field-oriented control, input-output linearization, flux observers, least-squares identification methods, state feedback trajectory tracking, and so on. This is a natural result of the emphasis here on high-performance control methods (e.g., field-oriented control) as opposed to classical methods (e.g., V/f , slip control, etc.).

There are of course many good books in the area of electric machines and their control. The author owes a debt of gratitude to Professor W. Leonhard for his book [1] (see the most recent edition [2]), from which he was educated in the modeling and control of electric drives. The present book is narrower in focus with an emphasis on the modeling and operation of electric machines based on elementary classical physics and an emphasis on high-performance control methods using a state-space formulation. The books by P. C. Krause [3] and P. C. Krause et al. [4] are complete in their derivation of the mathematical models of electric machines while C. B. Gray [5] presents electromagnetic theory in the context of electric machines. A comprehensive treatment using SIMULINK to simulate electric machinery is given in C-M. Ong's book [6]. The graduate level books by D. W. Novotny and T. A. Lipo [7], P. Vas [8], J. M. D. Murphy and F. G. Turnbull [9], I. Boldea and S. A. Nasar [10], B. Adkins and R. G. Harley [11], A. M. Trzynadlowski [12], M. P. Kazmierkowski and H. Tunia [13], B. K. Bose [14], and R. Krishnan [15] all cover the modeling and control of electric machines while the books by R. Ortega et al. [16], D. M. Dawson et al. [17], and F. Khorrami et al. [18] emphasize advanced control methods.

The introductory-level books by S. J. Chapman [19], H. Woodson and J. Melcher [20], L. W. Matsch and J. D. Morgan [21], G. McPherson and R. D. Laramore [22], D. V. Richardson [23], P. C. Krause and O. Wasynczuk [24], N. Mohan [25], G. R. Slemon and A. Straughn [26], J. Sokira and W. Jaffe [27], G. J. Thaler and M. L. Wilcox [28], V. Deltoro [29], M. El-Hawary [30], P. C. Sen [31], and G. R. Slemon [32] are among the many books on electric machines from which this author has benefited.

The beautifully written textbooks *PSSC Physics* by the Physical Science Curriculum Study [33], *Physics* by D. Halliday and R. Resnick [34], *Principles of Electrodynamics* by M. Schwartz [35], and *Electromagnetic Fields* by R. K. Wangness [36] are used as references for the theory of electricity and magnetism.

This book borrows from these above works and hopefully makes its own contribution to the literature on electric machines.

Part I of the book consists of the first three chapters. Chapters 1 and 2 present a detailed review of the basic concepts of electricity and magnetism in the context of DC machines and an introduction to control methods, respectively, which will be used extensively in the remaining chapters. The third chapter on magnetic fields and magnetic materials is intended to be a detailed introduction to the subject. For example, most textbooks assume that the reader understands Ampère's law in the form $\oint \vec{H} \cdot d\vec{\ell} = i_{\text{free}}$ and that $\vec{B} = \mu\vec{H}$ in (soft) magnetic materials, yet it is the experience of the author that students do not have a fundamental understanding of these concepts.

These first three chapters are elementary in nature and were written to be accessible to undergraduates. The reason for this is that often control engineers do not have any background in electric machinery while power/electric-machine engineers often do not have any background in basic state-space concepts of control theory. Consequently, it is hoped that these chapters can bring the reader "up to speed" in these areas.

Chapter 1 reviews the basic ideas of electricity and magnetism that are needed to model electric machines. In particular, the notions of magnetic fields, magnetic force and Faraday's law are reviewed by using them to derive the standard model of a DC motor.

Chapter 2 provides an elementary introduction to the control techniques required for the high-performance control of electric machines. This includes an elementary presentation of state feedback control, observers, and identification theory as applied to DC machines to prepare the reader for the subsequent chapters.

Chapter 3 goes into the modeling of magnetic materials in terms of their use in electric machines. The fundamental result of this chapter is the modification of Ampère's law $\oint_C \vec{B} \cdot d\vec{\ell} = \mu_0 i$ so that it is valid in the presence of magnetic material. This introduces the magnetic intensity field $\vec{H}$ and its relationship to magnetic induction field $\vec{B}$ via the magnetization vector $\vec{M}$ to obtain the more general version of Ampère's law $\oint \vec{H} \cdot d\vec{\ell} = i_{\text{free}}$. All of this requires a significant discussion of the modeling of magnetic materials. The approximation $\vec{H} = 0$ in magnetic materials is discussed, and then it is shown how this approximation along with Ampère's law can be used to find the radial component of $\vec{B}$ in the air gap of electric machines. Also presented is Gauss's law for $\vec{B}$; this leads to the notion of conservation of flux, as well as the fact that $\vec{B}$ is normal to the surface of

soft magnetic materials. This chapter should be read, but the reader should not get “bogged down” in the chapter. Rather, the main results should be remembered.

Part II consists of Chapters 4 through 10 and presents the modeling and control of AC machines.

Chapter 4 uses the results of Chapters 1 and 3 to explain how a radially directed rotating magnetic field can be established in the air gap of AC machines. In particular, the notions of distributed windings and of sinusoidally wound turns (phase windings) are explained. Ampère’s law is then used to show that a sinusoidal (spatially) distributed radial magnetic field is established in the air gap by the currents in the phase windings. The concept of flux linkage in distributed windings is explained, and the chapter ends with an optional section on the azimuthal magnetic field in the air gap.

Chapter 5 explains the fundamental Physics behind the working of induction and synchronous machines. Specifically, this chapter uses a simplified model of the induction motor and shows how voltages and currents are induced in the rotor loops by the rotating magnetic field established by the stator currents. Then it is shown how torque is produced on these induced currents by the same stator rotating magnetic field that induced them introducing the idea of slip. Similarly, the synchronous machine is analyzed to show how the rotating radial magnetic field established by the stator currents produces torque on a rotor carrying constant current.

An optional section on the microscopic point of view of the Physics of the induction motor is also presented. This includes a discussion of how the electric and magnetic fields change as one goes between coordinate systems that are rotating with respect to each other and how one reinterprets the Physics of the machine’s operation. The chapter ends with another optional section of the steady-state behavior of an induction machine with a squirrel cage rotor.

Chapter 6 derives the systems of differential equations that mathematically model the two-phase induction and synchronous machines. The concept of leakage is presented and accounted for in the derived models. These models are the accepted models used throughout the literature and form the basis for high-performance control of these machines. In an optional section it is shown that the stator and rotor *magnetic fields* of an induction motor rotate synchronously together as they do in a synchronous machine. The chapter ends with another optional section on the concepts of field energy and co-energy, and how the expression for the torque of an electric machine can be derived using these notions.

Chapter 7 presents the derivation of the models of three-phase AC machines and their two-phase equivalent models. These derivations readily follow from the results of Chapter 6. The classical steady-state analysis of the induction motor is also presented including its equivalent circuit. The chapter ends with a discussion of why the standard power system is an AC

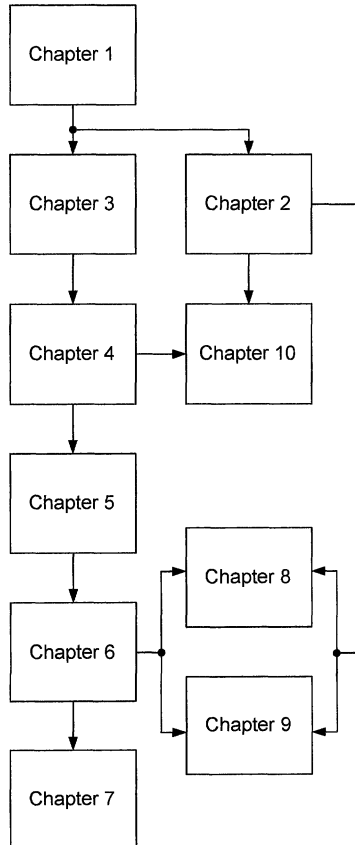
sinusoidal three-phase 60-Hz (or 50-Hz) system.

Chapter 8 covers the control of induction motors presenting both field-oriented control and input-output linearization control. Flux observers, field weakening, and speed observers are also presented along with experimental results. The chapter ends with an optional section on how to identify the induction motor parameters using a nonlinear least-squares technique.

Chapter 9 covers the control of synchronous motors describing field-oriented control, field weakening, speed observers and identification methods. The operation and modeling of permanent magnet stepping motors is also covered.

Chapter 10 covers the modeling and control of PM synchronous motors with trapezoidal back emf, which are also known as brushless DC (BLDC) motors.

The logical dependence of the chapters is shown in the block diagram below assuming that the optional sections are *not* covered.



Logical dependence of the chapters.

Finally, the author's intent for this book was for the reader to understand how electric machines are modeled and to understand the basic techniques in their control. The references at the end of the book are only those directly referenced in the book and are *not* representative of (nor give proper recognition to) the many important contributions made by researchers throughout the world. The reader is referred to Professor Leonhard's book [2] for a much more extensive reference list.

Comments on the Use of the Book

In using this book in a one-semester graduate-level course, the following material was usually covered:

Chapter 1, Sections 1.1–1.7
 Chapter 2, Sections 2.1–2.4
 Chapter 3, Sections 3.1–3.4
 Chapter 4, Sections 4.1–4.5
 Chapter 5, Sections 5.1–5.3
 Chapter 6, Sections 6.1–6.10
 Chapter 7, Sections 7.1–7.3
 Chapter 8, Sections 8.1–8.3
 Chapter 9, Section 9.1

Sections marked with an asterisk (*) may be omitted without loss of continuity. Some of these optional sections assume familiarity with Maxwell's equations in *differential* form.

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Mohamed Zribi was the first student I worked with in this area, leading to a paper on feedback linearization control of stepper motors. Ron Rekowski suffered through our first attempts to do some experiments for which I am grateful. My Ph.D. student Bob Novotnak continued this work and did the experiments on the control of the stepper and induction motors presented in Chapters 8 and 9 of this book. Through his skill we were able to obtain experimental results demonstrating very high performance. Jennifer Stephans (Marc Bodson's student) did the early work on identification for the induction motor while my student Kaiyu Wang did the identification experiments for the induction motor given in Chapter 8. Andy Blauch (Marc Bodson's student) did the identification experiments for the PM stepper motor presented in Chapter 9.

I first taught (and learned!) induction motor control using the book by Professor Werner Leonhard, and I am very grateful for his writing that book. I later had the opportunity to visit his institute in Braunschweig Germany from which I left with even more enthusiasm for the field.

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ftp://ftp.wiley.com/public/sci_tech_med/high_performance_control for downloading an errata sheet for the book. Instructors, upon obtaining password privileges, will also be able to download the simulation files that go with this textbook. A solutions manual is available to instructors by contacting their local Wiley representative.

Any comments, criticisms, and corrections are most welcome and may be sent to the author at chiasson@ieee.org.

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