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Electric Machinery (Sixth Edition)

电机学（第6版）

A. E. Fitzgerald
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清华大学出版社

Electric Machinery

(Sixth Edition)

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国际知名大学原版教材

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出　版　说　明

郑大钟

清华大学信息科学与技术学院

当前，在我国的高等学校中，教学内容和课程体系的改革已经成为教学改革中的一个非常突出的问题，而为数不少的课程教材中普遍存在“课程体系老化，内容落伍时代，本研层次不清”的现象又是其中的急需改变的一个重要方面。同时，随着科教兴国方针的贯彻落实，要求我们进一步转变观念扩大视野，使教学过程适应以信息技术为先导的技术革命和我国社会主义市场经济的需要，加快教学过程的国际化进程。在这方面，系统地研究和借鉴国外知名大学的相关教材，将会对推进我们的课程改革和推进我国大学教学的国际化进程，乃至对我们一些重点大学建设国际一流大学的努力，都将具有重要的借鉴推动作用。正是基于这种背景，我们决定在国内推出信息技术学科和电气工程学科国外知名大学原版系列教材。

本系列教材的组编将遵循如下的几点基本原则。(1)书目的范围限于信息技术学科和电气工程学科所属专业的技术基础课和主要的专业课。(2)教材的范围选自于具有较大影响且为国外知名大学所采用的教材。(3)教材属于在近5年内所出版的新书或新版书。(4)教材适合于作为我国大学相应课程的教材或主要教学参考书。(5)每本列选的教材都须经过国内相应领域的资深专家审看和推荐。(6)教材的形式直接以英文原版形式印刷出版。

本系列教材将按分期分批的方式组织出版。为了便于使用本系列教材的相关教师和学生从学科和教学的角度对其在体系和内容上的特点和特色有所了解，在每本教材中都附有我们所约请的相关领域资深教授撰写的影印版序言。此外，出于多样化的考虑，对于某些基本类型的课程，我们还同时列选了多于一本的不同体系、不同风格和不同层次的教材，以供不同要求和不同学时的同类课程的选用。

本系列教材的读者对象为信息技术学科和电气工程学科所属各专业的本科生，同时兼顾其他工程学科专业的本科生或研究生。本系列教材，既可采用作为相应课程的教材或教学参考书，也可提供作为工作于各个技术领域的工程师和技术人员的自学读物。

组编这套国外知名大学原版系列教材是一个尝试。不管是书目确定的合理性，教材选择的恰当性，还是评论看法的确切性，都有待于通过使用和实践来检验。感谢使用本系列教材的广大教师和学生的支持。期望广大读者提出意见和建议。

Electric Machinery (Sixth Edition)

影 印 版 序

本书主要介绍了电机学和机电能量转换的基本原理，并简介了一些新型电机原理和电机控制方法方面的内容。概括起来，本书有如下特点：

（1）内容系统全面。从磁路和磁性材料开始讲起，不但介绍了传统的变压器和旋转电机（同步电机、感应电机、直流电机），还涉及了机电能量转换原理、永磁电机、单相感应电机、开关磁阻电机、直线电机、电力电子技术介绍、电机的速度与转矩控制等内容。基本上涵盖了目前常见的各种电机和基本控制方法。

（2）本书的内容编排方式与常见的电机学教材不同。本书在介绍旋转电机之前，先比较详细地介绍了机电能量转换原理；然后，对旋转电机（包括交流电机和直流电机）的共同问题（磁动势、电动势、电磁转矩等）统一进行了介绍；最后，分别说明各类电机的特性。通过采用这种由面及点的方式，可加深读者对各类旋转电机的基本原理、共同规律及其内在联系的总体把握。但对于初学电机学的学生来说，按照传统的编排，先具体后抽象，先特殊后一般，则较易于掌握。

（3）注重概念方法。从内容的整体编排到具体内容的叙述，都体现了突出电机学的物理概念、强调电机学基本分析方法的指导思想。为避免读者陷入复杂的数学计算中，还引入了 Matlab 作为辅助的计算工具。全书思路清晰，文字严谨流畅，说理清楚，易于读者理解和掌握。

（4）理论联系实际。电机学是一门与工程实际有密切联系的课程。书中采用了许多实物的图片，来简明扼要地介绍各种电机的结构，并在附录中专门介绍了一些电机工程实际问题。这样可使读者比较清楚地了解电机理论与实际电机间的对应关系，有助于对基本原理和概念的理解。

（5）例题习题丰富。书中有大量的例题和习题，每个例题后面又配有一个练习题。作者或者通过例题对前面内容做进一步的解释，或者直接把例题本身作为对基本概念和原理的带有定量计算的说明。将例题和其他内容有机地融为一体，是本书的特色之一。

本书的三位作者都曾在美国 MIT 担任过教学工作，且都是 IEEE 的 Fellow，因此本书具有较高的科学性和权威性。本书的主干内容与国内教材基本一致，因此很适合作为国内电机学和相关课程的教学参考书。在当前大力推进高等院校双语教学的形势下，本书更是目前英文版教材中一个较好的选择。

朱东起　孙旭东
清华大学电机工程与应用电子技术系
2003 年 5 月

ABOUT THE AUTHORS

The late **Arthur E. Fitzgerald** was Vice President for Academic Affairs at Northeastern University, a post to which he was appointed after serving first as Professor and Chairman of the Electrical Engineering Department, followed by being named Dean of Faculty. Prior to his time at Northeastern University, Professor Fitzgerald spent more than 20 years at the Massachusetts Institute of Technology, from which he received the S.M. and Sc.D., and where he rose to the rank of Professor of Electrical Engineering. Besides *Electric Machinery,* Professor Fitzgerald was one of the authors of *Basic Electrical Engineering,* also published by McGraw-Hill. Throughout his career, Professor Fitzgerald was at the forefront in the field of long-range power system planning, working as a consulting engineer in industry both before and after his academic career. Professor Fitzgerald was a member of several professional societies, including Sigma Xi, Tau Beta Pi, and Eta Kappa Nu, and he was a Fellow of the IEEE.

The late **Charles Kingsley, Jr.** was Professor in the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, from which he received the S.B. and S.M. degrees. During his career, he spent time at General Electric, Boeing, and Dartmouth College. In addition to *Electric Machinery,* Professor Kingsley was co-author of the textbook *Magnetic Circuits and Transformers.* After his retirement, he continued to participate in research activities at M.I.T. He was an active member and Fellow of the IEEE, as well as its predecessor society, the American Institute of Electrical Engineers.

Stephen D. Umans is Principal Research Engineer in the Electromechanical Systems Laboratory and the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, from which he received the S.B., S.M., E.E., and Sc.D. degrees, all in electrical engineering. His professional interests include electromechanics, electric machinery, and electric power systems. At MIT, he has taught a wide range of courses including electromechanics, electromagnetics, electric power systems, circuit theory, and analog electronics. He is a Fellow of the IEEE and an active member of the Power Engineering Society.

PREFACE

The chief objective of *Electric Machinery* continues to be to build a strong foundation in the basic principles of electromechanics and electric machinery. Through all of its editions, the emphasis of *Electric Machinery* has been on both physical insight and analytical techniques. Mastery of the material covered will provide both the basis for understanding many real-world electric-machinery applications as well as the foundation for proceeding on to more advanced courses in electric machinery design and control.

Although much of the material from the previous editions has been retained in this edition, there have been some significant changes. These include:

- A chapter has been added which introduces the basic concepts of power electronics as applicable to motor drives.
- Topics related to machine control, which were scattered in various chapters in the previous edition, have been consolidated in a single chapter on speed and torque control. In addition, the coverage of this topic has been expanded significantly and now includes field-oriented control of both synchronous and induction machines.
- MATLAB®[1] examples, practice problems, and end-of-chapter problems have been included in the new edition.
- The analysis of single-phase induction motors has been expanded to cover the general case in which the motor is running off both its main winding and its auxiliary winding (supplied with a series capacitor).

Power electronics are a significant component of many contemporary electric-machine applications. This topic is included in Chapter 10 of this edition of *Electric Machinery* in recognition of the fact that many electric-machinery courses now include a discussion of power electronics and drive systems. However, it must be emphasized that the single chapter found here is introductory at best. One chapter cannot begin to do justice to this complex topic any more than a single chapter in a power-electronics text could adequately introduce the topic of electric machinery.

The approach taken here is to discuss the basic properties of common power electronic components such as diodes, SCRs, MOSFETs, and IGBTs and to introduce simple models for these components. The chapter then illustrates how these components can be used to achieve two primary functions of power-electronic circuits in drive applications: rectification (conversion of ac to dc) and inversion (conversion of dc to ac). Phase-controlled rectification is discussed as a technique for controlling the dc voltage produced from a fixed ac source. Phase-controlled rectification can be used

[1] MATLAB is a registered trademark of The MathWorks, Inc.

to drive dc machines as well as to provide a controllable dc input to inverters in ac drives. Similarly, techniques for producing stepped and pulse-width-modulated waveforms of variable amplitudes and frequency are discussed. These techniques are at the heart of variable-speed drive systems which are commonly found in variable-speed ac drives.

Drive-systems based upon power electronics permit a great deal of flexibility in the control of electric machines. This is especially true in the case of ac machines which used to be found almost exclusively in applications where they were supplied from the fixed-frequency, fixed-voltage power system. Thus, the introduction to power electronics in Chapter 10 is followed by a chapter on the control of electric machines.

Chapter 11 brings together material that was distributed in various chapters in the previous edition. It is now divided into three main sections: control of dc motors, control of synchronous motors, and control of induction motors. A brief fourth section discusses the control of variable-reluctance motors. Each of these main sections begins with a discussion of speed control followed by a discussion of torque control.

Many motor-drive systems are based upon the technique of field-oriented control (also known as vector control). A significant addition to this new edition is the discussion of field-oriented control which now appears in Chapter 11. This is somewhat advanced material which is not typically found in introductory presentations of electric machinery. As a result, the chapter is structured so that this material can be omitted or included at the discretion of the instructor. It first appears in the section on torque control of synchronous motors, in which the basic equations are derived and the analogy with the control of dc machines is discussed. It appears again in its most commonly used form in the section on the torque control of induction motors.

The instructor should note that a complete presentation of field-oriented control requires the use of the dq0 transformation. This transformation, which appeared for synchronous machines in Chapter 6 of the previous edition, is now found in Appendix C of this edition. In addition, the discussion in this appendix has been expanded to include a derivation of the dq0 transformation for induction machines in which both stator and rotor quantities must be transformed.

Although very little in the way of sophisticated mathematics is required of the reader of this book, the mathematics can get somewhat messy and tedious. This is especially true in the analyis of ac machines in which there is a significant amount of algebra involving complex numbers. One of the significant positive developments in the last decade or so is the widespread availability of programs such as MATLAB which greatly facilitate the solution of such problems. MATLAB is widely used in many universities and is available in a student version.[2]

In recognition of this development, this edition incorporates MATLAB in examples and practice problems as well as in end-of-chapter problems. It should be emphasized, though, that the use of MATLAB is not in any way a requirement for the adoption or use of *Electric Machinery*. Rather, it is an enhancement. The book

[2] The MATLAB Student Version is published and distributed by The MathWorks, Inc. (http://www.mathworks.com).

now includes interesting examples which would have otherwise been too mathematically tedious. Similarly, there are now end-of-chapter problems which are relatively straightforward when done with MATLAB but which would be quite impractical if done by hand. Note that each MATLAB example and practice problem has been notated with the symbol, found in the margin of the book. End-of-chapter problems which suggest or require MATLAB are similarly notatated.

It should be emphasized that, in addition to MATLAB, a number of other numerical-analysis packages, including various spread-sheet packages, are available which can be used to perform calculations and to plot in a fashion similar to that done with MATLAB. If MATLAB is not available or is not the package of preference at your institution, instructors and students are encouraged to select any package with which they are comfortable. Any package that simplifies complex calculations and which enables the student to focus on the concepts as opposed to the mathematics will do just fine.

In addition, it should be noted that even in cases where it is not specifically suggested, most of the end-of-chapter problems in the book can be worked using MATLAB or an equivalent program. Thus, students who are comfortable using such tools should be encouraged to do so to save themselves the need to grind through messy calculations by hand. This approach is a logical extension to the use of calculators to facilitate computation. When solving homework problems, the students should still, of course, be required to show on paper how they formulated their solution, since it is the formulation of the solution that is key to understanding the material. However, once a problem is properly formulated, there is typically little additional to be learned from the number crunching itself. The learning process then continues with an examination of the results, both in terms of understanding what they mean with regard to the topic being studied as well as seeing if they make physical sense.

One additional benefit is derived from the introduction of MATLAB into this edition of *Electric Machinery*. As readers of previous editions will be aware, the treatment of single-phase induction motors was never complete in that an analytical treatment of the general case of a single-phase motor running with both its main and auxiliary windings excited (with a capacitor in series with the auxiliary winding) was never considered. In fact, such a treatment of single-phase induction motors is not found in any other introductory electric-machinery textbook of which the author is aware.

The problem is quite simple: this general treatment is mathematically complex, requiring the solution of a number of simultaneous, complex algebraic equations. This, however, is just the sort of problem at which programs such as MATLAB excel. Thus, this new edition of *Electric Machinery* includes this general treatment of single-phase induction machines, complete with a worked out quantitative example and end-of-chapter problems.

It is highly likely that there is simply too much material in this edition of *Electric Machinery* for a single introductory course. However, the material in this edition has been organized so that instructors can pick and choose material appropriate to the topics which they wish to cover. As in the fifth edition, the first two chapters introduce basic concepts of magnetic circuits, magnetic materials, and transformers. The third chapter introduces the basic concept of electromechanical energy conversion. The fourth chapter then provides an overview of and on introduction to the various machine types. Some instructors choose to omit all or most of the material in Chapter 3 from an introductory course. This can be done without a significant impact to the understanding of much of the material in the remainder of the book.

The next five chapters provide a more in-depth discussion of the various machine types: synchronous machines in Chapter 5, induction machines in Chapter 6, dc machines in Chapter 7, variable-reluctance machines in Chapter 8, and single/two-phase machines in Chapter 9. Since the chapters are pretty much independent (with the exception of the material in Chapter 9 which builds upon the polyphase-induction-motor discussion of Chapter 6), the order of these chapters can be changed and/or an instructor can choose to focus on one or two machine types and not to cover the material in all five of these chapters.

The introductory power-electronics discussion of Chapter 10 is pretty much stand-alone. Instructors who wish to introduce this material should be able to do so at their discretion; there is no need to present it in a course in the order that it is found in the book. In addition, it is not required for an understanding of the electric-machinery material presented in the book, and instructors who elect to cover this material in a separate course will not find themselves handicapped in any way by doing so.

Finally, instructors may wish to select topics from the control material of Chapter 11 rather than include it all. The material on speed control is essentially a relatively straightforward extension of the material found in earlier chapters on the individual machine types. The material on field-oriented control requires a somewhat more sophisticated understanding and builds upon the dq0 transformation found in Appendix C. It would certainly be reasonable to omit this material in an introductory course and to delay it for a more advanced course where sufficient time is available to devote to it.

McGraw-Hill has set up a website, **www.mhhe.com/umans**, to support this new edition of *Electric Machinery*. The website will include a downloadable version of the solutions manual (for instructors only) as well as PowerPoint slides of figures from the book. This being a new feature of *Electric Machinery*, we are, to a great extent, starting with a blank slate and will be exploring different options for supplementing and enhancing the text. For example, in recognition of the fact that instructors are always looking for new examples and problems, we will set up a mechanism so that instructors can submit examples and problems for publication on the website (with credit given to their authors) which then can be shared with other instructors.

We are also considering setting up a section of the website devoted to MATLAB and other numerical analysis packages. For users of MATLAB, the site might contain hints and suggestions for applying MATLAB to *Electric Machinery* as well as perhaps some Simulink®[3] examples for instructors who wish to introduce simulations into their courses. Similarly, instructors who use packages other than MATLAB might

[3] Simulink is a registered trademark of The MathWorks, Inc.

want to submit their suggestions and experiences to share with other users. In this context, the website would appear again to be an ideal resource for enhancing interaction between instructors.

Clearly, the website will be a living document which will evolve in response to input from users. I strongly urge each of you to visit it frequently and to send in suggestions, problems, and examples, and comments. I fully expect it to become a valuable resource for users of *Electric Machinery* around the world.

Professor Kingsley first asked this author to participate in the fourth edition of *Electric Machinery;* the professor was actively involved in that edition. He participated in an advisory capacity for the fifth edition. Unfortunately, Professor Kingsley passed away since the publication of the fifth edition and did not live to see the start of the work on this edition. He was a fine gentleman, a valued teacher and friend, and he is missed.

I wish to thank a number of my colleagues for their insight and helpful discussions during the production of this edition. My friend, Professor Jeffrey Lang, who also provided invaluable insight and advice in the discussion of variable-reluctance machines which first appeared in the fifth edition, was extremely helpful in formulating the presentations of power electronics and field-oriented control which appear in this edition. Similarly, Professor Gerald Wilson, who served as my graduate thesis advisor, has been a friend and colleague throughout my career and has been a constant source of valuable advice and insight.

On a more personal note, I would like to express my love for my wife Denise and our children Dalya and Ari and to thank them for putting up with the many hours of my otherwise spare time that this edition required. I promised the kids that I would read the Harry Potter books when work on this edition of *Electric Machinery* was completed and I had better get to it! In addition, I would like to recognize my life-long friend David Gardner who watched the work on this edition with interest but who did not live to see it completed. A remarkable man, he passed away due to complications from muscular dystrophy just a short while before the final draft was completed.

Finally, I wish to thank the reviewers who participated in this project and whose comments and suggestions played a valuable role in the final form of this edition. These include Professors:

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Stephen D. Umans
Cambridge, MA
March 5, 2002

BRIEF CONTENTS

CONTENTS

CHAPTER 1

Magnetic Circuits and Magnetic Materials

The objective of this book is to study the devices used in the interconversion of electric and mechanical energy. Emphasis is placed on electromagnetic rotating machinery, by means of which the bulk of this energy conversion takes place. However, the techniques developed are generally applicable to a wide range of additional devices including linear machines, actuators, and sensors.

Although not an electromechanical-energy-conversion device, the transformer is an important component of the overall energy-conversion process and is discussed in Chapter 2. The techniques developed for transformer analysis form the basis for the ensuing discussion of electric machinery.

Practically all transformers and electric machinery use ferro-magnetic material for shaping and directing the magnetic fields which act as the medium for transferring and converting energy. Permanent-magnet materials are also widely used. Without these materials, practical implementations of most familiar electromechanical-energy-conversion devices would not be possible. The ability to analyze and describe systems containing these materials is essential for designing and understanding these devices.

This chapter will develop some basic tools for the analysis of magnetic field systems and will provide a brief introduction to the properties of practical magnetic materials. In Chapter 2, these results will then be applied to the analysis of transformers. In later chapters they will be used in the analysis of rotating machinery.

In this book it is assumed that the reader has basic knowledge of magnetic and electric field theory such as given in a basic physics course for engineering students. Some readers may have had a course on electromagnetic field theory based on Maxwell's equations, but an in-depth understanding of Maxwell's equations is not a prerequisite for study of this book. The techniques of magnetic-circuit analysis, which represent algebraic approximations to exact field-theory solutions, are widely used in the study of electromechanical-energy-conversion devices and form the basis for most of the analyses presented here.