# PREFACE

The aim of this book is to give deep exposition of the theory of electromechanical devices, with specific emphasis on the theory of rotating electric machines. The basic concepts have remained more or less the same over the years since the first edition of this text appeared in 1985.

Since the appearance of the third edition in 2004, most of the advances in the application and control of electric machines have taken place owing to the further breakthroughs in power electronics and microprocessor/computer-based control systems. As a result, a much broader spectrum of electric machine types are now available. Particularly, permanent-magnet and variable-reluctance machines are now used in many applications and this is bound to increase further in future. AC drives are becoming more and more attractive in many applications, such as those requiring variable speed and flexible control, while earlier dc machines were the only choice. Realising this fact, these machine types find increased coverage in the fourth edition.

This book presents simple, explicit, and yet rigorous and comprehensive treatment of transformers and electric machines in a single volume. Considerable emphasis is laid on the fundamentals, physical concepts, principles and on rigorous development of circuit model equivalents of both transformers and machines. Each circuit model is closely related to the physical reality, the underlying assumptions are sharply focussed and consequent limitations on the range of operation over which the model is valid are fully explained. The clarity of the physical basis of models developed would be most satisfying to the reader and it would enable him to make intelligent use of the models in the solution of machine problems and in the design of systems using these devices. The prediction of device performance follows as an immediate sequel to its model. Furthermore, as a next step (not covered in this book), the circuit parameters could be conveniently related to the physical dimensions and properties of the materials used in the device. While the circuit theory approach to electro-mechanical devices is introduced early in Chapter 2, the machine analysis in the bulk of the book follows the field-theory approach which, as is well-known, is better understood and appreciated by undergraduates and provides a deep insight into and a clear understanding of the electric machine.

This is the only book which clearly brings home to the reader the distinction in the sign convention between the synchronous machine model and the transformer-type model, also employed for the induction machine. Another distinguishing feature of the book is the clarity with which it brings out the difference between a sinusoidally spaced distributed quantity (field) represented as a vector and sinusoidally time-varying quantities represented as phasors and how a rotating vector creates a time phasor. In order that the teacher and student can both make convenient use of symbols on the blackboard or on paper, the phasors are symbolically represented by capital letters with superbars and the vectors are represented by capital letters with superarrows.

The book covers all the essential ingredients of machine knowledge expected of a modern-day undergraduate in electrical engineering. With new and vital topics crowding the curriculum in electrical engineering, machine courses have rightly been squeezed into two time slots of one-semester duration each.

The book is designed to meet this need. The book is primarily designed to cater to a one-semester core course common for all engineering disciplines and a one-semester topping off course for those majoring in electrical engineering. The core course may comprise Chapters 1, 2, Secs 3.1 to 3.9 (except Sumpner's test), 3.11, 3.12 (partly), Chapters 4,5 and Secs 7.1 to 7.4 for dc machine coverage along with a quick resume of armature reaction, commutation, methods of excitation and characteristics of generators and motors. These topics are covered in initial portions of the relevant sections of Chapter 7. The dc machine winding can be explained to the class by merely projecting the two developed winding diagrams of Chapter 6. The remaining portions of the book would then comprise the second course. The book is written in a flexible style and a high degree of selectivity is inbuilt so that the teacher may leave out advanced articles of various topics in coping with the time factor without any loss of continuity. It is even possible to select a single one-semester course out of the book where time exigencies so demand.

The theory and applications of various machines as control-system actuators is treated at appropriate places in the book. The methods of control-system analysis have not been included as these form a full course in a modem curriculum. Linear approximations are employed for tackling non-linearities associated with most machines. Wherever warranted, the effect of magnetic nonlinearity is accounted for in steady-state analysis.

Although the models advanced are strictly applicable for steady-state analysis of device performance, these are extended to the dynamic case at a few places by making strong assumptions. The transient analysis of the synchronous machine is treated qualitatively and a graphical picture of the phenomenon is presented.

The reader is expected to have a prior grounding in electricity and magnetism, introductory circuit theory, basic mechanics and elementary differential equations. However, appendices on ac steady-state circuit analysis and three-phase systems have been included for ready reference.

### New to this Edition

The chapters on dc machines and synchronous machines are re-written completely. The highlights of this edition are large number of **solved problems** and practice problems that have been added in all the chapters.

The key features of this edition are

- New chapter on 'Generalized Theory of Electric Machines'
- Detailed description of Transformers, dc Machines, dc Machines Excitation, Predetermination of external characteristics of dc Generator, Parallel operation of dc Generators, Efficiency and Testing of dc Machines, Speed control of Induction Motor, Linear Induction Motor
- Enhanced coverage of Permanent Magnet dc Motors, Permanent Magnet Materials and their applications
- Discussion on Silicon Controlled Rectifier (SCR), Insulated Gate Bipolar Transistor (IGBT), MOS Turn off Thyristor (MTO) and Emitter Turn off Thyristor (ETO) to cover new trends
- Synchronous generator (alternator), MMF Method, ASA Method, V curves and inverted V curves, Rating of alternator, phasor diagrams, Reactive power flow from generator
- MATLAB examples to facilitate problem-solving skills
- Excellent pedagogy including
    - Over 200 Solved examples
    - Over 300 Practice questions, most provided with answers
    - Over 140 Review questions

- Over 50 Objective type questions
- 10 MATLAB Examples

Though no sophisticated knowledge of mathematics is required for the reader of this book, the mathematics involved in this subject at times can get messy and tedious. This is particularly true in the analysis of ac machines in which there is a significant amount of algebra involving complex numbers. One of the significant positive developments in the recent years is the widespread availability of software such as MATLAB which greatly facilitates the solution of such problems. MATLAB is freely used in many institutions and colleges and is also available in a student version (*http://www.mathworks.com*). This edition, therefore, incorporates MATLAB in some sample solved examples. It should be emphasized here that the use of MATLAB is not a prerequisite for using this book. It is just an enhancement, an important one though! Further, it may be noted that even in the cases where it is not specifically suggested, some of the problems in the book can be attempted using MATLAB or an equivalent program. Some additional programs for solving problems using MATLAB are included in this book.

The **introductory chapter** discusses electrical–electrical and electromechanical energy conversion processes and devices from a general point of view with the explicit purpose of motivating the reader for studying transformers and electric machines. This chapter, however, is not a prerequisite for the rest of the book. **Chapter 2** brushes up magnetic circuits and the principle of induction.

In **Chapter 3**, the transformer is treated exhaustively. The circuit-model approach is emphasized and for obvious reasons the role of the phasor diagram is underplayed. This chapter lays the ground work for the understanding of electromechanical energy conversion processes in machines and the circuit model of the induction machine in particular.

Then follows **Chapter 4** on the underlying principles of electromechanical energy conversion in the end of which is answered the question, "Why is electric field not used as a coupling medium instead of the magnetic field?" Cases of both linear and nonlinear magnetization (saturation) are treated.

Exposition of the basic concepts of rotating machines from a generalized point of view as well as engineering aspects, such as cooling, rating and load mechanics is advanced in **Chapter 5**. General expressions for emf and torque are derived. The torque production is explained here via interaction of two magnetic fields assumed to be sinusoidally distributed. An alternative current-sheet approach is also given for the interested reader. Elementary treatment of specific machine types—synchronous and induction—then follows and their important characteristics are visualized on a field-interaction basis. Since interacting fields are assumed to be sinusoidal, which is justified in these two classes of machines only, a most rudimentary treatment of the de machine is given here because the fields in this class of machines are essentially nonsinusoidally distributed.

While Chapter 5 gives the essential treatment of ac windings, the details including important practical features are dealt with in **Chapter 6** devoted entirely to ac windings. Also given is a reasonably detailed account of dc armature windings in **Chapter 7**. Where time is a limiting factor, ac winding details can be skipped and dc winding directly introduced via the two developed diagrams with a brief explanation of parallel paths, commutation and brush location.

**Chapters 7–9** cover in depth the three basic machine types—the dc machine, synchronous machine and induction machine. The approach adopted in all the three is one of rigorous modelling with due stress on explanation of the underlying assumptions. The dc machine is the first to be dealt with as its steady-state model is the simplest. The modelling in each machine results in a circuit model of the linear kind by virtue of the assumptions made, which for all practical purposes are quite valid for steady-state performance analysis as well as under certain transient situations. In **Chapter 8**, on the synchronous machine, a heuristic methods are advanced to account for the effect of strong magnetic nonlinearity on the machine performance.

Tests to determine circuit-model parameters are advanced at appropriate places. Assumptions involved in machine modelling are once again stressed at this stage. Once the circuit model of the machine has been arrived at, the discussion is then focussed on power flow and operating characteristics. The constructional features and important practical details are included at suitable places and the circumstances under which a particular machine would be employed as a motor are discussed.

With the availability of electronic calculators, circle-diagram methods have lost their significance. However, the circle diagram for the induction machine is included as it gives the complete machine performance at a glance and is quite useful in qualitative reasoning.

A simple approach to machine dynamics is given in all the three machine types. In the case of the synchronous machine, dynamics is restricted to the phenomenon of "hunting", while transient stability receives elementary treatment.

**Chapter 10** deals with the important topic of fractional-kW motors. A qualitative-cum-heuristic analysis of a single-phase induction motor and its circuit model are followed by a rigorously developed circuit model for a two-winding motor. This rigorous coverage may be skipped when time does not permit it. A variety of single-phase induction, synchronous and series commutator types of motors are treated. Comprehensiveness is imparted to this chapter by the inclusion of stepper motors, ac servomotor and ac tachometer; the latter two follow simply as a corollary from the two-winding motor analysis.

**Chapter 11** is an entirely new chapter and deals with the generalised theory of electrical machines.

Probably the most significant development in recent years in the allied area of motor control is the use of power semiconductors—diodes, power transistors and thyristors. The growth in this area has already qualified for a separate undergraduate level course. However, for the sake of completeness, a comprehensive chapter is included in this book. This in our view is a better approach than to burden the previous chapters by spreading out the relevant details. **Chapter 12** on this topic has a wide coverage and includes all the three varieties of SCR (silicon controlled rectifier) circuitry, namely converters, choppers and inverters. The contents and effects of non-smooth dc and nonsinusoidal ac outputs of these control equipment on the circuit behaviour and on machine performance are beyond the scope of this book.

With the phenomenal developments in SCR circuitry for power control, cross-field machines and ac commutator machines have become almost obsolete. However, to fulfil the need of such universities which still include these topics in their curriculum, fairly detailed appendices (IV and V) on these topics are added.

A number of cross-sectional views of built-up machines and their parts are included and the student is exhorted to carefully study these to help him visualize the physical picture of the machine being modelled. Laboratory exercises always associated with a machines course will further aid this process.

A large number and variety of illustrative examples are spread throughout the book. These would greatly help in imprinting a clear physical picture of the devices and associated physical reasoning on the student's mind. An equally large number of unsolved problems are given as exercises at the end of each chapter. Answers to all the unsolved problems are given. Some of these problems are devised to illustrate some points beyond what is directly covered in the text.

International Standard (SI) units are used throughout the book. The list of symbols is necessarily large. Apart from being illustrated at the point of occurrence, the symbols used are listed in the beginning of the book.

### Web Supplements

The web supplements can be accessed at *http://www.mhne.com/electmach4e* and contain the following material:

For Instructors: Solution Manual and Power Point Lecture Slides
For Students: Interactive Quiz and Web links for Study Material.

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### Feedback

We welcome any constructive criticism of the book and will be grateful for any appraisal by the readers. The suggestions can be sent on my email: dpk0710@yahoo.com

**D P Kothari**
**I J Nagrath**

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