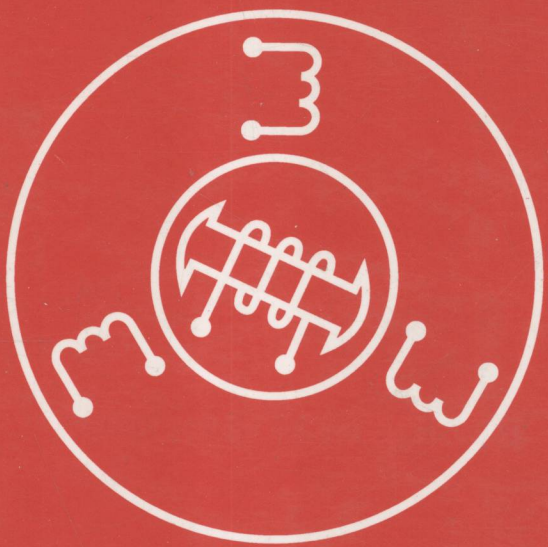
Principles of Electric Machines and Power Electronics

Second Edition



P.C. Sen

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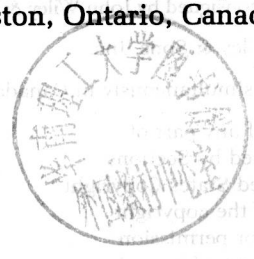
SECOND EDITION

P. C. SEN

Professor of Electrical Engineering
Queen's University
Kingston, Ontario, Canada



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PRINCIPLES OF ELECTRIC MACHINES AND POWER ELECTRONICS

To
My lively children, Debashis, Priya, and Sujit;
My loving wife, Maya;
And Manidi and Sudhirda, whose affection
is always appreciated.

About the Author

Paresh C. Sen is Professor of Electrical Engineering at Queen's University, Kingston, Ontario, Canada. Dr. Sen received his Ph.D. degree from the University of Toronto in 1967. He has worked for industries in India and Canada and has been a consultant to electrical industries in Canada. He has authored or coauthored over 100 papers in the general area of power electronics and drives and is the author of the book *Thyristor DC Drives* (Wiley, 1981). He has taught electric machines, power electronics, and electric drive systems for twenty-five years. His fields of interest are electric machines, power electronics and drives, microcomputer control of drives, modern control techniques for high-performance drive systems, and power supplies.

Dr. Sen served as an Associate Editor for the IEEE Transactions on Industrial Electronics and Control Instrumentation and as Chairman of the Technical Committee on Power Electronics. He has served on program committees of many IEEE and international conferences and has organized and chaired many technical sessions. At present, he is an active member of the Industrial Drive Committee and Industrial Power Converter Committee of IEEE. Dr. Sen is internationally recognized as a specialist in power electronics and drives. He received a Prize Paper Award from the Industrial Drive Committee for technical excellence at the Industry Application Society Annual Meeting in 1986. Dr. Sen is a Fellow of IEEE.

PREFACE TO THE SECOND EDITION

Technology never stands still. Since the first edition of this book there have been new developments in the applications of, for example, permanent magnet motors and solid-state devices for control. The basics of electric machines and machine control remain the same, however. Thus, preserving the content of the first edition, which has had widespread acceptance, this edition endeavors to enhance, to update, and to respond to the suggestions of readers and instructors. To these ends the following new material has been incorporated.

- A large number of new problems and some new examples have been added. Most of these problems are presented in the chapters and sections which appear to have been used by most instructors. The number of problems in the second edition is nearly double the number in the first edition.
- Coverage of permanent magnet motors has been introduced, including permanent magnet dc motors (PMDC), printed circuit board (PCB) motors, permanent magnet synchronous motors (PMSM), brushless dc motors (BLDC), and switched reluctance motors (SRM).
- Constant-flux and constant-current operation of induction motors is discussed.
- Additional material is included on new solid-state devices, such as insulated gate bipolar transistors (IGBT) and MOS-controlled thyristors (MCT). This material appears in Chapter 10. This chapter also includes, for the first time, material on Fourier analysis of waveforms, current source inverters using self-controlled solid-state devices, and three basic configurations of choppers.
- A concise treatment of three-phase circuits is presented in Appendix B.
- Answers to odd-numbered problems are presented in Appendix E to assist students in building confidence in their problem-solving skills and in their comprehension of principles.

Many individuals have expressed their opinions on the first edition and have made suggestions for the second edition. I acknowledge with gratitude these contributions, as well as the generous comments of many who have written and spoken to me—students, instructors, and research workers. The number is so large that it would be inappropriate to name them all and the risk of omission would be great.

I am grateful to my graduate students, Yan Fei Liu and Zaohong Yang, for their valuable assistance. I thank the departmental secretary, Debby Robertson, for typing the manuscript of the second edition at various stages, Jennifer Palmer and Patty Jordan for secretarial assistance, and Perry Con-

rad, the departmental manager, who made the administrative arrangements. I thank my wife Maya and my children, Sujit, Priya, and Debashis, who were a constant and active source of support throughout the endeavor. Last but not least, I express my profound gratitude to Chuck (Prof. C.H.R. Campling), who again spent many hours reading and correcting the text. His friendship, valuable counsel, and continued encouragement are greatly appreciated.

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January 1996

PREFACE TO THE FIRST EDITION

Electric machines play an important role in industry as well as in our day-to-day life. They are used in power plants to generate electrical power and in industry to provide mechanical work, such as in steel mills, textile mills, and paper mills. They are an indispensable part of our daily lives. They start our cars and operate many of our household appliances. An average home in North America uses a dozen or more electric motors. Electric machines are very important pieces of equipment.

Electric machines are taught, very justifiably, in almost all universities and technical colleges all over the world. In some places, more than one semester course in electric machines is offered. This book is written in such a way that the instructor can select topics to offer one or two semester courses in electric machines. The first few sections in each chapter are devoted to the basic principles of operation. Later sections are devoted mostly to a more detailed study of the particular machine. If one semester course is offered, the instructor can select materials presented in the initial sections and/or initial portions of sections in each chapter. Later sections and/or later portions of sections can be covered in a second semester course. The instructor can skip sections, without losing continuity, depending on the material to be covered.

The book is suitable for both electrical engineering and non-electrical engineering students.

The dc machine, induction machine, and synchronous machine are considered to be basic electric machines. These machines are covered in separate chapters. A sound knowledge of these machines will facilitate understanding the operation of all other electric machines. The magnetic circuit forms an integral part of electric machines and is covered in Chapter 1. The transformer, although not a rotating machine, is indispensable in many energy conversion systems; it is covered in Chapter 2. The general principles of energy conversion are treated in Chapter 3, in which the mechanism of force and torque production in various electric machines is discussed. However, in any chapter where an individual electric machine is discussed in detail, an equivalent circuit model is used to predict the torque and other performance characteristics. This approach is simple and easily understood.

The dc machine, the three-phase induction machine, and the three-phase synchronous machine are covered extensively in Chapters 4, 5, and 6, respectively. Classical control and also solid-state control of these machines are discussed in detail. Linear induction motors (LIM) and linear synchronous motors (LSM), currently popular for application in transportation systems, are presented. Both voltage source and current source equivalent circuits for the operation of a synchronous machine are used to predict its performance. Operation of self-controlled synchronous motors for use in variable-speed drive systems is discussed. Inverter control of induction machines and the

effects of time and space harmonics on induction motor operation are discussed with examples.

Comprehensive coverage of fractional horsepower single-phase motors, widely used in household and office appliances, is presented in Chapter 7. A procedure is outlined for the design of the starting winding of these motors. Special motors such as servomotors, synchro motors, and stepper motors are covered in Chapter 8. These motors play an important role in applications such as position servo systems or computer printers. The transient behavior and the dynamic behavior of the basic machines (dc, induction, and synchronous) are discussed in Chapter 9. Solid-state converters, needed for solid-state control of various electric machines, are discussed in Chapter 10.

All important aspects of electric machines are covered in this book. In the introduction to each chapter, I indicate the importance of the particular machine covered in that chapter. This is designed to stimulate the reader's interest in that machine and provide motivation to read about it. Following the introduction, I first try to provide a "physical feel" for the behavior of the machine. This is followed by analysis, derivation of the equivalent circuit model, control, application, and so forth.

A large number of worked examples are provided to aid in comprehension of the principles involved.

In present-day industry it is difficult to isolate power electronics technology from electric machines. After graduation, when a student goes into an industry as an engineer, he or she finds that in a motor drive, the motor is just a component of a complex system. Some knowledge of the solid-state control of motors is essential for understanding the functions of the motor drive system. Therefore, in any chapter where an individual motor is discussed, I present controller systems using that particular motor. This is done primarily in a qualitative and schematic manner so that the student can understand the basic operation. In the controller system the solid-state converter, which may be a rectifier, a chopper, or an inverter, is represented as a black box with defined input–output characteristics. The detailed operation of these converters is presented in a separate chapter. It is possible to offer a short course in power electronics based on material covered in Chapter 10 and controller systems discussed in other chapters.

In this book I have attempted to combine traditional areas of electric machinery with more modern areas of control and power electronics. I have presented this in as simple a way as possible, so that the student can grasp the principles without difficulty.

I thank all my undergraduate students who suggested that I write this book and, indeed, all those who have encouraged me in this venture. I acknowledge with gratitude the award of a grant from Queen's University for this purpose. I am thankful to the Dean of the Faculty of Applied Science, Dr. David W. Bacon, and to the Head of the Department of Electrical Engineering, Dr. G. J. M. Aitken, for their support and encouragement. I thank my colleagues in the power area—Drs. Jim A. Bennett, Graham E. Dawson, Tony R. Eastham, and Vilayil I. John—with whom I discussed electric ma-

chines while teaching courses on this subject. I thank Mr. Rabin Chatterjee, with whom I discussed certain sections of the manuscript. I am grateful to my graduate students, Chandra Namuduri, Eddy Ho, and Pradeep Nandam, for their assistance. Pradeep did the painful job of proofreading the final manuscript. I thank our administrative assistant, Mr. Perry Conrad, who supervised the typing of the manuscript. I thank the departmental secretaries, Sheila George, Marlene Hawkey, Marian Rose, Kendra Pople-Easton, and Jessie Griffin, for typing the manuscript at various stages. I express my profound gratitude to Chuck (Prof. C.H.R. Campling), who spent many hours reading and correcting the text. His valuable counseling and continued encouragement throughout have made it possible for me to complete this book. Finally, I appreciate the patience and solid support of my family—my wife, Maya, and my enthusiastic children, Sujit, Priya, and Debashis, who could hardly wait to have a copy of the book presented to them so that they could show it to their friends.

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April 1987

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