ELECTROMECHANICAL ENERGY CONVERTERS

HARIT MAJMUDAR

Allyn and Bacon Series in Electrical Engineering

Electromechanical Energy Converters

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Teaching consists in presenting a problem, or a situation, to the student, who learns by developing the thought processes required to solve the problem either by himself or at times with the guidance of the teacher.

This book is dedicated to those who have influenced me most in my development as a teacher.

Vishnuprasad Majmudar

Framroze Karani

John Burriss

Archie Miller

Wilbur LePage

Erika Majmudar

John Ruptash

Foreword

It was a pleasure for me to be associated with Dr. Harit Majmudar in the conception and writing of this book. My role was mainly that of critic and editor, and it is in this role that I welcome the opportunity to say a few words.

Men have always sought *to explain* the phenomena occurring in their natural environment and *to predict* the occurrence of such phenomena under specified conditions. But in addition to these, an engineer seeks *to control* his environment in order to induce events which he considers to be beneficial and desirable.

In undertaking to study an area of knowledge a student must learn about the basic phenomena and the explanations currently available for understanding them. He must also learn about some of the important devices or classes of devices used for "controlling" the human environment in this area of knowledge. He must learn about the techniques used in analyzing devices, systems or processes once they are known. He must obtain some understanding, if not of specific methods of design, at least of the basic considerations that are involved in carrying out the "design" or "control" activity of an engineer.

In this process of learning the student should not be a passive recipient of the knowledge of the past, properly classified, codified and catalogued. Learning should be undertaken in a spirit of adventure, the adventure of discovery. The *quantity* of knowledge he obtains in any given area is of secondary importance. What is of primary importance is the *method* he develops for *acquiring* knowledge.

All of this has implications for the way in which textbooks are written. At every turn a textbook should seek to present the development and unfolding of an area of knowledge in such a way that the student is a participant, not a bystander watching things happening. As much as possible the student should be made aware of why a certain thing should be done and what value it has in the overall picture. The textbook should help generate in the student an attitude, an inquiring frame of mind, that will lead him to creative activity of his own.

This book has been written with such thoughts as guide. The degree of success achieved is left for you, the reader, to decide.

Syracuse, New York *Norman Balabanian*

Preface

General Comments. The sphere of activities of an "electrical engineer" has been expanding at an ever increasing rate for the past two decades. However, the time required to earn the first college degree, which is supposed to prepare an individual to pursue the profession of electrical engineering, has remained practically unchanged. Engineering educators have responded by continually evaluating and changing the curriculum in content as well as in philosophy in order to meet the needs of the profession. It has now become abundantly clear, from a professional point of view, that the main objective of an undergraduate program should be to acquaint the student with the *language* and *philosophy* of engineering. The language deals with physical phenomena and the associated mathematics, and the philosophy deals with both the "scientific" method and the "engineering" method.

The net effect of this in electrical engineering curricula has been the reduction of time devoted to the traditional subjects of so-called power engineering, namely, electrical machinery and power systems, to an absolute minimum. The present book, Part I in particular, is my attempt to treat the old subject of electrical machinery in a manner suitable for a one-term course on the subject. In this Preface I hope to describe the philosophy I have pursued in writing this book and a few suggestions for its use as a text.

Objectives. Prior to describing the particular approach adopted in this book, it might be proper first to state the objectives to be achieved in an introductory course in the subject under consideration. I have in mind the following set of primary objectives for Part I of this book.

(1) An understanding of the concepts of induced electromotive force, electromagnetic force, and electromechanical energy conversion.
(2) An understanding of the basic geometrical and electrical topology (that is, mechanical and electrical configuration) of conventional rotating electric machinery.
(3) An understanding of the steady-state terminal behavior of the machines discussed in (2).

These objectives may be related in turn to the broader aspect of the study of engineering which is, in essence, the study of scientific theory, its application to particular devices or device theory, and the application of the latter to real engineering systems or system theory.

Part II of this book is designed for a second course in the subject and should be reserved for students with a special interest in power apparatus and systems. The objective of this portion of the book is to introduce the student to Kron's generalized theory of machines and to the transient behavior of synchronous machines.

Approach. The theory of rotating electrical machinery and of other devices treated in this book is developed from a coupled-circuit point of view. According to this a device is represented by a model containing a number of magnetically coupled circuits, some of which are in relative motion. This method has proven to be very powerful in unifying the theory of the various machines and is almost essential to the study of their transient behavior. However, it does not reveal directly the simple physical visualizations of the basic processes taking place in the machines. Moreover, it is undoubtedly more abstract and mathematical than the field, or mmf, point of view. Hence the field picture, which shows that the steady electromagnetic torque is the result of the interaction between two magnetic fields stationary with respect to each other, is also fully developed. The various machines differ in the manner in which these two fields are produced, but are essentially the same insofar as the basic mechanism of electromagnetic torque is concerned. In addition, the equivalence between the two points of view is also demonstrated.

A quick glance at the contents will show that Kron's generalized theory is not introduced at all in Part I of the book. Experience has taught me that a better pedagogical practice, at least for a subject as complex as rotating machinery, is one in which the general case evolves inductively from a consideration of particular cases. This seems to be particularly true for a course intended for third or fourth year college students.

There exists a doubt, and I believe it to be a legitimate one, regarding the real value of tensor analysis in the study of electrical machinery. I have, therefore, confined myself to matrix analysis in Chapter 7 in which Kron's generalized theory is introduced.

Finally a word about the device versus the system point of view. Although the major objective in this book is an understanding of the terminal behavior of machines, details of the "inside" of the machines that are essential for a reasonably good understanding of the "outside" are discussed.

Suggestions for use. As mentioned before, Part I of this book is designed for a one-term course—36 to 45 lectures—which is likely to be the first and the only one of its kind in most curricula in electrical engineering in the United States. Consequently, an attempt has been made to make it as complete as possible without sacrificing rigor of treatment. It will be found that continuity in the subject matter can be maintained even if some sections are omitted.

For example, sections dealing with the coupled-circuit derivation of the equations of direct-current and induction machines can be omitted if desired. This permits a certain amount of flexibility to suit the personal taste of different instructors.

The general background assumed is that of a third year student in electrical engineering. The essential aspects of electromagnetic theory necessary for the study of the subject are, however, reviewed in Chapter 1.

Part II of the book can be used as the basis for a second course on the subject. It is essentially an introduction to advanced topics and, therefore, no attempt at completeness has been made. However, a basic foundation has been laid for further course work or self-study to pursue the works of either Kron, Gibbs, Bewley, Lynn, and Takeuchi, or of Concordia, Lewis and Kimbark.

ACKNOWLEDGMENTS

I must concede at the outset that if this book has any merit it is primarily due to the influence of my teachers, my colleagues, and several excellent books from which I have learned the subject matter of this book.

I am most grateful to Professor N. Balabanian who first proposed that I take up this project in the spring of 1961. Since I had no previous experience at book writing, I promised to accept this challenging task if he would agree to read and criticize whatever I wrote. I acknowledge with pleasure my indebtedness to Balabanian who read almost all of Part I of the book, made many suggestions for improvement, and edited wherever necessary.

Among those who reviewed the manuscript I wish to single out W. A. Lewis who took an unusual interest in it, read carefully both parts of the book, and wrote an extremely comprehensive review. I have tried to incorporate most of his suggestions in the final version of the manuscript. People who are familiar with Professor Lewis's book, *The Principles of Synchronous Machines*, will recognize that I am heavily influenced by his writings.

I have also benefited from the review comments of P. L. Alger and from personal discussions with him. Thanks are due to R. M. Saunders for his review, and to W. T. Hunt, Jr. and R. Stein for giving permission to use some problems from their book *Static Electromagnetic Devices*.

Among the several textbooks that have left a lasting impression on me I must include *Electric Machinery*, 1st ed., by Fitzgerald and Kingsley and *Electromechanical Energy Conversion* by White and Woodson.

There is very little about the synchronous machine that I have not learned from Professor A. R. Miller. I have no words to express how much I owe him.

Most of the writing was done when I was teaching at Carleton University. I am grateful to John Ruptash, Dean of the Faculty of Engineering of

Carleton University for his moral support and for making available the stenographic help as well as the duplicating facilities needed to prepare the manuscript.

Thanks are due to Mrs. Valerie Mackinnon who did an excellent job at typing most of the manuscript.

Finally, I am indebted to my wife who shared with me the burden of the pregnancy of the book that lasted nearly four years.

Worcester, Massachusetts *Harit Majmudar*

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Part I

CHAPTER 1

Fundamental Laws

1-1 INTRODUCTION

Among the varied professional activities of an electrical engineer is the important task of converting energy from some other form to electric energy, distributing the electric energy to the locations where it will be used, and reconverting the electric energy to useful forms. Many devices exist for the conversion of energy from one form to another. These include (1) solar cells (or photovoltaic cells) which convert light energy into electric energy; (2) thermoelectric generator, which utilizes the Seebeck effect (the fact that an electric current will flow when heat is applied to one junction of a circuit containing dissimilar metals); (3) thermionic devices in which electrons are bailed off a heated cathode and collected at a cold anode; (4) fuel cells, in which the free energy of a fuel (such as hydrogen or a hydrocarbon) is converted directly into electric energy, and (5) magnetohydrodynamic (MHD) generators, which produce electricity by forcing an ionized gas through a magnetic field.

However, the quantity of energy that can be converted by these devices is relatively small at the time when this book is being written. With advances in research and technology, it is perfectly possible that some of these devices will be designed to generate large amounts of electric power in the future. At the present time, they are of great value where only small amounts of energy are required (as in experimental earth satellites). But when large quantities of electric energy are required, the converting device known as an *electromagnetic* (or simply *electric*) *generator* still reigns supreme. More than 99