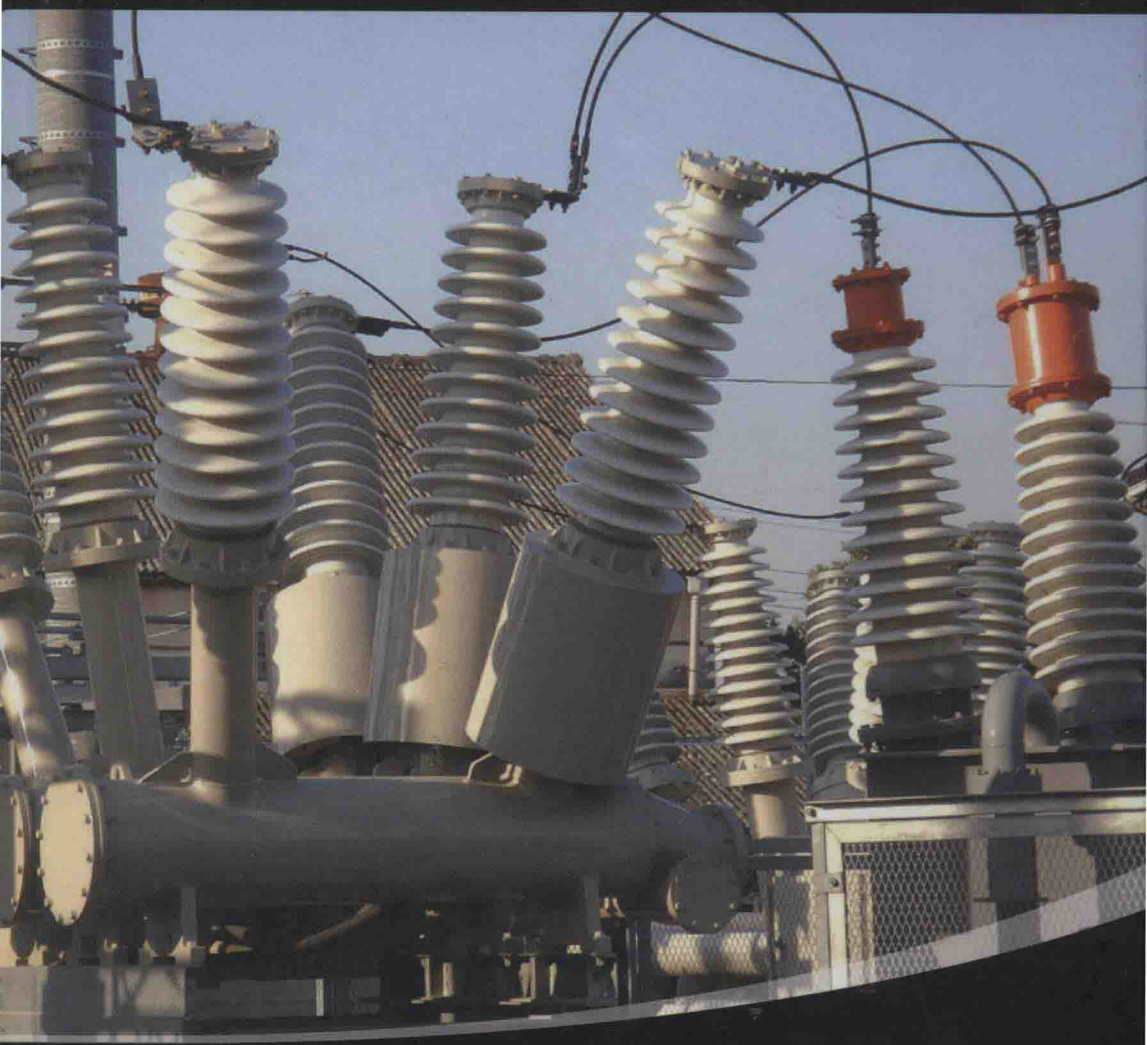
FUNDAMENTALS OF ELECTRIC POWER ENGINEERING

Isaak D. Mayergoyz • Patrick McAvoy



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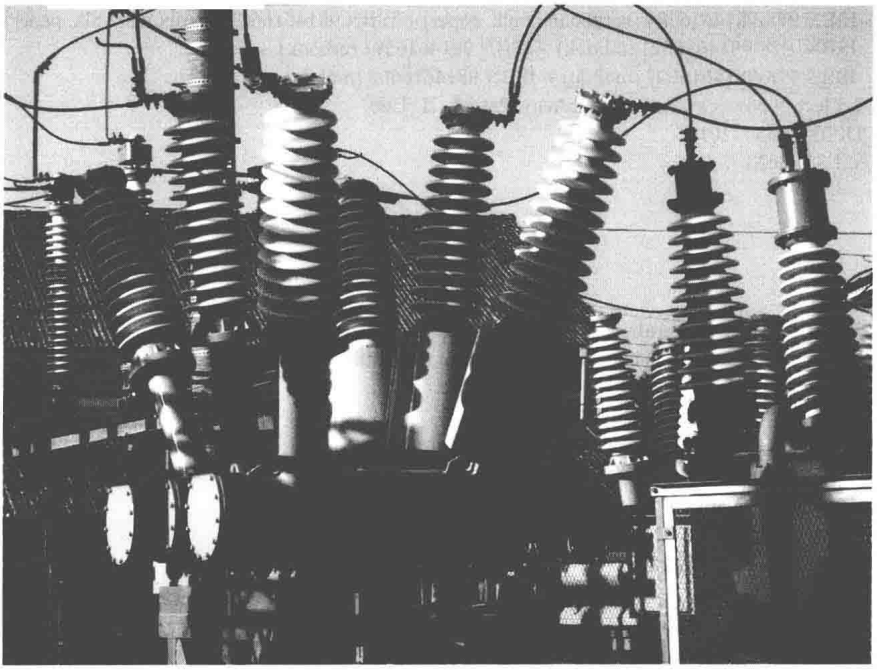

Isaak D. Mayergoyz • Patrick McAvoy
University of Maryland, USA.

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TO OUR STUDENTS

Preface

You have in your hands an undergraduate text on fundamentals of electric power engineering. This text reflects the experience of the first author in teaching electric power engineering courses in the Electrical and Computer Engineering Department of the University of Maryland College Park during the past thirty-four years. These courses have constituted the educational core of the electric power engineering program. This program was originally established (in the early 1980s) with the financial support and sponsorship of Baltimore Gas and Electric (BGE) Company, Potomac Electric Power Company (PEPCO), Virginia Electric Power Company (VEPCO), Bechtel Corporation and General Electric (GE) Foundation. This program has been designed as a sequence of senior elective courses in the area of electric power engineering. This design has two main advantages. First, students in such elective courses usually have strong interest in electric power and are really motivated to learn the related material. Second, senior students have already been exposed to fundamentals in electric and electronic circuits, electromagnetics and control theory. This opens the opportunity to cover the material in power courses at sufficiently high level and with the same mathematical and physical rigor which is now practiced in courses on communication, control and electromagnetics. This text on fundamentals of electric power engineering reflects this approach to teaching power courses.

Electric power engineering has always been an integral part of electrical engineering education. This is especially true nowadays in view of renewed emphasis in the area of energy in general and electric power engineering in particular. This textbook may provide a viable alternative to existing textbooks on the market by covering in one volume in a concise and rigorous manner such topics as power systems, electrical machines and power elec-

tronics. For this reason, this book can be used for teaching three different courses such as Power Systems, Electrical Machines and Power Electronics. These power courses form the mainstream of electric power engineering curriculum at most universities worldwide.

The book consists of three parts. The first part of the book deals with the review of electric and magnetic circuits. This review stresses the topics which nowadays are usually deemphasized (or ignored) in required circuits and electromagnetics courses. Namely, the phasor diagrams for ac circuits and analysis of electric circuits with periodic non-sinusoidal sources are stressed. Phasor diagrams have practically disappeared from circuit courses and textbooks, while these diagrams are still very instrumental in electric power engineering. Analysis of electric circuits with periodic non-sinusoidal sources is very important in the study of steady-state operation of power electronics converters. The frequency-domain and time-domain techniques for such analysis are presented in the book. In the review of magnetic circuits, a special emphasis is made on the analysis of magnetic circuits with permanent magnets. This is justified, on the one hand, by the proliferation of permanent magnets in power devices and, on the other hand, by the insufficient discussion of this topic in the existing undergraduate textbooks. Furthermore, the analysis of nonlinear magnetic circuits and eddy current losses for circularly (or elliptically) polarized magnetic fields are presented. The former is important because magnetic saturation of ferromagnetic cores often occurs in power devices. The latter is of interest because ferromagnetic cores of ac electric machines are subject to rotating (not linearly polarized) magnetic fields.

The second part of the book can be used for teaching courses on power systems and electrical machines. This part starts with a brief review of the structure of power systems, analysis of three-phase circuits and the discussion of ac power and power factor. Next, the analysis of faults in power systems is presented. This analysis is first performed by using the Thevenin theorem. Then, the concept of symmetrical components is introduced and the sequence networks are derived. Finally, the analysis of faults based on sequence networks is discussed. The next chapter deals with transformers. Here, the design and principle of operation of transformers are first considered along with the study of the ideal transformer. Then, the equivalent circuit for a single-phase transformer is derived on the basis of equivalent mathematical transformation of coupled circuit equations and the importance of leakage inductances (leakage reactances) is stressed. Next, open-circuit and short-circuit tests are described as the experimen-

tal means of determining parameters of equivalent circuits. The chapter is concluded by the discussion of three-phase transformers. The following chapter deals with synchronous generators. Here, the design and principle of operation of synchronous generators with cylindrical rotors and salient pole rotors are first considered. Then, the mathematical analysis of armature reaction magnetic fields of ideal cylindrical rotor generators is carried out. The results of this analysis are used in the discussion of the design of stator windings and in the computation of their synchronous reactance. It is stressed that stator windings are designed as filters of spatial and temporal harmonics. This is achieved due to their distributed nature, their two-layer structure and the use of fractional pitch. Next, the two-reactance theory of salient pole synchronous generators is presented. The chapter is concluded by the derivation of formulas for the power of synchronous generators and by the discussion of static stability of these generators as well as of their performance when connected to an infinite bus. The next chapter deals with the power flow analysis and dynamic (transient) stability of power systems. Here, the nonlinear power flow equations are first derived and then their numerical solutions by using Newton-Raphson and continuation techniques are discussed. The analysis of the transient stability is carried out by using the "swing" equation for mechanical motion of rotors of synchronous generators. This equation is presented in the Hamiltonian form, which leads to the phase portrait of rotor dynamics. This phase portrait results in a simple algebraic criterion for transient stability of rotor dynamics which contains as a particular case the celebrated equal area stability criterion. The last chapter of the second part deals with induction machines. In the past, induction machines have mostly been used as motors. However, recently induction machines have found applications as generators in wind energy systems. First, the design and principle of operation of induction machines is discussed. Then, by using the fact that in the induction machines the electromagnetic coupling between the rotor and stator windings is mostly realized through rotating magnetic fields, the coupled circuit equations are derived. The equivalent mathematical transformation of these coupled circuit equations leads to the equivalent electric circuits for induction machines. The chapter is concluded by the discussion of mechanical (torque-speed) characteristics of induction machines, which reveal the possibility of frequency control of speed of induction motors.

The third part of the book deals with power electronics and it consists of four chapters. The first chapter covers the material related to power semiconductor devices. It starts with a brief review of the scope and nature

of power electronics and then provides the summary of basic facts of semiconductor physics. This is followed by the discussion of p-n junctions and diodes, where all the basic relations are derived and characteristic features of power diodes are outlined. Then, the principles of operation and designs of bipolar junction transistors (BJTs) and thyristors (SCRs) are presented and the special emphasis is placed on the understanding of operation of these devices as switches. Next, such devices as the MOSFET, power MOSFET and IGBT are discussed and their main advantages as power electronics switches are articulated. The chapter is concluded with brief descriptions of snubber circuits and resonant switches. The principles of zero-current switching (ZCS) and zero-voltage switching (ZVS) are outlined and it is stressed that the design of resonant (quasi-resonant) power converters is a very active and promising area of research. The next chapter deals with rectifiers. Here, single-phase bridge rectifiers with RL, RC and RLC loads are first discussed along with center-tapped transformer rectifiers. The time-domain technique is extensively used to derive analytical expressions for currents and voltages in such rectifiers. Then, three-phase diode rectifiers are studied and various circuit topologies of these rectifiers are presented along with derivation of analytical expressions for voltages and currents. The chapter is concluded with the discussion of phase-controlled rectifiers, and single-phase as well as three-phase versions of such rectifiers are studied in detail. The following chapter deals with inverters. It starts with the discussion of single-phase bridge inverters, and the design of bidirectional (bilateral) switches needed for the operation of the inverters is motivated and described. This is followed by the detailed study of pulse-width modulation (PWM) and analytical expressions for spectra of PWM voltages are derived. The chapter is concluded with the discussion of three-phase inverters. The design of ac-to-ac converters by cascading three-phase rectifiers with three-phase inverters is then briefly outlined along with their applications in ac motor drives. The last chapter of the third part of the book deals with dc-to-dc converters (choppers). Here, the buck converter, boost converter and buck-boost converter are first covered, and continuous and discontinuous modes of their operation are studied in detail. The chapter is concluded with the discussion of "flyback" and "forward" (indirect) converters, and physical aspects of their operation are carefully described along with all pertinent analytical formulas.

Each part of the book is supplemented by a list of problems of varying difficulty. Many of these problems are pointed questions related to the theoretical aspects discussed in the text. It is hoped that this may motivate

readers to go through the appropriate parts of the text again and again, which may eventually result in the better comprehension of the material.

We have made an effort to produce a relatively short book that covers the fundamentals of the very broad area of electric power engineering. Naturally, this can only be achieved by omitting some topics. We have omitted the discussion of transmission lines because this subject is usually covered in courses on electromagnetics. We have also omitted the discussion of power system protection and economic operation (optimal dispatch) of generating resources. In our view, these topics are more suited for more advanced courses. In the power electronics portion of the book, we have limited our discussion to the most basic facts related to the circuit topology and principles of operation of power converters. This book has a strong theoretical flavor with emphasis on physical and mathematical aspects of electric power engineering fundamentals. It clearly reveals the multidisciplinary nature of power engineering and it stresses its connections with other areas of electrical engineering. It is believed that this approach can be educationally beneficial.

In undertaking this project, we wanted to produce a student-friendly textbook. We have come to the conclusion that students' interests are best served when the discussion of complicated concepts is not avoided. We have tried to introduce these concepts in a straightforward way and strived to achieve clarity and precision in exposition. We believe that material which is carefully and rigorously presented is better absorbed. It is for students to judge to what extent we have succeeded.

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