VINCENT DEL TORO

Principles of Electrical Engineering

SECOND EDITION

PRENTICE-HALL
ELECTRICAL ENGINEERING SERIES

second edition

PRINCIPLES OF ELECTRICAL ENGINEERING

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principles of
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PRENTICE-HALL SERIES IN ELECTRICAL ENGINEERING

preface
to the second edition

There are two major revisions appearing in this edition: (1) the inclusion of a substantial amount of new material and (2) the reorganization of the original material.

Experience with the first edition disclosed several areas in which reorganization of the subject matter could easily enhance the teaching as well as the studying aspects of the book. The material on electronics has been arranged in a way that now allows the options of either focusing exclusively on semiconductor electronics or else including as much of vacuum-tube electronics as is deemed appropriate. If only semiconductor electronics is to be taught, this can be readily achieved without any loss of continuity by assigning Chaps. 7, 9, and 11 in that order. Chapter 7 is concerned with an exposition of the input-output characteristics of semiconductor devices. Chapter 9 treats the analysis of electronic circuits in which the semiconductor device appears as a circuit element. This is then followed in Chapter 11 by a treatment of the more important special applications of electronic circuits. Because of the far greater importance of semiconductor electronic circuitry in today's technology, attention in Chapter 11 is confined solely to applications involving semiconductor devices.

The treatment of vacuum-tube electronics proceeds in a manner similar to that employed for the semiconductor devices. One Chapter (Chapter 8) is devoted to an explanation of the theory that underlies the input–output characteristics exhibited by these devices, while Chapter 10 concerns itself with their behavior in typical electronic circuits. This material is included for completeness and for the convenience of those who desire to teach vacuum-tube electronics for whatever reasons.

Those fundamental laws relating to electronics, which in the first edition appeared in the first chapter, have now been placed more appropriately in Chapters 7 and 8. Continuity certainly will be better served by this change. Moreover, consistent with this theme, the chapter on Laplace transforms was moved to a place just preceding those chapters where it is first needed.

The material on electromechanical energy conversion has been moved ahead so that it now becomes Part III rather than Part IV. Furthermore, in the interest of facilitating the assignment and handling of the subject matter, it is now divided into eight chapters instead of three. In curricula where relatively little time can be allotted to the study of electromechanical energy conversion, Chapters 12–14 can be used to provide an understanding of the essential elements of the subject matter. In situations where ample time is available, Chapter 14 can be followed by Chapters 15–18 where attention is directed to a description of the operation, characteristics, performance and applications of the various types of electrical machines. In addition to these modifications, some of the heaviness associated with the derivation of the basic torque equations encountered early in the treatment of energy conversion has been lifted by placing the details of the derivations in the appendix.

New material appears in each of the four parts of the book. However, the major portion is to be found in the section devoted to Electronics. Research in this area has continued at an impressive rate and the results have led to the introduction and acceptance by the industry of new and important devices. Accordingly, in this revised edition, considerable attention is given to field effect transistors (FET's), metal oxide semiconductor field effect transistors (MOSFET's) and integrated circuits (IC's). New material also appears in the chapter on electronic circuitry (Chap. 9). There the hybrid equivalent circuit of the transistor is replaced by the simpler h-parameter version. Moreover, throughout the treatment, emphasis is put on the derivation of generalized expressions for current gain and voltage gain for all devices and amplifiers. Linear modelling also receives a good deal of attention.

The section on Circuit Theory has been expanded to include an exposition of duality as well as circuit response to pulse and impulse driving forces.

Another significant change concerns the inclusion of a chapter on direct energy conversion. Thus in Chapter 19 attention is focused on the generation of electrical energy from non-electromechanical sources. This leads to a discussion of the solar cell, the fuel cell, the thermoelectric cell and magnetohydrodynamic energy conversion.

Finally, in Part IV, which now is devoted to control systems and computers, there appears an improved method of magnitude scaling that should go a long way towards eliminating the mystery of scaling that seems to surround the study of the analog computer.

The text material contained herein can be used in a variety of ways depending on the goals to be achieved and the amount of time available. Moreover because the material extends over a wide range, a considerable amount of flexibility is possible. Listed below are some suggestions that might serve as guide lines in the use of the text material:

1. One-quarter course on Electric Circuit Theory
   Chaps. 1–6
2. One-quarter course on Electronics
   Chaps. 7–11
3. One-quarter course in Electromechanical Energy Conversion
   Chaps. 12–19
4. One-quarter course on Control Systems
   Chaps. 20–23
5. One-semester course in Electrical Engineering (no dynamics)
   Chaps. 1–3
   Chap. 6 (select topics as time permits)
   Chap. 7
   Chap. 9 (select topics as time permits)
   Chaps. 12–14
6. Two-semester course on Electrical Engineering
   1st Semester (Course on Circuits & Electronics)
   Chaps. 1–7
   Chap. 9
   Chap. 11
   2nd Semester (Course on Machines & Systems)
   Chaps. 12–21
   Chap. 23
7. One-semester course on Circuits and Energy Conversion
   Chaps. 1–4
   Chap. 5 (secs. 5–1 to 5–4)
   Chap. 6
   Chaps. 12–19
8. One-semester course on Circuits & Systems
   Chaps. 1–5
   Chap. 6 (secs. 6–1 to 6–10)
   Chaps. 20–23

The pace in options 1 to 4 ought to be moderate thus allowing more time for the solution and discussion of additional problems. Option 5 presents a fuller schedule but the pace should prove to be manageable. Options 6, 7, & 8 are much more demanding. Unless the students bring an exceptionally strong background to these courses, it will likely be necessary to eliminate material in several chapters. This will be found particularly necessary if ample class discussion of assigned problems is desired.

preface
to the first edition

The introduction of new devices and the application of basic principles to new situations have been occurring at as rapid a rate in electrical engineering as in the mathematical and physical sciences. However, the amount of time allotted in the curriculum for studying the subject matter is usually no greater than it was in the past and in some instances even less. If students leaving engineering colleges today are to be essentially up-to-date, it becomes necessary every so often to make available text material that adequately reflects the new emphasis on devices and principles. *Principles of Electrical Engineering* was written to achieve this goal.

Twenty years ago the vacuum tube was the cornerstone in the complex structure of electronics. Today, the semiconductor (transistor) is the electronic device of primary importance. Perhaps a few years from now the transistor will be supplanted by an even more revolutionary unit. However, the basic laws governing the behavior of equipment in associated circuitry continue to be valid. For example, Kirchhoff's laws are applicable in a lumped parameter circuit whether the circuit includes a vacuum tube or a transistor. The difference between the two devices is effectively described by the variance in their external characteristics. Thus the manner in which current varies with voltage at the terminals of a semiconductor involves a different principle—diffusion current—than that which applies for the vacuum tube. But the relationship of the vacuum tube or the semiconductor to the other elements of a circuit is still governed by the same unchanging laws of circuit theory.

Emphasis on the fundamental laws of electrical engineering is a theme that is established in the first chapter and referred to often in the development of the subject matter of this book. It is the objective of Chapter 1 to stress the fact that the whole science of electrical engineering is based upon a few experimentally established fundamental laws. Once these principles are grasped and understood, a base is built from which the study of the various areas of electrical engineering follows with considerable ease. Thus electric circuit theory is seen to develop naturally from five basic laws: Coulomb's law, which leads to the concept of capacitance; Ohm's law, which leads to the concept of resistance; Faraday's law, which leads to the concept of inductance; and finally Kirchhoff's voltage and current laws, which provide a systematic formulation of the principles involved in the first three laws. In a similar fashion, the subject matter of electro-mechanical energy conversion is derived from two basic laws: Faraday's law and Ampere's law. The situation in electronics is the same, although a two-part division is necessary. In vacuum-tube electronics, it is the Richardson-Dushman equation and the Langmuir–Child law that are fundamental in describing the properties and characteristics of the vacuum devices. In semiconductor electronics, on the other hand, it is the Boltzmann relationship that is important.

A second major emphasis in this book concerns the use of the Laplace transform as the mathematical language. The Laplace transform has many advantages to offer, and it requires no more than an understanding of integration as a background. Through the Laplace transform, a consistent, systematic, and readily interpretable language is made available for analytical and design purposes. Primarily, the Laplace transform is used in this book to solve linear differential equations, and its application in this connection often means that the transformed solution of a problem may be written in a single step. This method stands in sharp contrast to the classical method of solving such equations. Moreover, the systematic formulation afforded by the Laplace transform permits treating forcing functions and external disturbances in a unified and uniform fashion, thus placing stress on the close kinship the Laplace transform bears to the handling of initial conditions. As a mathematical tool, the Laplace transform provides a generality in analysis that is difficult to match by other procedures. Thus it is an easy matter in the study of electric circuits, for example, to treat the more general problem of the transient response (Chapter 5) before the sinusoidal steady-state response (Chapter 6). This approach also results in other noteworthy dividends. The Laplace-transform formulation leads naturally to the important concepts of transfer functions and transform impedance as operators that not only characterize the system or circuit but also lead directly to the required response functions.

As one gains experience in the use of the Laplace transform, the analytical formulations and the interpretation of the resulting mathematical solutions come easily and naturally irrespective of the area of electrical engineering being studied.

Thus the meaning and the interpretation of a transformed solution is the same whether it be concerned with circuits, amplifiers, control systems, or computers.

Chapter 2 furnishes a treatment of the Laplace transform that is sufficiently detailed for the purposes of this book. As the direct Laplace transforms of many useful functions are developed in the chapter, they are tabulated for future use. No attempt is made to evaluate the inverse Laplace transform, because this requires a knowledge of integration in the complex plane, which is usually beyond the scope of undergraduate courses in mathematics for engineers. Instead, the inverse operation is performed through the use of tables. There should be no objection to such a procedure, since we often resort to the use of appropriate tables in evaluating logarithms or certain difficult integrals.

Finally, it is worthwhile to note that the use of the Laplace transform does not involve the loss of any physical insight to a problem. Initial conditions are handled in a direct and systematic fashion irrespective of the order of the system. Then, when the transformed solution is obtained, one may apply the initial- and final-value theorems to get information about the variable as well as its derivatives.

This book is written for a one-year course in electrical engineering for non-electrical majors. However, it can also be used for electrical majors, particularly when the amount of time allotted to this material is restricted as it is in an engineering science curriculum. A satisfactory syllabus for electrical majors is possible for two reasons. One, no compromise was made in the rigor or depth of the treatment of the subject matter. Prepublication experience with this material has indicated that the nonelectrical majors are in favor of such an approach. Two, sections specifically for electrical majors have been included in most of the chapters. The beginning of each of these sections is indicated by a double slash style mark in line with the left margin. A single slash mark precedes the subtitles, and a double slash mark in line with the right margin identifies the close of the section.

The book is divided into four major parts: Electric Circuit Theory; Electronics; Control Systems and Computers; and Electromechanical Energy Conversion. This selection was made to meet the needs of the nonelectrical majors in terms of today's requirements. The treatment of electronics gives due recognition to the importance of semiconductor devices by placing more emphasis on them than on vacuum tubes. This is the first extensive treatment of the subject matter in a book of this kind. A second area of major departure occurs in Part III where there is presented the first stand-alone treatment of control systems. More and more, nonelectrical majors, such as mechanical, aeronautical, and chemical engineers, are in need of firmer and more extensive background in this area.

Part I is devoted to an exposition of the theory of electric circuits. This is begun in Chapter 3 by a discussion of circuit parameters as they derive from the fundamental laws. An outstanding feature here is that each parameter is treated from three viewpoints: circuit, energy, and geometry. In this way a complete rather than a partial picture results. How often does it happen that a student knows how to identify inductance in terms of current and voltage (circuit viewpoint), but has no idea about what to do to change its value (geometrical viewpoint)? Chapter 4 concerns itself with the elementary network theorems. In the interest of placing maximum emphasis on the theorems, networks consisting solely of resistors are used, thereby freeing the treatment of the clutter of complex numbers. The subject matter is developed in a logical fashion. The response of a network is found first by the more cumbersome methods of network reduction and superposition. Improvements in the solution process, through the use of mesh currents and node-pair voltages, are then revealed. When the situation warrants, further simplifications are effected by the use of Thevenin's and Norton's theorems. The chapter is amply illustrated with examples. Chapter 5 deals with the forced and transient responses of circuits to standard forcing functions. An important feature of this chapter is the solution of a second-order system in terms of figures of merit that make the solution universally applicable to all linear second-order systems irrespective of composition. Chapter 6, designed to serve both electrical and nonelectrical majors well, presents an extensive treatment of the important topic of the sinusoidal steady-state response of circuits.

Part II is devoted to an exposition of electronics. Chapter 7 describes the external characteristics and control capabilities of diodes and triodes of both the semiconductor and vacuum-tube types. Once the theoretical explanations are given, the devices are then expressed in terms of appropriate circuit parameters so that the powerful tools of circuit analysis may be conveniently applied in the circuits where they appear. Chapter 8 covers the chief topics necessary to an understanding of electronic circuits. It is concerned with the behavior and performance calculations of circuits that use diodes and triodes for control and amplifying purposes. The topic is handled with the systems concept in mind, the amplifier being discussed not for its own sake, but rather as a part of an overall system. Accordingly the two-stage, then the three-stage, and finally the four-stage amplifiers are analyzed, with the latter arrangement representing an intercommunication system. In Chapter 9 attention is directed to some special topics and electronic circuit applications, including transistor logic circuits.

Part III deals with control systems and computers. The underlying principles of automatic control are carefully explained and illustrated in Chapter 10 with examples from various fields of engineering. This is followed in Chapter 11 with a general treatment of the dynamic behavior of control systems. Here the student is exposed to systems analysis by dealing directly with the differential equation approach as well as with the transfer function approach. The advantages and the implementation of such procedures as error-rate, output-rate, and integral-error control are also described. The combination of Chapters 10 and 11 should provide a sufficiently strong background in control system theory where the time in the curriculum is limited. Chapter 12 is recommended for a more extensive treatment of the subject matter. Here the technique of describing the dynamic behavior of a system by the sinusoidal steady-state frequency response is described. Part III ends with a discussion of the manner in which the analog computer can be used to solve differential equations, linear or nonlinear.

Electromechanical energy conversion is the topic of Part IV, which begins with a chapter on magnetic theory and circuits, thus providing the background needed for the study of electrical machinery. Chapter 15 deals with the theory and operation of the transformer, which is a prerequisite to the study of a-c machinery. The first part of Chapter 16 is devoted to an analysis of the general expression for electromagnetic torque as derived from Ampere's law and an analysis of induced voltages as derived from Faraday's law. The treatment is kept as general as possible to stress that the same basic laws underly the operation of a-c and d-c machines. Once this objective is achieved, attention is directed to a description of the operation, performance, characteristics, and applications of the various categories of electrical machines: the three-phase induction motor, the three-phase synchronous motor, the d-c machines, and the single-phase induction motor. To make this treatment of machinery as useful as possible for the nonelectrical majors, particular attention is given to the ratings and applications of electric motors which are conveniently summarized in suitable tables. Controllers for these motors are also discussed quite extensively. When this text is used for a two-semester course for nonelectrical majors, the instructor must be selective in treating the subjects of Part IV, since such a great deal of material is covered.

As mentioned previously, *Principles of Electrical Engineering* may be used as an introduction to electrical engineering for electrical majors. Part I (Electric Circuit Theory) can very well serve as a prerequisite to a full course devoted to networks. Similarly, Part II taken in its entirety can precede a full course in electronics, before attention is given to advanced topics. A detailed study of Chapter 10–12 can readily be used as the preparation for a beginning graduate course in control systems. Finally, the material in Part IV was planned so that it could also meet the needs of a one-semester course in electric machinery for electrical majors.

It is with pleasure that I acknowledge gratitude to my colleagues and friends at The City College of New York for the fruitful technical discussions I have had with them. I want also to express my sincere appreciation to Miss Sadie Silverstein, administrative assistant of the Electrical Engineering Department, for her truly outstanding performance in assisting with the preparation of the manuscript.

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