Electric Circuits Fundamentals

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PREFACE

This book is designed to serve as a text for a first course or course-sequence in circuits in an electrical engineering curriculum. The prerequisites or corequisites are *basic physics and calculu*s. Special topics such as differential equations and complex algebra are treated in the text as they arise. The book can be used in a two-semester or in a three-quarter course sequence, or in a single-semester course.

The goal of the book is twofold: (*a*) to teach the **foundations of electric circuits**, and (*b*) to develop a thinking style and a problem-solving methodology based on **physical insight**. This approach is designed to benefit students not only in the rest of the curriculum, but also in the rapidly changing changing technology that they will face after graduation.

Since the study of circuits is the foundation for most other courses in the electrical curriculum, it is critical that we guide the reader in developing an **engineering approach** from the very beginning. Armed, on the one hand, with the desire to finally apply the background of prerequisite math courses, and overwhelmed, on the other, by the novelty and wealth of the subject matter, students tend to focus on the mathematics governing a circuit without developing a sufficiently deep feel for its physical operation. After all, circuit theory possesses a mathematical beauty of its own, and many a textbook emphasizes its abstract aspects without sufficient attention to its underlying physical principles, not to mention applications. Quite to the contrary, we believe that the role of a circuits course is to provide an engineering balance between **mathematical conceptualization** and **physical insight**. Whether analyzing existing circuits or designing new ones, engineers start from a physical basis and then resort to mathematical tools to gain a deeper and most systematic under-standing. But, in the true spirit of engineering, results are ultimately checked against physical substance, not just mere mathematical abstraction. This is especially true in computer-aided analysis and design, where results must be interpreted in terms of known physical behavior. Students who are not given an early opportunity to develop physical intuition will subsequently have to do so on their own in order to function as engineers. This book was written to provide this early opportunity without necessarily watering down the mathematical rigor.

As an enthusiastic practitioner of circuit theory, the author firmly believes that a circuits course should be accompanied by a **laboratory** to provide experimental reinforcement of the theory as well as to introduce the student to instrumentation and measurements. Whenever the opportunity arises, we attempt to relate concepts and principles to laboratory practice, but we do so without disrupting the flow of the material. Lacking a laboratory, the use of SPICE should be promoted as a **software breadboard** alternative for trying out the circuits seen in class. Moreover, the Probe graphics post-processor available with PSpice provides an effective form of **software oscilloscope** for the visualization of waveforms and transfer curves. Ultimately, however, the student must be stimulated to interpret SPICE results in terms of known physical behavior.

PEDAGOGY AND APPROACH

The material covered is fairly standard in terms of topic selection. To prevent excessive conceptualization from obfuscating the physical picture, the book tries to be as mathematically rigorous as needed. Moreover, to maintain student interest and motivation, it attempts, whenever possible, to relate the theory to real-life situations. In this respect, ideal transformers and amplifiers are introduced early enough to stimulate the reader with a foretaste of real-life engineering. The book also makes extensive use of the operational amplifier to provide sa practical illustration of abstract but fundamental concepts such as impedance transformation and root location control, always with a vigilant eye on the underlying physical

basis. To this end analogies are often drawn to non-electrical systems such as mechanical and hydraulic systems.

To comply with ABET's emphasis on integrating **computer tools** in the curriculum, the book promotes the use of SPICE as a means for checking the results of hand calculations. The features of SPICE are introduced gradually, as the need arises. SPICE coverage has been kept separate from the rest of the material, in end-of-chapter sections that can be omitted without loss of continuity.

Each chapter begins with an **introduction** outlining its objectives and its relation to the rest of the subject matter, and it ends with a **summary** of its key points. Whenever possible, chapters and sections have been designed to proceed from the *elementary* to the more *complex*.

The text is interspersed with **351 worked example**s, **414 exercise**s, and **1000 end-of-chapter problem**s. The goal of the examples is not only to demonstrate the direct application of the theory, but also to develop an engineering approach to problem solving based on *conceptual understanding and physical intuition* rather than on rote procedures. It is felt that if students are given the opportunity to identify a basic core of principles and a common thread of logic, they will in turn be able to apply these principles and logic to the solution of a wide range of new and more complex problems.

In the solution of the numerous examples, the book stresses the importance of *labeling*, *inspection*, *physical dimensions*, and *checking*; critical points are highlighted by means of **remarks**. Students are continually challenged to question whether their findings make physical sense, and to use alternative approaches to check the correctness of their results.

The exercises are designed to provide immediate reinforcement of the student's grasp of principles and methods, and the end-of-chapter problems are designed to offer additional practice opportunities. For the convenience of students and instructors alike, the problems have been keyed to individual sections. To give students a better appreciation for the human and historical sides of electrical engineering, each chapter contains an essay or interview. Subjects include biographies of famous inventors, interviews with well-established engineers and recent graduates, and topics of current interest.

CONTENT

Following is a coarse content description. Additional details and rationale considerations can be found in the introductions to the individual chapters.

Chaptes 1-4 introduce basic *circuit concept*s, *law*s, *theorem*s, and *analysis techniques* for circuits consisting of *resistances* and *independent source*s. Dependent sources and energy-storage elements have been deferred to later chapters because it is felt that the student should first develop an intuitive feel for simpler circuits. To facilitate this task, we have tried to contain circuit complexity, but without sacrificing generality. In fact, many of the circuits and procedures are of the type engineers see every day.

Anticipating a concurrent laboratory, the book introduces early on basic signal concepts such as average and rms values. The emphasis on *i-v curves* to characterize not only individual elements but also one-ports is designed to provide a more intuitive framework for *Thevenin and Norton theorem*s. Much emphasis is placed on the concepts of *equivalenc*e, *modelin*g, *loadin*g, and the use of *test sources* to find equivalent resistances. The analytical advantages of circuit theorems are demonstrated with one-ports driving *linear* as well as *nonlinear* loads such as diodes and diode-connected BJTs and MOSFETs. However, this brief exposure to nonlinear techniques, designed to provide also a foretaste of electronics, can be omitted without loss of continuity.

Chapter 5 discusses *dependent sources* and their application to the modeling of simple two-ports such as *ideal transformers* and *amplifier*s. This material is designed to motivate the reader with practical applications and also to provide further opportunities for practicing with the analytical tools of the previous chapters. Additional applications are presented in **Chapter** 6, but using the *op amp* as a vehicle. We have chosen basic *instrumentation circuits* that are of potential interest to EE majors and nonmajors alike, and that can easily be tried out in the lab or simulated via PSpice.

Chapters 7-9 deal with the *time-domain analysis* of circuits containing *energy-storage element*s. The discussion of the natural response emphasizes energetic considerations. The complete response is investigated via the integrating-factor method in order to provide a rigorous treatment of its *natura*l, *force*d, *transien*t, *DC steady-stat*e, and *AC steady-state* components. **Chapter 8** deals with the transient response f *first-order circuit*s, including switched networks and the step, pulse, and pulses-train responses of *RC* and

RL pairs; **Chapter 9** investigates *transients in RLC* and *second-order KRC circuits.*

Significant attention is devoted to correlating response characteristics to root location in the *s* plane. In this respect, the book demonstrates the use of the op amp to effect *root location control* both for first-order and second-order circuits, and investigates the *physical basis of converging, steady, and diverging response*s. It is felt that combining simple physical insight with the pictorial immediacy of s-plane diagrams should help demystify the material in anticipation of the network functions and transform theory of subsequent chapters. However, depending on curricular emphasis, the s-plane material can be omitted without loss of continuity.

Chapters **10-13** cover *AC circuit*s. After introducing phasors as graphic means to emphasize amplitude and phase angle, the book uses time-domain techniques to develop a basic understanding of AC circuit behavior, especially the *frequency response* and its relationship to the *transient re-spons*e. Then, phasor techniques are developed, and the concept of *AC impedance* is used to in-estigate *AC power, polyphase system*s, and *AC resonanc*e, and also to illustrate practical applications thereof. To provide the reader with a foretaste of electronics, the op amp is now used to demonstrate *impedance transformations* as well as *resonant characteristics control in inductor-less circuit*s; but, again, this last material can be omitted without loss of continuity.

Recognizing the difficulties encountered by the beginner in trying to reconcile complex variables and physical circuits, the book uses the correspondence $dx/dt \leftrightarrow j\omega X$ and $\int x dt \leftrightarrow X/j\omega$ to introduce phasor algebra from a time-domain perspective, and to develop the subject from a decidedly circuital viewpoint. Moreover, it gives equal weight to single-frequency phasor analysis for AC power and variable-frequency analysis for communication and signal processing.

Chapter 14 generalizes phasor techniques to *network-function techniques* in order to provide a unified approach to the study of the *natural, forced, transient, steady-state,* and *complete response,* as well as the *frequency response*. The *physical significance of zeros and poles* is investigated in depth, along with the effect of their s-plane location upon the characteristics of the various re-ponses. This chapter emphasizes dimensional and asymptotic verifications, and provides an exhaustive treatment of *Bode diagram*s, including the use of PSpice to generate frequency plots of network functions.

We have chosen to introduce network functions via *complex exponential signal*s, rather than via Laplace transforms, to comply with the many curricula that defer Laplace to courses other than circuit courses. But, if desired, one can rearrange the material by omitting the first part of Chapter 14 and appending the remainder to the end of Chapter 16, which covers Laplace transforms.

Chapter 15 discusses *two-port network*s, and it applies the two-port concept as well as network-function techniques to the study of *coupled coil*s. Two-port measurements and modeling are illustrated via a variety of examples, including transistor amplifiers and linear transformers.

Chapters 16 and 17 provide an introduction to *Laplace* and *Fourier technique*s. True to our intent to proceed from the elementary to the more complex, we present the Laplace approach as a generalization of the network-function approach of Chapter 14. Using a variety of examples, we demonstrate its ability to accommodate a wider range of forcing functions, to account for the initial conditions automatically, and to provide a more systematic link between the *time-domain* and the *requency-domain* behavior of a circuit via the *initial-value* and *final-value theorem*s, the *impulse response*, and *convolutio*n. The treatment stresses the *physical basis* of the *step* and *impulse response*s, and of the natural and forced response components.

Fourier techniques are presented as a better alternative to Laplace techniques in those situations in which the focus is on the *information and energy content of a signal* as well as the manner in which a circuit processes this content. Though some authors introduce Fourier before Laplace, our desire to emphasize *Laplace as a circuit-analysis tool* and *Fourier as a signal-processing tool* has led us to introduce Laplace first, as a generalization of the network-function method. Moreover, even though the Fourier transform could be introduced on its own terms, we find it physically more enlightening—if mathematically somewhat less rigorous—to introduce it as a limiting case of the Fourier series.

Applications of both the Fourier series and transform are demonstrated via a variety of signal and circuit examples emphasizing input and output spectra. Moreover, the effects of filtering are illustrated both in the time domain and the frequency domain. We conclude with practical comparisons of the Laplace and Fourier transforms.

COURSE OPTIONS

This book can be used in a *two-semester* or *three-quarter* course sequence, or in a *single-semester* course.

In a *two-semester* sequence the first semester typically covers the material up to AC power (Section 12.2), and the second semester covers the remainder of the text. In a *three-quarter* sequence the material can be subdivided as follows: Chapters 1-8, Chapters 9-14, and Chapters 15-17.

For a *single-semester* course we identify two options: (*a*) an option emphasizing *analytical techniques* and covering approximately the same material as the first course of the two-semester sequence; (*b*) an option emphasizing *specialized areas* and thus including specific chapters or sections. An emphasis in *power* would include Section 5.3, all of Chapter 12, and the second half of Chapter 15; an emphasis in *electronics* would include Section 5.4, Chapter 6, and parts of Chapter 14; an emphasis in *systems* would include Chapters 8, 9, 14, 16, and 17. To facilitate omissions without loss of continuity, the optional material identified by the symbol • usually appears at the beginning of sections or chapters.