FUNDAMENTALS OF CIRCUITS, ELECTRONICS, AND SIGNAL ANALYSIS

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PREFACE

This text is primarily intended to be used in an introductory course for electrical engineering majors. It is designed to serve as a text for a preparatory course for other, higher-level courses in several areas. It begins with a treatment of simple circuits. Then it presents general techniques of network analysis. It then uses these techniques to introduce the student to basic electronics. These analyses of electronic circuits also serve, at the same time, as exercises for the study of circuit analysis. After that, we turn our attention to the analysis of signals, both in the time domain and in the frequency domain, as well as their interrelationship in these two domains. These ideas are further generalized into the systems concept, using networks as examples. To some extent, this approach unifies several basic topics — some of which are common or overlapping — in circuits, electronics, transforms, signal analysis, and systems.

Because of this unified approach, the student will not have to repeat the same topics that used to appear in several texts in the same curriculum. These topics are instead viewed as the same background material for several areas, such as networks, system theory, devices, electronics, communication, power, control engineering, instrumentation, digital systems, and computers. It is particularly suited for curriculums in which students are not required to take higher-level courses in all the aforementioned areas. In these curriculums, the course in which this text is used will be the terminal course for those students whose programs do not indicate further courses in areas in which they are not specializing.

The text can also be used for an introductory course in electrical engineering for students in allied fields whose interest in electrical engineering requires a more definitive treatment than can be found in a general superficial survey of all topics in electrical engineering. It is particularly suited to students whose future careers will be benefited if they understand the basic principles and terminology in certain areas in electronics and electrical engineering. These students include those in many branches of engineering and technology, physics, chemistry, mathematics, computer science, biological sciences, medicine, behavioral science, and so forth.

The fields of electrical and computer engineering have broadened so much in the last few decades that it is no longer possible to cover every subarea in the same depth as used to be possible in a four-year curriculum in these fields. Yet these subareas are all somewhat interrelated. Hence some tradeoff between depth and breadth is necessary. One option in designing an electrical-engineering curriculum is to have a broad requirement at the basic level and to allow the student to choose — and pursue in depth — only a few of the many subareas. Also this approach makes it possible to present some of the overlapping topics more efficiently. This text is designed to accomplish some of these goals.

Another important need that this text is designed to meet is the need of many engineers and scientists whose specialties are not in traditional electrical engineering. These people often find that they are working more and more closely with electronics. A basic text that would enable them to become somewhat conversant with areas such as circuits, electronics, instrumentation, computers, and so forth, would be extremely helpful in their careers.

On the basis of the foregoing reasons, we have adopted the following editorial practices.

1 The treatment of devices is confined to qualitative descriptions and terminal characteristics. We believe that the best place to treat devices in detail is in a separate course dealing with the physics of materials and devices.

2 Although considerations of aspects of engineering design are occasionally touched on, the emphasis in this volume is primarily on basic principles and methods of analysis.

3 We assume that the student has had only basic courses in calculus and physics. Beyond that there is no real body of knowledge in mathematics that is absolutely needed for this text. There is an appendix on matrices, which is organized as if it were a chapter.

4 The chapter on state variables is quite independent of the rest of the text, and may be omitted from a course if the instructor so desires. Some instructors regard this topic as very basic. Others argue that it is best introduced where this method is most useful — in system theory, computer-aided analysis or design, nonlinear systems, time-varying systems — but not as a basic tool. We feel that it should be taught in a basic course, but not as a prerequisite for the bulk of the material.

5 The chapter on digital circuits is also organized as a self-contained entity. This level of treatment is adequate for a survey course.

6 The style of presentation emphasizes conciseness and brevity. This is done for two reasons. Since we are assuming that the instructor will maintain a fairly rapid pace in covering the material in the text, a more detailed and wordy exposition would tend to distract the mainstream of thought. The other reason is a practical one: A detailed treatment of every topic would lead to a book that was just too voluminous. But we believe that the extent and thoroughness of our coverage is quite adequate for the purposes for which it is intended.

7 For similar reasons, we choose to emphasize plausibility, rather than rigor. We believe that most engineering students benefit more from practical aspects of engineering, correctly handled, than from abstractions and over-exacting treatment of the subject matter. Occasionally, we rely on examples to illustrate certain points.

Chapter 1 gives basic definitions of terms and symbols used in the text, and terminal characteristics of resistance, inductance, capacitance, and controlled sources. The descriptions of these elements are not confined to linear time-invariant aspects, but are general in their applications.

Chapter 2 introduces Kirchhoff's voltage and current laws, and develops several simple relationships and techniques of analysis based on these laws, using simple memoryless circuits to illustrate them. In order to save time, topological considerations of networks are implemented right on the network diagrams rather than on separately constructed graphs.

The concept of linear networks is first defined in Chapter 3, which describes several special properties of linear networks in the form of network theorems. We introduced Tellegen's theorem here, though its validity is not restricted to linear networks, because there is really no other logical place for it in this volume.

Energy-storing elements begin to appear in circuits in Chapter 4. Here we treat some simple circuits involving memory elements, more to illustrate how complicated these circuit problems can be than to attempt to develop any general method of treating complicated memory networks. These examples also serve to show the roles of a certain special class of differential equations in memory networks and lead to the formulation of ac-circuit problems and the introduction of the complex frequency variable in Chapter 5.

We approach the notion of ac circuit analysis from the viewpoint of the solution for the steady-state response of a network with exponential excitations. We then extend the analysis techniques developed for memoryless networks in Chapters 2 and 3 to circuits with complex-number elements and source strengths. Several aspects of ac power, including the maximum-power theorem, are then examined.

Chapter 6 treats circuits with nonlinear and linear memoryless elements, with particular attention being paid to circuits with diodes as nonlinear elements. We give qualitative descriptions of some diodes, but the emphasis is on their terminal characteristics. We also give some applications of these circuits.

Up until this point, we have been concerned only with two-terminal elements. Before delving into electronic circuits, Chapter 7 presents some basic rules and techniques for handling multi-terminal or multi-port devices. It emphasizes how networks with two ports are analyzed when they are unterminated, terminated in an impedance, or interconnected. Amplifiers, magnetically coupled inductors, and ideal transformers appear as two-ports in networks and systems. Chapter 7 also gives examples on how to handle three-terminal devices, such as transistors.

Chapters 8, 9, and 10 treat the basics in electronics: the field-effect transistor, the bipolar transistor, the vacuum tube, integrated circuits, and the operational amplifier. When appropriate, three types of problems are treated — the dc, the slow-varying large-signal, and the small-signal ac. Here the emphasis is on acquiring a facility in analyzing a given circuit and an understanding of the underlying principles rather than on considerations of design, formulas for specific circuits, or specialty circuits. Up to this point, all electrical quantities are either dc, single-frequency sinusoidal, or some special functions of time.

In Chapter 11, we begin to look into methods of determining the performance of networks when the frequency is varied. In Chapter 12, we carry out network analysis in the time domain.

Our exposition of the concept of transforms begins with the idea of Fourier series expansion of periodic quantities in Chapter 13. This admittedly is a purely mathematical topic. However, by identifying these series with electrical quantities in circuits, we are able to give some physical significance to the connection between the time domain and the frequency domain. We then extend this concept to nonperiodic quantities in Chapter 14, which deals with the Fourier integral. In Chapter 15, we treat the two-sided Laplace transform as a generalization of the Fourier transform by replacing $j\omega$ by s and interposing the regions of convergence. Then we specialize the two-sided transform to the one-sided transform. Thus we do not emphasize the Laplace transform as being a tool for solving network problems, although we do include this application. On the whole, Laplace transform is treated from the standpoint of both circuit-analysis and signal-analysis techniques.

Chapter 16 gives an account of the state-variable method as it applies to linear networks. Perhaps this is not the best way to show the versatility and outstanding features of this method. But to do it any other way would be impractical in this volume.

The last chapter gives a survey of the fundamentals of digital circuits. It defines basic binary operations and gates, then gives examples of what they do, how they work, and how they can be constructed.

Three appendixes are included. Appendix A gives proofs of several theorems stated in Chapter 3. Appendix B presents pertinent topics in matrix algebra. The instructor can use this appendix as a regular chapter, if a curriculum is so designed that this topic is taught — or should be reviewed — in the course sequence covering the material of this text. (A logical place to use it would be between Chapters 6 and 7.) Appendix C gives answers to selected homework problems.

The text is ideally suited for a three-semester or a four-quarter sequence if all topics included are to be covered adequately. Of course, the number of hours in each term depend somewhat on the overall curriculum. Our estimate is that nine semester-hours or twelve quarter-hours would be typical.

The instructor can also adapt this text to suit many other curriculum needs by selecting only certain appropriate topics. For example, a three-quarter course for E.E. majors may cover only the first 15 chapters. Or a two-quarter survey course in electronics may include only Chapters 1, 2, 3, 4, 5, 6, 8, 9, 10, and 17, plus part of Chapter 7, with possible omissions of topics such as Tellegen's theorem, indefinite admittance matrix, and the like. Another possibility would be to leave out the electronics part of this volume (Chapters 8, 9, 10 and 17) and use the text in a course in circuits and signal analysis. All these combinations are feasible without disruption or discontinuity in the presentation of the course material.

This book is the outgrowth of a set of class notes prepared for several basic courses at Georgia Tech in the last five years. While the manuscript of this book was being prepared and class-tested, many of my colleagues and students have been inconvenienced. They had to put up with the various forms of reproduction of early versions of the manuscript. I don't feel that an apology to them would be appropriate, although I do appreciate their patience and support. Rather, I wish to say that I sincerely feel that they all had a part in the preparation of the manuscript. To those who offered suggestions and comments, I am deeply grateful. I want especially to thank my dear friend and colleague, Professor Thomas M. White, for his careful reading of the final manuscript. I am also indebted to Professor John Carr, of the University of Pennsylvania, Professor Harvey Doemland, of the University of Kansas, Professor Ward J. Helms, of the University of Washington, and Professor R.P. Santoro, of the U.S. Naval Academy, for their constructive comments on the book during its various stages of development.

I owe a special debt of gratitude to my life partner, Jennifer, for her patience and understanding during the preparation of this book.

K. L. S.

CONTENTS

1 PRELIMINARIES AND CIRCUIT ELEMENTS

1.1 Introduction

We live in an age of highly developed technology: instant communication, extremely high mobility, extensive computerization, and space explorations. We can safely state that these feats would not have been possible without the advent of electrical and electronics engineering. The four major areas of this engineering field are: analog systems, digital systems, electromagnetic field theory, and properties of materials. This volume deals with the basic tools and concepts in two of these areas: *analog systems* and *digital systems*.

The mathematical tools used in this area are, to a great extent, common to a large variety of systems, such as mechanical, acoustical, hydraulic, commodity flow, and of course electrical systems. You should keep in mind that most of the techniques you are going to learn here are directly applicable to many other systems.

In an analog system, electrical quantities may assume any values, sometimes within a certain range. In a digital system, the quantities can assume only certain discrete values, or ranges of values. In a binary system, a quantity may assume one of two values, say, either 1 or 0. In a trinary system, a quantity may assume only one of three values, say, 2, 1, or 0. And so on.

An interconnection of a number of electrical *elements* is called an electric *circuit*, *network*, or *system*. Usually a relatively simple interconnection is known as a *circuit*. A more complex interconnection is known as a *network*. The term *system* usually connotes an interconnection of components each of which is a circuit, a network, or another system. There is no clearly definable line of demarcation among these three terms. They are strictly subjective. Thus, for our purposes, these three terms may be used interchangeably.

A circuit can be used to deliver power, to process or transmit signals, to measure a physical quantity, or to store information. Whatever the purpose, the function of a circuit is usually manifested in the magnitude or time variation of either a *voltage* or a *current*. An *input* of a circuit is the locality at which a voltage or current is applied. An *output* is the locality at which a voltage or current is observed. The electric quantity (voltage or current) applied at the input is called the *excitation*, *input*, or *stimulus*. The quantity at the output is known as the *response*, or, more simply, the *output*. Generally both the excitation and the response—as well as all internal quantities of a circuit—are functions of time. If these functions of time are specified for *all* time, then we have a *continuous-time system*. If the values of these functions at only certain fixed instants are of interest, then the system is a *discrete-time system*. Figure 1.1 illustrates how a system quantity may be analog or digital, and may be either a continuous-time or a discrete-time system.

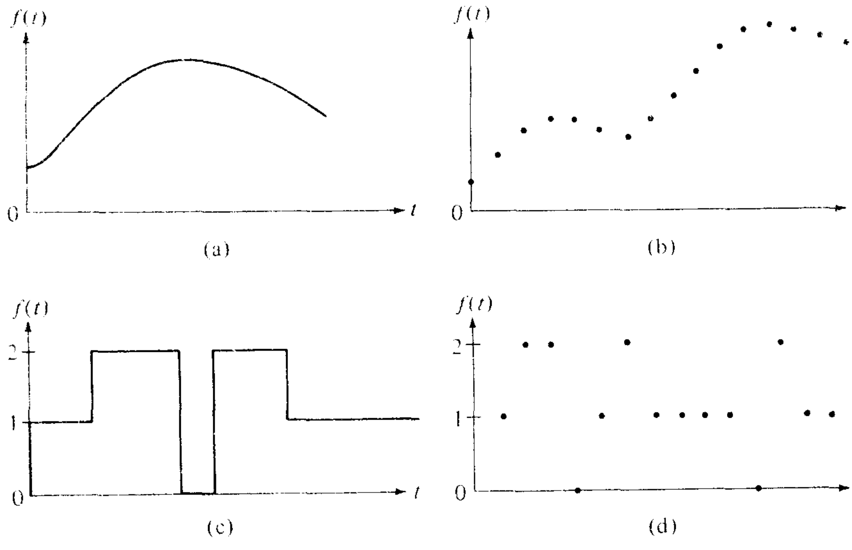

Figure 1.1 A quantity in (a) a continuous-time analog system, (b) a discrete-time analog system, (c) a continuous-time digital (trinary) system, and (d) a discrete-time digital (trinary) system.

In this volume, we shall deal exclusively with the *analysis* of electrical systems. In an analysis problem, a circuit and one or several inputs are given, and the output or outputs are to be found. In a more difficult type of problem—the *synthesis* or *design*—one or several inputs and their corresponding desired output(s) are given, and a circuit is to be found or designed.

1.2 Basic symbols and notation

A circuit *element* is usually a mathematical model of a physical device. It represents the external electrical behavior of the device in mathematical terms. In representing a physical device by a circuit element, we almost always need some approximation. Hence it is extremely important to keep in mind the limited ability of the circuit element to represent its real-world counterpart accurately. Within these limitations, however, we shall regard these models as the *exact* representation of the corresponding device and apply all facilities and finesses at our disposal to attack the problem at hand. But we must exercise due precautions in interpreting our results.

We shall assume that you are sufficiently familiar, from physics courses, with the basic electromagnetic quantities listed in Table 1.1. Certain frequently used prefixes that indicate multiples or submultiples are given in Table 1.2 for your reference.

Table **1.1** Some basic physical quantities

Quantity	Unit	Abbreviation
Time	second	s
Electric charge	coulomb	C
Electric current	ampere	A
Voltage (potential difference)	volt	V
Magnetic flux	weber	Wb
Energy	joule	J
Power	watt	W

Table **1.2** Prefixes and abbreviations for multiples and submultiples

Multiple or submultiple	Prefix	Abbreviation
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

A *terminal* is simply a connecting point or junction in a network. The physical counterpart of a terminal may be either a *terminal post* or a *soldered joint*. It is represented by a small dot—solid or hollow—as shown in Figure 1.2(a).

A *short circuit* (or simply *short*) is a path along which an electric current is free to flow. A short circuit may represent a highly conducting wire. It is also frequently used to connect points in a network that have the same potential. It is represented symbolically by a solid line, as shown in Figure 1.2(b).

An *open circuit* is a condition in which no electric current can flow between two points. This situation is represented by the lack of a path, as illustrated in Figure 1.2(c).

A *switch* connected between two terminals places a short circuit between the two terminals when it is *closed*, and an open circuit when it is *opened*. The latter status is shown in Figure 1.2(d).

A *grounded terminal* or *ground* is one whose absolute potential is assumed to be zero. A grounded terminal may be merely one whose potential is used for reference purposes. Or else it may be the representation of an actual grounding, achieved by physically connecting that point to earth. The symbol for a ground is shown in Figure 1.2(e).

In electrical engineering, an *electric potential* is more commonly known as a *voltage*. The absolute potential at a point is the voltage of that point (above ground). The relative potential between two points is the voltage difference between those points. There are two ways to describe the voltage difference between two points: (1) The *voltage rise* from A to B is the amount of voltage by which B exceeds A. (2) The *voltage drop* from C to D is the

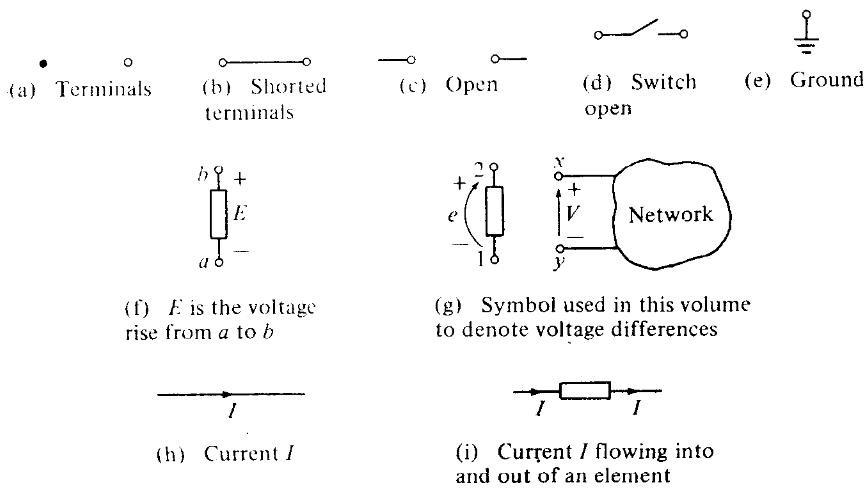

Figure 1.2 Some basic notations and symbols.