Circuits and Signals: An Introduction To Linear and Interface Circuits

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Preface

This book evolved from teaching an introductory circuits course over several years. In writing it, our objective was to merge the essentials of linear circuit theory with the imperatives of integrated circuit technology. An electronic world dominated by chips is a world dominated by digital systems. As a result, the applications of classical linear circuits have been driven to the periphery of the system—its interfaces.

The digital domain moreover is dominated by design, rather than by analysis considerations. In this regard it is important to distinguish between the design *of* integrated circuits and design *with* integrated circuits. The former (design of) requires the ability to deal with large-scale circuits, with an attendant emphasis on the concepts needed to understand computer-aided circuit analysis and design. The latter (design with) basically implies the interconnection of standard, commercial assemblies. Design in this context normally involves only relatively simple circuits that are invariably located at the interfaces between chips.

The purpose of this book is to develop the viewpoint and skills that ultimately will lead to an ability to design *with* integrated circuits. The focus of the book is perhaps best captured in its subtitle—*An Introduction to Linear and Interface Circuits*. In pursuit of this focus there is an early introduction to the concept of a circuit interface as a pair of terminals at which certain signal conditions may be prescribed or observed. There is also an integrated treatment of the premier linear interface device—the OP AMP. Over the past decade or so the OP AMP has revolutionized the way in which electrical engineers design linear circuits. Its inclusion in a book that first teaches them how to think about linear circuits is clearly necessary.

The content is packaged in three blocks. Block I (Chapters 1–5) treats most of the classical topics of circuit theory in the context of resistance circuits and introduces the OP AMP as a circuit element. A central theme of this block is that circuit response is the result of constraints that arise from two sources: circuit connections and circuit devices. This theme reappears in several places and is crucial to the development in later chapters. Block II (Chapters 6–10) introduces time-varying waveforms and energy storage elements, or memory elements as we call them. This is followed by an introduction to the classical methods of solving first- and second-order linear differential equations, and an axiomatic introduction to the Laplace transformation. This block culminates with the concept of transforming the circuit into the *s*-domain and viewing the circuit response in terms of transforms rather than waveforms. Block III (Chapters 11–13) presents three important applications of the *s*-domain approach: step response (transients), sinusoidal response (phasors), and frequency response (filters). This area makes extensive use of the pole-zero approach to explain the results.

An important organizational feature of the book is the use of Bloom's taxonomy[1] to provide a framework of educational objectives and supporting homework. *En route Objectives* are explicitly listed at the end of each chapter. The *Exercises* related to the en route objectives are designed to test mastery at the knowledge, comprehension, and application levels of the taxonomy. The *Problems* at the end of each chapter require the integration or extension of several en route objectives and, as such, often test mastery beyond the application level. *Block Objectives* listed at the beginning of each block require the integration of en route objectives across several chapters and provide opportunities to encourage creativity. The problems supporting the block objectives are given in Appendix A and are designed to test mastery at the analysis, design (synthesis), and evaluation levels of the taxonomy. This framework of objectives allows the development of well-organized courses in which students need never ask what they are expected to know.

The book is intended to provide the foundations for subsequent courses in electronics and in systems, and it contains sufficient material for a two-semester sequence if all en route and block objectives are used. Two-quarter and one-semester treatments are possible by the proper selection of en route objectives and reduction of the expected level of achievement in the block objectives. Some examples of en route objective selections are shown in Table 1, included as part of this preface. This basic coverage can then be followed by different application emphasis, as suggested in Table 2, which follows Table 1. These examples illustrate that it is possible to maintain an unambiguous framework of objectives for the student. A

	Basic En route Objectives	
Chapter	**One Semester**	**Two Quarters**
1	All	All
2	All	All
3	3-2, 3-3, 3-5	All
4	4-1, 4-3, 4-4	4-1, 4-2, 4-3, 4-4
5	5-1	5-1
6	6-1	6-1, 6-2
7	7-1	7-1, 7-2, 7-4
8	8-1	8-1
9	9-1, 9-2, 9-3	9-1, 9-2, 9-3
10	10-1, 10-3	10-1, 10-3, 10-4

TABLE 1
Suggested Basic En route Objective Selections for Varying Course Lengths

[1]"Taxonomy of Educational Objectives—The Classification of Educational Goals," *Handbook I, Cognitive Domain*, Benjamin S. Bloom (editor), Longman Inc., New York, 1956.

Application Emphasis En route Objectives				
Chapter	General	Systems	Power	Filters
11	11-1, 11-2	11-1 thru 11-4	11-1	11-1
12	12-1, 12-2	12-1	12-1 thru 12-5	12-1
13	13-2, 13-3	13-1, 13-2		13-1 thru 13-5

TABLE 2
Possible Application Alternatives

more detailed presentation of various alternatives is given in the accompanying *Teacher's Manual*, including a one-semester course for nonelectrical engineers that emphasizes OP AMP interfacing in instrumentation systems.

We are deeply indebted to the many Air Force Academy cadets who suffered through the ever-changing pattern of the thoughts recorded here. Special thanks are due the faculty members who contributed to this evolution, and especially to M. J. O'Brien, W. H. Block, A. C. Dwelis, C. J. Corley, J. J. Connery, Jr., S. L. Hammond, M. Alexander, W. C. Hobart, Jr., P. L. Sisson, W. D. Wilson, and J. E. Erickson. We also are indebted to C. V. Stewart for his meticulous review of earlier versions of this material, and to K. A. Rosa, who typed the final manuscript with efficiency and enthusiasm. Finally, we gratefully acknowledge the support of our wives, Juanita and Kathleen, who never ceased to encourage us in this work.

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BLOCK III
Applications

APPENDICES

BLOCK I
MEMORYLESS CIRCUIT

BLOCK OBJECTIVES

ANALYSIS

Given a memoryless circuit with prescribed input signals, determine prescribed output signals or input-output relationships using any analysis technique.

DESIGN

Devise a memoryless passive or active circuit or modify an existing circuit to obtain a specified output signal for given input signals or to implement a given input-output relationship.

EVALUATION

Given two or more circuits that perform the same signal-processing function, select the best circuit on the basis of given criteria such as performance, cost, parts count, power dissipation, and simplicity.

Chapter 1
Introduction

A Brief History
About This Book
Symbols and Units

Electrical networks are processors of electrical signals and the function to be performed is specified in terms of the input and output signals.

John G. Linvill

Electrical engineering involves a diversity of fast-changing topics. Yet the discipline is unified by an unchanging interest in two basic commodities—energy and information. The purpose of this chapter is to offer some background that can help the reader use this unifying concept to integrate the technical matters discussed in succeeding chapters. We begin with a brief historical sketch of the events leading up to the emergence of information systems as the primary field of electrical engineering. The next section uses the concept of signal processing to identify the broad outline of the scope of our study, and discusses how this text is structured to help the student develop the engineering abilities needed to analyze, design, and evaluate signal-processing circuits. The final section gives some of the standard notation used throughout the book.

1-1 A BRIEF HISTORY

The widespread use of electricity in our modern world is based on several of its unique properties. Electric energy can be transmitted to distant points almost instantaneously, and there efficiently converted into other forms of energy such as mechanical, chemical, thermal, and acoustical. In an electric power system, some form of stored energy is converted into an electrical form and transferred to consumers or "loads," where it is converted into the form required by the application. Much of the work of our industrial society is accomplished through the generation, transfer, and conversion of large blocks of electric energy.

Electric energy also can be transferred in very tiny, carefully controlled amounts. The transfer of energy can take the form of telephone conversations or of numbers exchanged between computers. Often electricity is the most effective means of controlling the flow of other forms of energy. In such applications the ability of electricity to convey information is the primary consideration. The use of electricity as a medium for information processing and interchange has become the dominant concern of electrical engineering in modern times.

A brief survey of the history of electrical engineering may provide the perspective to see that modern technology is the product of human experience in the fairly recent past. Today's technology may make more sense if one has even a very rudimentary concept of how it got to be that way. Perhaps one can also gain some humility in realizing that pioneers in technology cleared the paths through the wilderness that have led this generation to the electrical age.

The study of history can be organized in a variety of ways, with the most obvious a chronological development. Most other engineering fields have their historical roots in arts and crafts that go back to antiquity. In contrast, the chronology of electrical engineering covers a relatively brief time span since essentially all applications of electrical phenomena have been developed since the turn of the nineteenth century. Three major themes thread through this time span. The fundamental understanding provided by **electrical science** led to the development of engineering systems of two basic types—**energy systems** and **information systems.** In tracing these themes we will encounter the major historical personages whose contributions seem (at least to the authors) to have had the greatest impact. Electrical engineering, perhaps more than any other technological discipline, recognizes these individuals by the units and terminology it uses. The volt, ampere, ohm, hertz, and farad all honor people, as do such terms as the Edison effect, the Scott connection, the Nyquist criterion, the Bode plot, and the Shannon–Hartley law.

Electrical Science

The momentous discovery of Alessandro Volta in 1800 marked the first milestone in the electrical age. Volta found that by alternating disks of dissimilar metals, separated by acid-moistened pieces of paper, he could produce a continuous flow of electricity. The "Voltaic pile," or battery, provided a steady flow of electric charge that allowed experimenters to explore the properties of electricity in a repeatable and scientific way.

In 1820 the Danish scientist Hans Christian Oersted observed that a magnetic compass was influenced by the flow of electricity in a wire. Oersted's experiments showed that electric currents produce magnetic fields, and for the first time there was evidence of a connection between electricity and magnetism. By 1825 André Marie Ampere had formulated the quantitative relationships involved, and had also become the first to recognize the difference between electric current and voltage.

Early investigators were puzzled by the paradox that although electricity produced magnetism, apparently magnetism did not produce electricity. However, by 1831 Michael Faraday had found that a changing magnetic field would indeed produce a flow of electricity, an effect uncovered at about the same time by Joseph Henry. Faraday's discovery of magnetic induction provided the impetus for the initial development of the electric generator and telegraph.

By mid-century, Gustav Robert Kirchhoff had formulated the laws that govern the behavior of electric circuits. In 1873, after many years of study, James Clerk Maxwell published his classic paper *Electricity and Magnetism,* which unified all knowledge of electricity through a set of relationships that have come to be known as **Maxwell's equations.** Maxwell predicted electromagnetic waves as early as 1864, although it was not until 1887 that Heinrich Hertz experimentally verified this prediction. With the discovery of cathode rays and the electron in the last decade of the nineteenth century, most of the fundamental knowledge of electricity was at hand.

Energy Systems

The discovery of magnetic induction by Michael Faraday (1831) provided a means for converting mechanical energy into electrical form, and this triggered the development of electric generators, or dynamos as they were called. For nearly fifty years progress was rather slow since the scientific knowledge had not yet been translated into engineering design know-how. The early machines produced direct current (dc). Their performance was gradually improved through a series of trial-and-error developments until, by 1880, there were a number of isolated dc systems providing energy for illumination, traction, and electrotype applications.

In 1882 Thomas Alva Edison patented his incandescent lamp. The wide acceptance of this lamp by the public led to a rapid increase in the demand for electric power. But Edison did more than simply create a practical incandescent lamp. He and his associates produced dynamos, distribution lines, switches, fuses, sockets—in other words, all of the apparatus required in an economical working power system. The famous Pearl Street Station in New York City was the first of the power systems installed by

Edison. By 1884 there were 20 such stations operating around the United States.

The period of cut-and-try design of dc dynamos came to a close in the 1880s, as men trained in science and engineering were attracted to the growing field of energy systems. John Hopkinson, professor of electrical engineering at the University of London, redesigned Edison's dynamos and nearly doubled their capacity. In 1886 Hopkinson published a classic paper, *Dynamoelectric Machines,* which provided a mathematical description of the performance of a dc generator. Machine designers were then able to predict performance from design calculations. By the last decade of the nineteenth century, dc power system technology was fairly well advanced.

At about the same time a competing power system loomed on the horizon. The development of the power transformer in 1882, and Nicola Tesla's induction motor in 1887, provided the last missing links in the alternating-current (ac) power system. By 1895 Charles Steinmetz had published a series of classical papers that provided the mathematical foundation for the design of ac systems. The competition between the older dc and the newer ac systems developed into a heated controversy in the early 1890s. In the United States the controversy hinged on the system for a large power plant to be installed at Niagara Falls, N.Y. The decision to use an ac system was the precursor of a trend that led to the very large, highly interconnected ac power systems of today.

Information Systems

Faraday's discovery also triggered the development of the electric telegraph. Early systems were produced by Schilling (1832), Gauss–Weber (1833), and Wheatstone–Cooke (1837). The first commercial telegraph system in the United States was installed by Samuel F. B. Morse between Baltimore, Md., and Washington, D.C., in 1843. By the end of the Civil War, the Western Union telegraph system spanned the continent. The expansion of land-line telegraphy was accompanied by the development of underwater cables, or submarine cables as they were called. The first of these was laid across the English Channel in 1850. A proposed submarine cable across the Atlantic presented early telegraph engineers with many challenges. Sir William Thomson (Lord Kelvin) provided the theoretical analysis showing that telegraph signals could indeed be transmitted via cable over the distances involved. Kelvin also invented a sensitive meter to detect the very weak signals at the receiving end of submarine cables. In 1857 the first attempt was made to lay such a cable. However, it was not until 1866, after several failures, that the project was finally brought to a successful completion. By 1902 submarine cables circled the globe.

The first practical acoustical transducer was patented by Alexander Graham Bell in 1875, although there were precursors of this invention in the earlier works of Philipp Reis. The first telephone system based on