

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 em-

phasis 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.

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K. L. S.

CONTENTS

Preface xi

Chapter 1 Preliminaries and Circuit Elements **1**

- 1.1 Introduction 1
- 1.2 Basic symbols and notation 3
- 1.3 The resistor 5
- 1.4 The capacitor 10
- 1.5 The inductor 12
- 1.6 Remarks on two-terminal elements 15
- 1.7 Independent sources 16
- 1.8 Power and energy 17
- 1.9 Controlled sources 22
- 1.10 Concluding remarks 24
- Problems 24

Chapter 2 Network Equilibrium Equations and Analysis of LTI Networks **28**

- 2.1 Kirchhoff's laws 29
- 2.2 Series and parallel connection of like elements 31
- 2.3 Numbers of independent voltage and current variables 41
- 2.4 Network equilibrium equations 45
- 2.5 Cutset analysis 45
- 2.6 Loop analysis 49
- 2.7 Node analysis 52
- 2.8 Mesh analysis 56
- 2.9 Concluding remarks 61
- Problems 62

Chapter 3 Some Network Properties and Theorems	76
3.1 Linear networks	76
3.2 Superposition theorem	77
3.3 Thévenin's theorem	82
3.4 Norton's theorem	85
3.5 Tellegen's theorem	88
3.6 Reciprocity theorem	90
3.7 Concluding remarks	91
Problems	92
 Chapter 4 Analysis of Simple Circuits with Dynamic Excitations	 98
4.1 Singularity functions	98
4.2 Step and impulse responses of first-order circuits	103
4.3 Application of basic techniques to solve more complex circuit problems	106
4.4 Capacitors with initial voltages and inductors with initial currents	110
4.5 Classical approach to the solution of a complex circuit problem	113
4.6 Responses of a second-order circuit — RLC series circuit	117
4.7 Concluding remarks	121
Problems	122
 Chapter 5 Steady-State Circuit Analysis	 128
5.1 Complex arithmetic and Euler's formula	128
5.2 Steady-state response of a network to the excitation e^{st}	132
5.3 Classes of circuit problems implied by an exponential excitation	139
5.4 Alternating-current circuit analysis	144
5.5 Power in an ac circuit	152
5.6 Maximum power transfer	161
5.7 Concluding remarks	163
Problems	163
 Chapter 6 Two-Terminal Electronic Devices and Their Circuit Models	 171
6.1 Intrinsic and extrinsic semiconductors	171
6.2 The p - n junction and the semiconductor diode	174
6.3 Small-signal analysis — the dynamic resistance of a diode	179

- 6.4 Other diodes 181
- 6.5 The ideal diode and the piecewise linear model of a diode 185
- 6.6 Practical diode circuits 187
- 6.7 Concluding remarks 192
- Problems 193

Chapter 7 Two-Port and Three-Terminal Linear Networks 199

- 7.1 Definitions of two-port parameters 199
- 7.2 Three-terminal and four-terminal two-ports 205
- 7.3 Relationships among two-port parameters 207
- 7.4 Relationships in a loaded two-port 210
- 7.5 Circuit models of two-ports with known parameters 211
- 7.6 The mutual inductance and the transformer 212
- 7.7 Interconnection of two-ports 219
- 7.8 The indefinite admittance matrix 225
- 7.9 Reciprocal and nonreciprocal networks 231
- 7.10 Concluding remarks 232
- Problems 232

Chapter 8 Field-Effect Transistor Circuits 240

- 8.1 The junction field-effect transistor (JFET) 240
- 8.2 JFET characteristics 244
- 8.3 dc analysis of basic FET amplifier circuit 246
- 8.4 Large-signal analysis of basic FET amplifier circuit 247
- 8.5 Small-signal parameters of an FET 249
- 8.6 Relationships among small-signal components of quantities in an FET 251
- 8.7 Self-biased FET amplifier, 255
- 8.8 The source follower 260
- 8.9 The common-gate amplifier 262
- 8.10 The metal-oxide-semiconductor FET (MOSFET) or insulated-gate FET (IGFET) 263
- 8.11 The biasing of the MOSFET 268
- 8.12 ac analysis of MOSFET circuits 272
- 8.13 Other FET circuit considerations 273
- Problems 275

Chapter 9 Bipolar Transistor Circuits 283

- 9.1 The bipolar junction transistor 283
- 9.2 Current components in a transistor 284
- 9.3 Large-signal model for the junction transistor 288
- 9.4 Transistor configurations 289
- 9.5 The common-base transistor characteristics 290

9.6	The common-emitter transistor characteristics	292
9.7	dc analysis of basic common-emitter transistor amplifier	293
9.8	Other transistor circuit biasing schemes	297
9.9	Transistor ratings and biasing considerations	303
9.10	Stabilization of the operating point	305
9.11	Small-signal ac models for the bipolar transistor	306
9.12	Other ac transistor circuit models	310
9.13	Comparison of the three orientations of the transistor	312
9.14	ac analysis of transistor circuits	316
9.15	High-frequency equivalent circuits of a transistor	321
	Problems	322
Chapter 10	Other Electronic Devices and Circuits	332
10.1	Vacuum tubes	332
10.2	ac analysis of vacuum-tube circuits	338
10.3	Integrated electronics	339
10.4	Operational amplifier	345
10.5	Operational amplifier circuits	347
10.6	Concluding remarks	350
	Problems	350
Chapter 11	Network Analysis in the Frequency Domain	357
11.1	Network functions in the complex-frequency domain	357
11.2	Poles and zeros	361
11.3	Frequency characteristics of network functions	363
11.4	Resonance in second-order circuits	366
11.5	Bode diagrams	371
11.6	Concluding remarks	381
	Problems	381
Chapter 12	Network Analysis in the Time Domain and the System Concept	388
12.1	The impulse response	389
12.2	The convolution integral	391
12.3	Some properties of the convolution integral	398
12.4	Remarks on the convolution integral	401
12.5	The system concept	402
	Problems	403
Chapter 13	System Response to Periodic Excitations: Fourier Analysis	406
13.1	The Fourier series	406
13.2	Some special cases	411

- 13.3 Application to circuit problems 416
- 13.4 Effective value of a periodic quantity 417
- 13.5 Average power in a circuit with periodic excitations 418
- 13.6 Fourier series in complex form 420
- 13.7 Frequency spectrum and the concept of transform 422
- Problems 426

Chapter 14 Fourier Transform and Applications 431

- 14.1 The Fourier integral 431
- 14.2 Properties of the Fourier transform 436
- 14.3 Relationship between the impulse response and the network function 439
- 14.4 Circuit analysis using the Fourier transform 443
- 14.5 Ideal low-pass filters 444
- 14.6 Modulation theorem and amplitude modulation 450
- 14.7 Far-field pattern of an aperture antenna 452
- 14.8 The limiting cases of some Fourier transforms 456
- Problems 460

Chapter 15 Laplace Transform and Applications 464

- 15.1 The two-sided Laplace transform 464
- 15.2 Some properties of the two-sided Laplace transform 470
- 15.3 Application of two-sided Laplace transform to circuit problems 470
- 15.4 The one-sided Laplace transform 473
- 15.5 Some properties of the one-sided Laplace transform 476
- 15.6 The inverse Laplace transform: Tables of Laplace transform 481
- 15.7 Partial-fraction expansion of a rational function 485
- 15.8 Solution of differential equations by Laplace transform 488
- 15.9 The complete solution of network problems 490
- 15.10 Network elements with initial energy 492
- 15.11 The initial-value and final-value theorems 498
- 15.12 Calculation of impulse response by Laplace transform 501
- 15.13 Finding the two-sided Laplace transform from the one-sided Laplace transform 502
- Problems 505

Chapter 16 State-Variable Method of System Analysis 511

- 16.1 The concept of the state of a network and its state equation 512
- 16.2 The proper network and its state equation 515

16.3	Networks with controlled sources and mutual inductances	520
16.4	State equation of an improper network	521
16.5	Time-domain solution of the state equation	522
16.6	Laplace-transform solution of the state equation	525
16.7	Concluding remarks	527
	Problems	528
Chapter 17	Logic Circuits	532
17.1	The logic operations	533
17.2	Boolean algebra	538
17.3	Boolean expressions for a binary function	540
17.4	Circuits of logic gates	543
17.5	The binary number system	547
17.6	Combinational and sequential circuits	548
17.7	The flip-flop (FF)	549
17.8	Shift registers	554
17.9	The counter	555
17.10	The adder	556
17.11	The subtractor	558
17.12	The multiplier	560
17.13	The serial adder	561
17.14	A BCD-to-decimal decoder	563
17.15	Concluding remarks	565
	Problems	565
Appendix A	Proofs of Several Network Theorems	568
A.1	Proof of Thévenin's theorem	568
A.2	Proof of Norton's theorem	570
A.3	Proof of Tellegen's theorem	570
A.4	Proof of reciprocity theorem	572
Appendix B	Matrix Algebra	575
B.1	Definitions	575
B.2	Algebraic rules of matrices	577
B.3	Special matrices	578
B.4	Some useful theorems	581
B.5	Matrix notation in a set of linear simultaneous equations	582
B.6	Partitioning of matrices	583
	Problems	586
Appendix C	Answers to Selected Problems	590
Index		613

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.

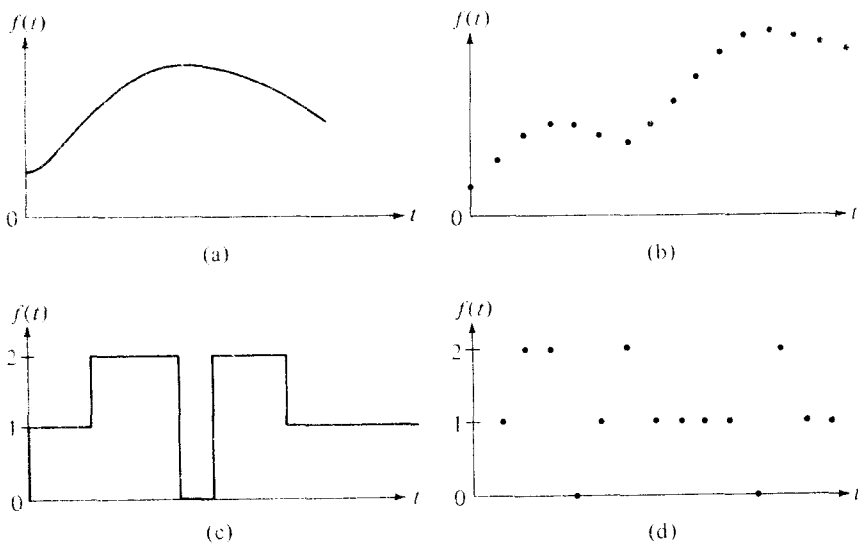


Figure 1.1 A quantity in (a) a continuous-time analog system, (b) a discrete-time analog system, (c) a continuous-time digital (ternary) system, and (d) a discrete-time digital (ternary) system.

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

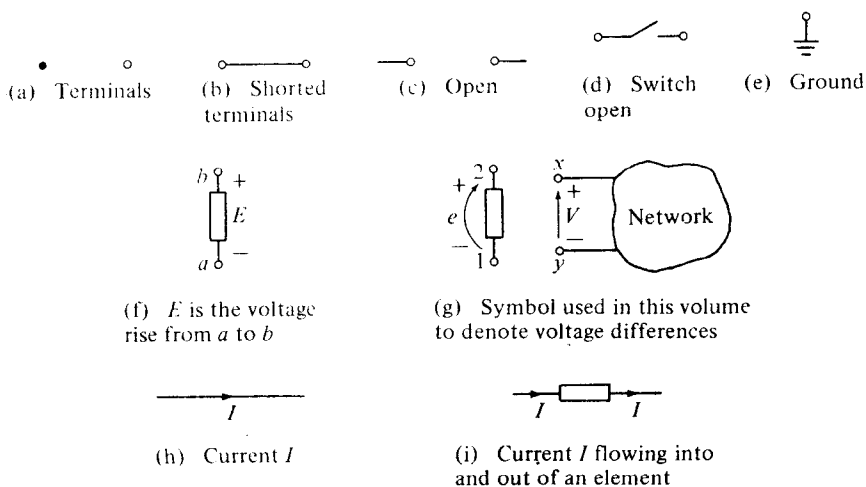


Figure 1.2 Some basic notations and symbols.