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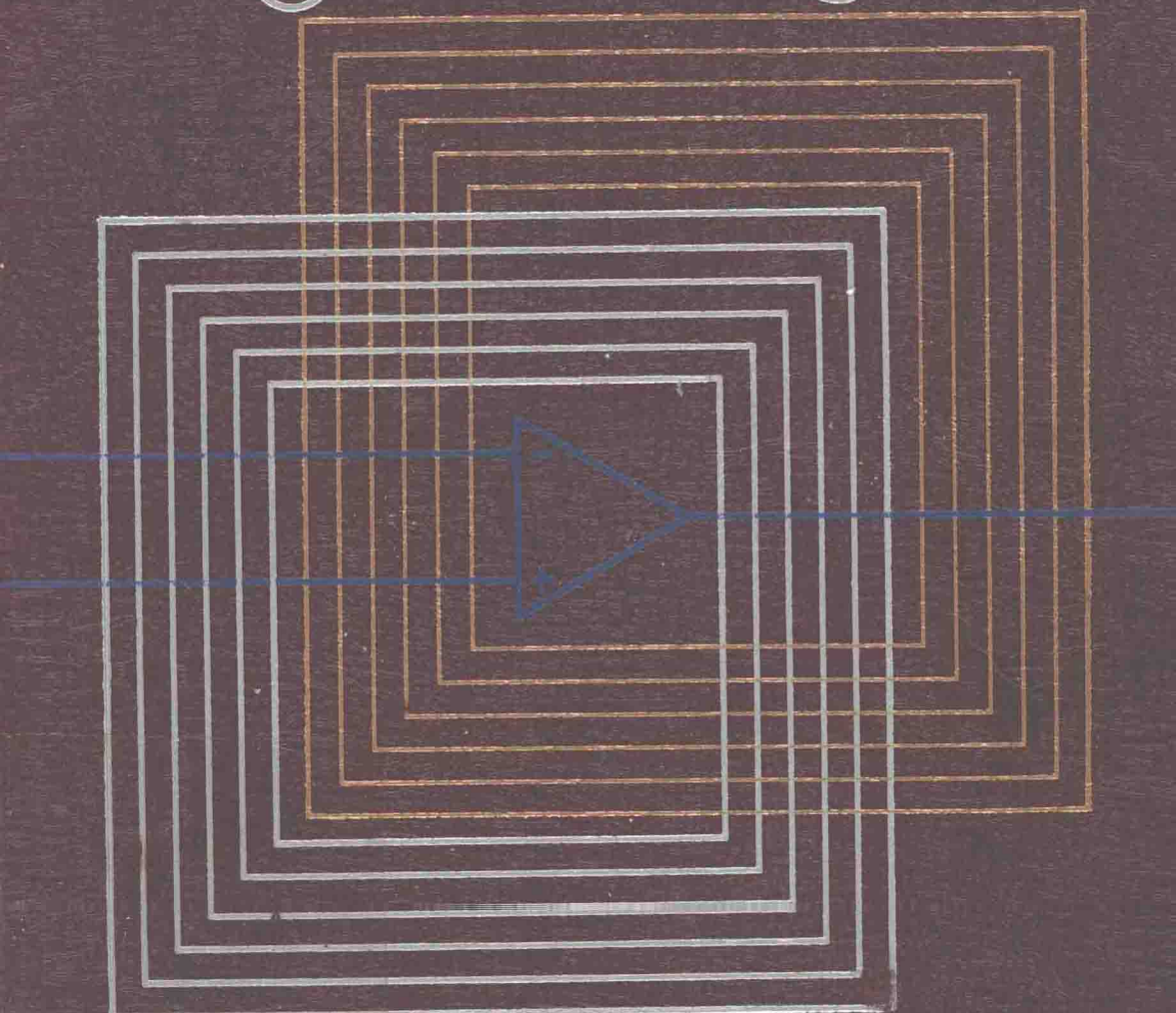
Basic Electrical Engineering

FIFTH EDITION



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BASIC ELECTRICAL ENGINEERING

CIRCUITS
ELECTRONICS
MACHINES
CONTROLS

Fifth Edition

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BASIC ELECTRICAL ENGINEERING

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PREFACE

The objective of this book—as it was for the four prior editions—is to introduce undergraduate engineering and science students to the essentials of electrical engineering. By stressing the fundamental physical concepts and the diversity of applications, we have attempted to convey both the substance and flavor of the discipline. The scope and treatment in this volume may also serve as a valuable adjunct to the continuing education of professionals in fields akin to engineering.

This book has been extensively rewritten and a substantial amount of new material has been added. As in previous editions, the text is divided into four major sections: circuit theory, electronics, electromechanical energy conversion, and analog and digital control systems. Sufficient description is given to the physical principles in each of these areas to make applications meaningful. The treatment is carried beyond a bare introduction so that the reader can make the transition to more advanced, specialized texts without undue intellectual embarrassment. Increased emphasis is given to the exciting applications made possible by operational amplifiers, microprocessors, and other integrated circuits and semiconductor devices which are part of current engineering practice and which will continue to influence future development.

The book is organized to provide a maximum of flexibility without loss of continuity, so that a variety of one- or two-semester courses can be presented. Thus, the individual faculty member can readily adapt the material to meet the needs of his or her students. An instructor's guide is available, one section of which describes several possible arrangements of the material for courses of different length, content, and sequence.

A chapter on the Laplace transform has been added; coverage of this material is optional. In the study of circuit theory, some professors may wish to introduce the concepts of the natural response prior to their treat-

ment of steady-state ac circuits. They may do so by first covering Sections 3-1 to 3-4 and Chapter 4 before returning to complete those sections in Chapter 3 that are important to them. Similarly, there is subject matter in Chapters 2 and 6 that can be skipped if the sections in electronics, machines, and controls which employ these techniques are also omitted.

The parts of the book relating to electronics and machines can be taken up interchangeably. The introductory chapters of these parts (Chapter 7 for electronics and Chapters 13 and 14 for machines) present the underlying physical concepts of the respective fields. These chapters may be supplemented by as many of the analytical chapters that follow as are appropriate in view of technical objectives. Furthermore, in the electronics section, it is possible to treat digital systems prior to analog systems.

The final chapter serves to introduce a variety of methods by which the performance of physical systems is controlled. By focusing on control aspects, the integration of many of the concepts used in the preceding chapters is effected.

The importance of electrical and electronic instrumentation is considerable. Rather than isolating this topic in a separate section, instrumentation is integrated throughout the book, particularly in the sections on circuit theory and electronics. In addition, a separate section on transducers is included in Chapter 17.

The book contains over 700 problems and 150 illustrative examples. The vast majority of these either are new or have been reworked and most have been classroom tested. Solutions to problems at the end of each of the chapters appear in the instructor's guide and answers to selected problems are given at the end of the text.

We have had the benefit of valuable advice and suggestions from the many professors and practicing engineers who used earlier editions of this book as either instructor or student. All these individuals have influenced this edition, so to them we express our thanks and appreciation.

The late A. E. Fitzgerald was the guiding force behind this book for over three decades. A truly professional gentleman, he had a distinguished career both as teacher and writer and as a practicing engineer. The intellect and spirit of my teacher, colleague, and friend appears on every page of this book.

Also apparent throughout this edition is the influence of the late David E. Higginbotham. The insight, sensitivity, and experience of this outstanding teacher have contributed immeasurably.

Arvin Grabel

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Electrical engineers have contributed significantly to technological achievements during the twentieth century. These contributions have resulted in the widespread use of electric energy and the advantages it affords. Electric energy has a number of desirable attributes not possessed by alternative energy forms. Among these attributes are the ease with which electric energy is converted to and from other forms of energy, the ability to distribute it over large areas, and the speed with which it is transported.

Economies result when large quantities of energy are generated at one location and distributed to sites where the energy is needed. Ease of transportation to geographically separate regions is a significant factor in realizing these economies. Information, in the form of electric signals, can be propagated at great speed. As a result the effectiveness of long-range communication systems, data-processing systems, and control systems is enhanced. In many cases it is the speed at which the energy is transferred that makes the system feasible.

As an end in itself, electric energy is not generally useful. In most applications, other forms of energy are converted to electric energy at the input and reconverted at the output. Between input and output, the electric energy is processed and transmitted to the desired location in a manner appropriate for use. Motors are the converters which provide the mechanical energy to operate the machinery in a factory. In turn, the electric energy to drive the motor is derived by converting mechanical energy in a steam-driven turbogenerator at the power plant. Similarly, the information in the sound and picture in a television system is converted to electric signals at the studio by means of microphones and vidicons. Reconversion to optical and acoustical information in the receiver is accomplished by cathode-ray tubes and loudspeakers. The availability of devices that readily perform the interconversion of energy is crucial to the use of electric energy. These conversion devices, coupled with the generally small size of electric components, form the basis for the use of electric energy in a variety of control, communication, and instrumentation systems.

The study of electrical engineering becomes one of investigating the characteristics and uses of devices and systems for energy conversion, processing, and transfer. Such devices and systems impact on all professional branches of engineering and science. Most instrumentation and control systems are, in part, electrical or electronic in nature. The incorporation of the digital computer in such systems increases the utilization of electrical instrumentation. A variety of engineers deal with motors and power distribution in building systems, process control, and the design of manufacturing facilities. Medical scientists use electric devices in diagnostics, in prosthetics, and for environmental control. The aforementioned applications have, in turn, a vital impact on the economic, structural, and behavioral aspects of organizations and are, therefore, of vital concern to managers and executives.

For convenience, a basic study of electrical engineering is traditionally divided into treatments of circuit theory, of electronics and electronic devices, of energy conversion and electromechanical conversion devices, and of control devices and systems. This chapter will lay the groundwork for such a study by developing the elementary concepts and defining the basic terms. The typical reader already will have encountered much of this material. Thus, for many, it will simply be a coordinated review reflecting the general viewpoint of the remainder of the book.

1-1 ENERGY AND INFORMATION

The earliest uses of electric energy were the telegraph, telephone, and electric lighting. Both the telephone and telegraph have as their objective the transfer of information from one location to another. In the latter, the sender codes the message into electric impulses (the familiar Morse code representation of the alphabet), whereupon it is transmitted, received, and decoded. Similarly, telephone transmission requires the conversion of the speaker's voice to a corresponding electric signal which can be faithfully reproduced at the listener's receiver. In both cases it is the form of the electric energy, which contains the information, that is most important. The amount of energy expended need be only what is necessary to recover the information at the receiving end.

To be effective in lighting buildings and streets, the incandescent lamp requires that electric energy be available at the point of use. The initial success of electric lighting resulted from incorporation of the lamp in a total system for the generation and distribution of the energy needed. Here the important factor is the quantity of energy transferred; its form is of secondary importance since no information transfer occurs.

As illustrated by these early applications, the uses of electric energy can be classified as systems that process information and those that process energy. Modern systems for communication, computation, and control are generally considered to process information; electric power-generating, conversion, and distribution systems are evidently energy processors. However, both classes of systems are concerned with the transfer of electric energy, i.e., with doing work by delivering energy to the right place, in the right form, and at sufficient power for the intended purposes. The general import of the preceding sentence can be gathered by thinking of the words *work, energy,* and *power* as they are used in ordinary speech. However, these terms, so basic to engineering, must be considered in their more precise and quantitative meanings.

Work is done when something is moved against a resisting force. For example, work is done when a weight is lifted against the pull of gravity. Quantitatively, the work done is found by multiplying the force applied by the distance through which the force moves. The unit of work in the meter-kilogram-second (SI) system of units is the *joule* (abbreviated J). It is the work done when a force of one *newton* (0.225 lbf.) acts through a distance of one meter. The English unit of work is the *foot-pound.* (1 J = 1 N · m =

0.738 ft-lbf.)[1] The SI system of units is used predominantly in this book. The English system is used only where dictated by common industrial usage.

Energy is the capacity for doing work; another way to think of work is as a transfer of energy. Mechanical energy is measured in the same units as work. When a mass is elevated, energy is expended by the human body or by some hoisting device. This mass, on the other hand, acquires *potential energy*. That is, by virtue of its elevation above the ground, the mass can do work. It can raise another weight by means of a pulley; or it can be allowed to fall, as in a pile driver, transferring its energy when it hits the pile at the bottom. In this case, the potential energy at the beginning of the fall would change into *kinetic energy* as the bottom was neared. That is, the body would have the ability to do work because of its motion. At impact the energy of a pile driver is transferred to the pile.

A general principle applicable to all physical systems is the *principle of conservation of energy,* which states that energy is neither created nor destroyed; it is merely changed in form. Energy can be changed into heat, light, or sound; it may be mechanical energy of position or of motion; it may be stored in a battery or in a spring; but it is not created or destroyed. The twentieth century interconversion of matter and energy is a refinement which does not affect the usefulness of the law for nonrelativistic processes.

For practical purposes we are very much concerned with the *rate* of doing work or otherwise delivering energy. This rate is called *power.* In SI units, power is measured in *watts* (abbreviated W), one watt equaling one joule per second. In English units, power is measured in foot-pounds per second. *Horsepower,* equivalent to 550 ft-lb/s (1 hp = 746 W), is still sometimes used to indicate power, particularly motor performance. Thus, from the definition of power, if W is the work accomplished or energy expended or delivered in time t_0 seconds, the average power for that period is

$$P = \frac{W}{t_0} \tag{1-1}$$

just as we get our average speed on a trip by dividing the distance traveled by the time required. We are also interested in the *instantaneous power,* however, just as we are interested in the momentary reading of the speedometer of the car. The expression for instantaneous power may be written

$$p = \frac{dW}{dt} \tag{1-2}$$

where the lowercase letter p indicates an instantaneous quantity and the term dW/dt is, of course, the usual mathematical notation for the time rate at which work is being done. Equation (1-2) can be rewritten as Eq. (1-3) to show the relationship between energy and power.

$$W = \int p \, dt \tag{1-3}$$

[1] In general, units are abbreviated in this book when they follow numerical value or a symbolic equation; otherwise, they are spelled out. A listing of abbreviations is given in Appendix A.

The average power, expressed in Eq. (1-1), can now be obtained from the evaluation of Eq. (1-3) during a desired time interval. This relation is given in Eq. (1-4) and can be recognized as the mean-value theorem:

$$P = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} p \, dt \tag{1-4}$$

where $t_2 - t_1$ represents the time interval over which the average is taken.

Because of the intimate relationship between power and energy, we often find energy expressed in such units as *wattseconds* or *kilowatthours* (which equals 1,000 × 3,600, or 3.6×10^6 wattseconds). A wattsecond is, of course, the same measurement as a joule; the picture conveyed is the amount of energy delivered in one second by a constant power of one watt.

1-2 FUNDAMENTAL ELECTRICAL QUANTITIES

Electric energy transfer occurs because of the actions of *electric charges*. An indication of the quantity of electricity, electric charge is usually denoted by Q or q and is measured in *coulombs* (abbreviated C). As a convention generally followed in this book, capital letters are used to represent quantities that do not vary with time; lowercase letters refer to time-varying quantities. While we can perceive of a wire or a similar object carrying a charge, it is difficult to visualize the charge itself being divorced from the object. The nature of electric charges is best understood in terms of the effects they produce. Justification for the existence of charged particles is based on a wealth of experimental evidence and the theoretical models which predict observed behavior.

One of the first phenomena observed in the study of electric charges was that there are two kinds: positive and negative. *Protons* are considered positive charges, *electrons* negative. The charge on an electron, sometimes called the *electronic charge*, is -1.602×10^{-19}C so that nearly 6.3×10^{18} electrons are required to form one coulomb.

A most significant effect of an electric charge is that it can produce a force. Specifically, a charge will repel other charges of the same sign; it will attract other charges of the opposite sign. Since the charge on an electron is negative, any charge which attracts (or is attracted by) an electron is accordingly a positive charge; the charge on a proton is an example. Note that the force of attraction or repulsion is felt equally by each of the charges or charged particles. The magnitude of the force between two charged bodies is proportional to the product of the charges and inversely proportional to the square of the distance between them. That is, the force F between two charged bodies having charges Q_1 and Q_2 is given by *Coulomb's law* as

$$F = k \frac{Q_1 Q_2}{d^2} \tag{1-5}$$

where d is the distance between the charges and k is a constant depending on the medium surrounding the charges. The direction of the force is along the line connecting the two charges. Note that this is the same sort of relation

that governs the forces of gravity between two masses. Such relations are referred to as *inverse-square laws*.

The situation defined in Eq. (1-5) can be described by saying that there is a region of influence in the neighborhood of an electric charge wherein a force will be exerted when another charge is introduced. The force will grow progressively weaker as the new charge is placed in more remote positions. Such a region of influence is called a *field*. The field set up by the presence of electric charges is an *electric field*. Since we are for the moment dealing with charges at rest, it can be called an *electrostatic field*. Note again the general similarity to gravity and gravitational forces. When we say, for example, that a space vehicle has left the earth's gravitational field, we mean that the force of gravity acting on the vehicle has become negligibly small. Obviously, a similar statement can be made about a charged particle with respect to an electric field.

The electric field is defined at a point as the force per unit-positive charge. That is, the electric field at any point is the force, in magnitude and direction, which would act on a unit-positive charge at that point. Contributions to the total field at any point are made by all the charges that are close enough to have any influence.

We are now in a position to think about work and energy transfer in connection with electric forces. Suppose we move a positive charge in an electric field in a direction opposite to that of the field, that is, against the force acting on it due to other electric charges. For example, if the field were caused by the existence of a nearby negative charge, we would move the positive charge farther from it. Now work would be done in moving the charge against the forces acting on it, just as work is done in lifting a weight in the earth's gravitational field. Moreover, the law of conservation of energy applies; that is, the particle would now be in a position of higher potential, just as the lifted weight would possess greater potential energy. Consequently, we may think of storing energy by means of the field and subsequently transferring this energy to do work.

An important electrical quantity, *potential difference* or *voltage*, is defined as the work per unit-positive charge in moving a charge between two points in the field. Mathematically, this is expressed as

$$V = \frac{W}{Q} \qquad \text{or} \qquad W = VQ \tag{1-6}$$

where V is the potential difference in volts and W is the work done in transporting a charge Q between two points a and b. The letter E is also used to represent voltage; in this book, both are used. Where a preference for E or V exists because of common usage or tradition, that preference is followed. Since work is the force F times the distance l between a and b and the strength of the electric field $\mathscr{E}$ is the force per unit charge, Eq. (1-6) is often given as

$$V = \frac{Fl}{Q} = \mathscr{E}l \tag{1-7}$$

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