McGRAW-HILL
ELECTRICAL AND
ELECTRONIC
ENGINEERING
SERIES

Basic Electrical Engineering

CIRCUITS MACHINES ELECTRONICS CONTROL

A. E. Fitzgerald, Sc.D.
Jackson & Moreland, Inc., Engineers
Formerly Professor of Electrical Engineering
Massachusetts Institute of Technology

David E. Higginbotham, S.M.
Associate Professor of Electrical Engineering
Tufts University

SECOND EDITION

1957

McGRAW-HILL BOOK COMPANY, INC.
New York Toronto London

BASIC ELECTRICAL ENGINEERING

Library of Congress Catalog Card Number 56-10312

THE MAPLE PRESS COMPANY, YORK, PA.

McGraw-Hill Electrical and Electronic Engineering Series
FREDERICK EMMONS TERMAN, *Consulting Editor*

Basic Electrical Engineering

McGraw-Hill Electrical and Electronic Engineering Series

FREDERICK EMMONS TERMAN, *Consulting Editor*

BAILEY AND GAULT · Alternating-current Machinery
BERANEK · Acoustics
BRUNS AND SAUNDERS · Analysis of Feedback Control Systems
CAGE · Theory and Application of Industrial Electronics
CUCCIA · Harmonics, Sidebands, and Transients in Communication Engineering
EASTMAN · Fundamentals of Vacuum Tubes
EVANS · Control-system Dynamics
FITZGERALD AND HIGGINBOTHAM · Basic Electrical Engineering
FITZGERALD AND KINGSLEY · Electric Machinery
GEPPERT · Basic Electron Tubes
GLASFORD · Fundamentals of Television Engineering
HAPPELL AND HESSELBERTH · Engineering Electronics
HARMAN · Fundamentals of Electronic Motion
HESSLER AND CAREY · Fundamentals of Electrical Engineering
HILL · Electronics in Engineering
JOHNSON · Transmission Lines and Networks
KRAUS · Antennas
KRAUS · Electromagnetics
LEPAGE · Analysis of Alternating-current Circuits
LEPAGE AND SEELY · General Network Analysis
MILLMAN AND SEELY · Electronics
MILLMAN AND TAUB · Pulse and Digital Circuits
ROGERS · Introduction to Electric Fields
RÜDENBERG · Transient Performance of Electric Power Systems
RYDER · Engineering Electronics
SEELY · Electronic Engineering
SEELY · Electron-tube Circuits
SEELY · Radio Electronics
SISKIND · Direct-current Machinery
SKILLING · Electric Transmission Lines
SKILLING · Transient Electric Currents
SPANGENBERG · Fundamentals of Electron Devices
SPANGENBERG · Vacuum Tubes
STEVENSON · Elements of Power System Analysis
TERMAN · Electronic and Radio Engineering
TERMAN AND PETTIT · Electronic Measurements
THALER · Elements of Servomechanism Theory
THALER AND BROWN · Servomechanism Analysis
THOMPSON · Alternating-current and Transient Circuit Analysis
TRUXAL · Automatic Feedback Control System Synthesis

PREFACE

The accelerated pace of developments in the field of electrical engineering has created serious problems in engineering education, especially in the selection and arrangement of material for training the engineers of tomorrow. A very common and sound approach to the problems has been to emphasize the scientific aspects of engineering. The widespread adoption of this approach both confirms the value of the general viewpoint adopted in the first edition of this book and provides a strong influence in the revision leading to the present edition.

Broadly speaking, there are three main objectives underlying the revision:

1. To take advantage of the years of teaching experience with the first edition in order to make the book more teachable and understandable.
2. To give full recognition to the importance of modern control and measurement techniques.
3. To incorporate recent developments and concepts in circuit theory, machinery, and electronics which are of broad significance to all branches of engineering.

As a consequence, both reorganization of material and complete rewriting of many chapters and of significant portions of the other chapters have been necessary. In line with the first objective, new concepts are introduced in a more gradual manner and fuller explanations are presented. For example, the introductory chapters on electric circuits, magnetic circuits, machinery, and electronics proceed from simple and elementary principles, most of which are the direct result of classical scientific experiments. The rather considerable expansion in the related fields of measurement and control has also had repercussions throughout the book, for we feel that such new and important material should not be presented merely as an unrelated appendage. Thus, the thought processes underlying feedback control make themselves felt in the chapters on circuit theory. They reappear in the treatments of machinery and electronics, so that many of them are already familiar when feedback control itself is reached. Among the devices and concepts newly introduced in accordance with this program are magnetic amplifiers, transistors, self-balancing recorders and controllers, phase-sensitive modulation and demodulation, control amplifiers, d-c and a-c control motors, and transfer-function and frequency-response analysis.

One inevitable result is that the book has grown longer. It contains more material than can be presented in a two-semester three-hours-per-week course. We have had flexibility of use continually in mind during the organization and writing, however, and we feel that a variety of courses of varying length and subject matter can be based on it. Under these circumstances, it is our hope that the instructor will have the advantage of selectivity to meet his particular needs and environment without appreciable sacrifice in continuity.

Many instructors have been kind enough to give us the benefit of their comments and suggestions, often at the expense of a very considerable amount of their time and energy. We have also had the advantage of intimate contact with the engineers of a variety of industries to aid us in questions of selectivity and relative emphasis of subject matter. To all these people we owe a large debt of gratitude.

A. E. FITZGERALD
DAVID E. HIGGINBOTHAM

CONTENTS

CHAPTER 1. D-C CIRCUITS 1

Basic Electrical Quantities—Electric-circuit Constants—Resistance; Ohm's Law—Fundamental Circuit Laws; Kirchhoff's Laws—D-C Circuits—More Complex D-C Circuits—Network Simplification—Principle of Superposition—Thévenin's Theorem

CHAPTER 2. ALTERNATING CURRENTS AND VOLTAGES 29

Generation of Alternating Voltages—Sinusoidal Voltages and Currents—Purely Resistive A-C Circuits—RMS or Effective Currents and Voltages—Self-inductance—Purely Inductive A-C Circuits—Capacitance—Purely Capacitive A-C Circuits—Circuit Parameters as Physical Entities

CHAPTER 3. PHASOR REPRESENTATION AND COMPLEX ALGEBRA. 49

Addition of Currents and Voltages; Phasor Representation—Phasors in Rectangular Form—Phasors in Polar Form—Phasors in Exponential Form—The Impedance Concept—Harmonics; Fourier Series

CHAPTER 4. A-C CIRCUITS: CURRENT-VOLTAGE RELATIONS. 71

Series Combination of Circuit Elements—Resistance-Inductance Series Circuits—Application of Complex Notation—Resistance-Capacitance Series Circuits—Resistance-Inductance-Capacitance Circuits—Parallel Circuits—Network Reduction; Series-parallel Circuits—Multiple-source Networks—Thévenin's Theorem

CHAPTER 5. A-C CIRCUITS: POWER AND FREQUENCY RESPONSE 98

Power and Reactive Power—Power Factor and Volt-Amperes—Power-factor Correction—Frequency Response and Resonance—Coupling Networks—Four-terminal Networks—Maximum-power Conditions—General Résumé

CHAPTER 6. POLYPHASE CIRCUITS 126

Generation of 3-phase Voltages—Three-phase Voltages, Currents, and Power—Y-connected Circuits—Δ-connected Circuits—Δ-Y Equivalence—Analysis of Balanced 3-phase Circuits; Single-line Diagrams—Three-phase Power Measurements—Other Polyphase Systems—Cost Considerations and Electric Rate Structures

CHAPTER 7. TRANSIENTS 150

Electrical Transients—*RL* Transients with Constant Applied Voltages—*RC* Transients with Constant Applied Voltages—Time Constants—*LC* Circuits; Oscillations—More General Transient Problems—A-C Transients

CHAPTER 8. MAGNETIC CIRCUITS 168

Magnetic Effects of Electric Current—Magnetic-circuit Concepts—*BH* Curves—Characteristics of Magnetic Materials—Practical Magnetic Circuits—Magnetic Circuits with D-C Excitation—Magnetic Force and Its Utilization—Magnetically Induced Voltages; Self-inductance—Magnetic Circuits with A-C Excitation—Hysteresis and Eddy-current Losses—Exciting Current—Magnetic Circuits with A-C and D-C Excitation; Saturable-core Reactors

CHAPTER 9. TRANSFORMERS 192

Transformer Construction—Action in an Ideal Transformer—Departure from the Ideal; Leakage Reactance; Evolution of the Equivalent Circuit—Equivalent Circuits—Short-circuit and Open-circuit Tests—Efficiency and Regulation—Variable-frequency Transformers—Autotransformers; Instrument Transformers—Transformers in 3-phase Circuits—Mutual Inductance; Air-core Transformers

CHAPTER 10. PHYSICAL ASPECTS OF ELECTRIC MACHINERY 220

Electromechanical Energy Conversion—Voltage and Torque—Interaction of Magnetic Fields—A-C Generators—D-C Generators—Electric Motors—Losses and Efficiency—Machine-application Considerations—Machine Ratings

CHAPTER 11. D-C MACHINES 259

Commutator Action—Armature EMF—The Equivalent Circuit—The Magnetization Curve—Generator Performance—Self-excited Generators—Motor Performance—Shunt Motors—Series and Compound Motors—Motor Starting—Speed Control—Commutating Fields—Armature Reaction; Compensating Fields

CHAPTER 12. THREE-PHASE INDUCTION MOTORS. . 288

Rotating Magnetic Fields—Induction-motor Action—The Equivalent Circuit—Analysis Based on Simplified Equivalent Circuit—No-load and Blocked-rotor Tests—Double-squirrel-cage Motors; Classification of Squirrel-cage Motors—Induction-motor Starting

CHAPTER 13. POLYPHASE SYNCHRONOUS MACHINES 307

Synchronous-motor Action—Synchronous Impedance and Excitation Voltage—The Equivalent Circuit and Phasor Diagram—Effects of Saliency and Saturation—Approximate Analysis of Motor Performance Based on the Equivalent Circuit—Power Factor of A-C Motors—Synchronous-motor Starting

CHAPTER 14. FRACTIONAL-HORSEPOWER MOTORS . 321

Single-phase Induction Motors—Starting and Running Performance of Single-phase Induction Motors—A-C Series Motors; Universal Motors—Repulsion Motors—Small D-C Motors; Split-series-wound and Split-compound-wound Motors.

CHAPTER 15. PHYSICAL ASPECTS OF HIGH-VACUUM TUBES AND THEIR ASSOCIATED CIRCUITS . . 329

Survey of Fundamental Processes—Electron Emission—High-vacuum Thermionic Diodes—Grid-controlled High-vacuum Tubes: Triodes—Tube Factors—Tetrodes and Pentodes; Beam Power Tubes—Comparison of High-vacuum Tubes—Quiescent Conditions and Dynamic Operation—Vacuum-tube Circuits: Amplifiers—Modulation and Demodulation—Vacuum-tube Oscillators

CHAPTER 16. HIGH-VACUUM TUBES AS CIRCUIT ELEMENTS 361

Voltage and Current Symbols—Graphical Analysis—The Equivalent Circuit—The Equivalent Circuit with Self-biasing

—Power Amplification; Comparison of Graphical and Equivalent-circuit Methods

CHAPTER 17. VACUUM-TUBE AMPLIFIERS 379

Classification of Amplifiers—Interelectrode Capacitance and Input Impedance—Resistance-capacitance-coupled Amplifiers—Transformer-coupled Amplifiers—Direct-coupled Amplifiers—Push-pull Circuits—Cathode-follower Amplifiers—Inverse-feedback Amplifiers

CHAPTER 18. VACUUM-TUBE OSCILLATORS 398

Conditions for Self-excitation—Necessary Conditions for Feedback Oscillators—Initiation and Limitation of Oscillations—Oscillator Circuits—Oscillator Applications; Induction and Dielectric Heating

CHAPTER 19. SPECIAL-PURPOSE TUBES AND SEMICONDUCTOR DEVICES 406

Gas-filled Thermionic Diodes—Rectification—Elementary Rectifier Analysis—Semiconductors; Transistors—Cold Cathode Gas Tubes: Glow Tubes, Mercury-arc Rectifiers, and Ignitrons—Photosensitive Tubes—Phototube Applications

CHAPTER 20. CONTROL AMPLIFIERS AND ASSOCIATED EQUIPMENT 430

Thyratrons—Thyratron Control Circuits—Magnetic Amplifiers—The D-C Generator as an Amplifier—The Rototrol and Regulex—The Amplidyne—Control Motors—Selsyns and Synchros

CHAPTER 21. INSTRUMENTATION 463

Electrical Measuring Instruments—Standard Cells—Potentiometers—Measurement of Transient and Cyclic Phenomena: Oscillographs—Resistance Bridges—Impedance Bridges—Measurement of Nonelectrical Quantities by Electrical Methods—Some Specific Examples—Self-balancing Continuous Recorders—Stroboscopes—Instrumentation in Specific Processes—The Relation of Instrumentation to Control

CHAPTER 22. FEEDBACK CONTROL SYSTEMS . . . 486

Types of Control Systems—Feedback Control of Electric-machine Performance—Discontinuous Feedback Control Systems—Steady-state Conditions; Gain Specification—Frequency

Response—Transfer Functions and Block Diagrams—Stability Considerations—Over-all Response—Compensation

APPENDIX

Wire Table for Standard Annealed Copper (Solid) . . . 525
Wire Table for Standard Annealed Copper (Stranded). . . 526
Operating Data for Vacuum Tubes 527

INDEX 529

CHAPTER 1

D-C CIRCUITS

Electrical engineering is concerned with the conversion of energy from other forms into electrical energy, with the transmission and distribution of the energy in electrical form, and with its control and reconversion for ultimate utilization. Electrical energy is not generally useful as an end in itself; rather, it is converted into useful mechanical energy in motors, relays, and electromagnets; into heat energy in furnaces and ovens; into sound energy in loudspeakers; into light energy (often after a conversion into heat) in lamps; or into chemical energy in electrolytic processes.

Electrical engineering is very closely associated with other professional branches. Mechanical engineers use the products of electrical engineering in the application and control of electric motors, as an integral part of power plants, and for remote metering and control, to mention only a few instances. Chemical engineers use the same products for process control, for heating and refrigeration, and in automatic recording and indicating equipment. Civil and structural engineers are concerned with motor applications, electric power distribution within buildings, and in stress and strain measurements. Aeronautical engineers deal with many essential applications for power production, measurement, and control in aircraft and missiles. Chemical and physical scientists find electrical measuring devices to be valuable adjuncts in their investigations. The economic aspects of the foregoing uses are of vital concern to the executive and administrator.

The noteworthy contributions made by electrical engineering to the technological advances of the twentieth century have been due primarily to the fact that energy in electrical form is not only easily convertible but is also easily controlled and conveniently and economically transported over large distances. A study of electrical engineering becomes a study of the devices used in energy conversion and transmission, with particular emphasis placed on the internal characteristics required to obtain desired external performance. This chapter will lay the groundwork for such a study by defining the basic terms and developing the necessary concepts. An introduction to electric-circuit theory will be based on the d-c circuit.

1-1. Basic Electrical Quantities. Before we are in a position to study the behavior of electrical systems and devices, we must first be familiar with the fundamental quantities used to express that behavior. The nature and identity of these quantities, as well as the laws which they obey, are the results of a large amount of experimental study, followed by theoretical correlation of the results of the experiments. Accordingly, many of the statements in the earlier sections of this chapter may appear arbitrary or without reasoned support simply because their justification rests solely on the fact that they satisfy all known experiments.

The most elemental quantity is *electric charge*, or quantity of electricity, just as volume of liquid may be considered elemental in hydraulic studies or displacement in mechanical studies. Charges may be positive (as in a proton) or negative (as in an electron). In the mks system, charge is measured in *coulombs*. For example, the charge on an electron is negative and equal to 1.591×10^{-19} coulomb. Conversely, about 6.4×10^{18} electrons are required to form a quantity of electricity equal to 1 coulomb.

The presence of charge gives rise to the possibility of force effects in the region surrounding it. Specifically, two charges will repel or attract each other (depending on whether their signs are alike or unlike) with a force directly proportional to the product of the charge magnitudes and inversely proportional to the square of their separation. This effect is often described by saying that a field of force exists in the vicinity of the charge; the field of force is called the *electric field*.

We are, however, more interested in charges in motion than in charges at rest, for charges must move in order to bring about energy transfer. We are particularly (although not exclusively) interested in those situations where the motion is confined to a definite path formed by materials such as copper and aluminum, which experience has shown to be good *conductors* of electricity. By way of contrast, other materials, such as porcelain, mica, glass, and, under many conditions, air, are known to be extremely poor conductors. They are called *insulators* and are used to confine the electricity to the specific conducting paths by constituting barriers to departure from these paths. The paths are called *circuits*. They are the analogues of piping systems in the hydraulic case.

The rate of motion of charge in a circuit is called *current*. The unit of current is the *ampere;* one ampere exists when the charge flows at the rate of one coulomb per second. Expressed quantitatively,

$$i = \frac{dq}{dt} \qquad \text{amp} \tag{1-1}$$

or conversely,

$$q = \int i \, dt \qquad \text{coulombs} \tag{1-2}$$

q being the charge flowing and t the time in seconds. The lower-case letters i, q, and t are used to represent the general case where i and q may be functions of time. Capital letters (for example, I, Q) will be used to represent magnitudes which are not time varying.

Notice that charge is the quantity which flows through the circuit; current is the time rate of flow of charge and is analogous to velocity in the mechanical system or to rate of fluid flow in the hydraulic system. Like velocity, current has both magnitude and direction. The direction of positive current is the direction of flow of positive charges, or opposite to the direction of electron flow.

Energy changes or energy transfer generally accompany the motion of electric charges. The *potential difference* between two points a and b in a circuit is the work or energy associated with the transfer of a unit positive charge (1 coulomb) from one point to the other. In mks units, the work or energy per unit charge is measured in *volts;* voltage is analogous to force in the mechanical system and to pressure or head in the hydraulic system. The energy associated with moving a charge q through a potential difference of e volts is

$$W = eq \quad \text{joules, or watt-sec} \tag{1-3}$$

If work has been done on the unit charge and consequently its potential energy increased in going from a to b, a *voltage rise* exists in the direction from a to b. Conversely, a *voltage drop* exists in the direction from b to a, for a unit positive charge would lose potential energy in going from b to a. When several alternative circuit paths exist between a and b, these statements are true regardless of which path is chosen. A potential difference associated with a source of electrical energy (i.e., associated with energy conversion, as in a battery, where chemical energy is converted to electrical energy) is called an *electromotive force* (abbreviated *emf*).

When a current exists in a circuit, another type of field of force comes into being in the vicinity of the circuit. This field, called the *magnetic field,* exists simultaneously with the electric field caused by the charges. It is capable of causing forces on other current-carrying elements or on pieces of iron. When the current causing it is changing with time, it is also capable of creating voltages, called *induced voltages,* in nearby circuits. These magnetic effects will be studied in Chap. 8. For the moment, the magnetic field may be regarded as an additional factor affecting the power- and energy-transfer properties of electric circuits.

In addition to the symbol e used in Eq. (1-3), the symbol v is also used to indicate voltage. For electric machinery and circuits associated with machinery, symbolic distinction is commonly made between the voltages induced within a machine and other voltages by the use of e for the former and v for the latter. Conventional symbols used in electronics do not make this distinction, however, the symbol e being used for all voltages. In this book the symbol e will be used except in the chapters dealing with transformers and machinery (Chaps. 9 to 14), when the above symbolic distinction between e and v will be made.

The *power*, or the rate at which energy is transferred, is the time derivative of the energy. Accordingly, power p is

$$p = \frac{dW}{dt} = e\frac{dq}{dt} = ei \qquad \text{watts, or joules/sec} \qquad (1\text{-}4)$$

If, as is true in many problems, the current and voltage are functions o time, the total energy involved in the transfer may be expressed as

$$W = \int_0^t p\,dt = \int_0^t ei\,dt \qquad \text{watt-sec, or joules} \qquad (1\text{-}5)$$

When e and i are constant at the values E and I (independent of time), the energy in time t becomes

$$W = EIt \qquad \text{joules} \qquad (1\text{-}6)$$

Table 1-1 gives a summation of the electric-circuit quantities with units and interrelationships. Shown also are the equivalent quantities in mechanical and hydraulic systems.

1-2. Electric-circuit Constants. In analyzing electric circuits, one or more impressed voltages (energy sources) may usually be regarded as the *cause* in the cause-and-effect relationship being studied. The currents which are brought into being in the various parts of the circuit may be looked upon as the *effect* in which one is interested, for when current is evaluated, other pertinent quantities may be obtained from relations such as Eqs. (1-2) to (1-6). The usual problem is to determine the effect (current) resulting from a known cause (voltage) or the cause (voltage) necessary to produce a desired effect (current).

TABLE 1-1. SUMMARY OF PRINCIPAL ELECTRICAL QUANTITIES

Electrical quantity	Symbol	Unit (mks system)	Related equation	Mechanical analogy	Hydraulic analogy
Charge.........	q, Q	Coulomb	....	Position	Volume
Current.........	i, I	Ampere	$i = dq/dt$	Velocity	Flow
Potential difference, or voltage	e, E, or v, V	Volt	$e = W/q$	Force	Head, or pressure
Power..........	p, P	Watt	$p = ei$	Power	Power
Energy, or work	W	Joule, or watt-second	$W = eq$, or $W = \int_0^t ei\,dt$	Energy, or work	Energy, or work

Relationships between voltages and currents in a circuit have been established on the basis of experiment. Three different types of interrelations exist, and hence three types of circuit elements must be recognized in order to include them. The interrelations and the corresponding types of circuit elements are as follows:

1. One type of circuit element requires a voltage directly proportional to the current through it. The constant of proportionality is called the *resistance*. This circuit constant, or parameter, is intimately related to energy dissipation as heat in the circuit. It will be studied in more detail in the next section.

2. Another type of circuit element requires a voltage directly proportional to the time derivative or rate of change of the current. The constant of proportionality is called the *inductance*. This circuit parameter is intimately related to the magnetic field of the circuit. It will be considered in Sec. 2-5.

3. The third type of circuit element requires a voltage proportional to the time integral of the current. The reciprocal of the constant of proportionality is called the *capacitance*. This circuit parameter is closely associated with the electric field of the circuit. It will be more fully introduced in Sec. 2-7.

All electric circuits consist of combinations of these three types of circuit elements, although for practical purposes, not all types need be considered present in every circuit. When a voltage is suddenly impressed on the circuit, the current ultimately follows a final pattern of behavior called the *steady state*. The steady state is not reached immediately, however, for an initial period of settling down to the final pattern is necessary. The period required for this adjustment is called the *transient* period. Predominant emphasis is given to the steady state in this book. An introduction to transient analysis is presented in Chap. 7.

1-3. Resistance; Ohm's Law. The first type of circuit element mentioned in the preceding section requires a voltage across the element directly proportional to the current through it. Expressed quantitatively, the voltage is

$$e = Ri \qquad \text{volts} \tag{1-7}$$

where i is the current in amperes. The proportionality constant R is the *resistance* of the element and is measured in *ohms*. A physical device whose principal electrical characteristic is resistance is called a *resistor*. The voltage-current relation expressed in Eq. (1-7) is known as Ohm's law.

Electrical resistance is comparable to pipe friction in the hydraulic analogue and also to friction in a mechanical system. Resistance or friction directly opposes the current, water flow, or motion, and the