PRINCIPLES

OF

ELECTRICAL ENGINEERING

BY

WILLIAM H. TIMBIE

Professor of Electrical Engineering and Industrial Practice
Massachusetts Institute of Technology

AND

VANNEVAR BUSH

President of Carnegie Institution of Washington

THIRD EDITION
Tenth Printing

NEW YORK

JOHN WILEY & SONS, INC.

LONDON: CHAPMAN & HALL, LIMITED

THIRD EDITION
Tenth Printing, December, 1947

PRINTED IN THE UNITED STATES OF AMERICA

PRINCIPLES OF
ELECTRICAL ENGINEERING

WORKS OF W. H. TIMBIE

BASIC ELECTRICITY FOR COMMUNICATIONS

603 pages. Cloth.

INDUSTRIAL ELECTRICITY: Direct-Current Practice

Second Edition. 635 pages. Cloth.

ELEMENTS OF ELECTRICITY

Third Edition. 569 pages. Cloth.

ESSENTIALS OF ELECTRICITY

Second Edition. 306 pages. Cloth.

By W. H. TIMBIE *and* H. H. HIGBIE

ALTERNATING-CURRENT ELECTRICITY AND ITS APPLICATION TO INDUSTRY

By W. H. Timbie and H. H. Higbie, Professor of Electrical Engineering, University of Michigan.

FIRST COURSE. *534 pages. Cloth.*

SECOND COURSE. *729 pages. Cloth.*

ESSENTIALS OF ALTERNATING CURRENTS

Second Edition. 377 pages. Cloth.

By W. H. TIMBIE *and* VANNEVAR BUSH

PRINCIPLES OF ELECTRICAL ENGINEERING

By W. H. Timbie and Vannevar Bush, President, Carnegie Institution of Washington. Third Edition.

542 pages. Cloth.

PREFACE TO THE THIRD EDITION

This third edition has been prepared in order that the text may continue to be abreast, not only of advances in the theory and practice of Electrical Engineering, but also of the advances in teaching methods which have been made since the last edition.

Electric power and communication systems continue to increase in scope and in complexity of interconnection. New types of communication channels employing high frequencies have appeared. The thermionic tube has found new and important uses in radio and wire communication, and in highly diverse applications elsewhere. This trend has emphasized the need for more powerful methods of analysis in connection with the extremely varied electrical circuits now employed.

Fundamental physics which forms the basis for electrical engineering has made striking advances. Some of these, particularly in the field of atomistics, have been spectacular. A far better understanding is being secured of the difficult phenomena of the conduction of electricity through gases, liquids, and solids. The physics basis of electrical engineering is becoming more extended and better established.

These two trends have necessitated modifications of this text, largely in the direction of further stressing of powerful analytical methods and still greater attention to the manner in which the transition from physics to engineering is accomplished.

Since this text is designed primarily for sophomores and juniors in Electrical Engineering, it does not enter into the more advanced physical or electrical engineering theories or make use of mathematics beyond differential equations. Nevertheless it is important that the ground covered should be consolidated in such manner that later advanced work will occasion no abrupt transition in the mind of the student. Starting on ground familiar to the student who has completed a good course in college physics, it therefore develops step-by-step as much electronic theory as is immediately understandable at this stage, and as will subsequently form a necessary and sufficient basis as he proceeds, if he is to complete a full course in Electrical Engineering. This same basis is adequate for those who will later build upon it the advanced circuit and field theory of post-graduate study in either physics or engineering.

The general arrangement of the previous editions has been retained.

The unrationalized MKS system of units is introduced early in the text, and, together with the *cgs* system is employed throughout.

In the preparation of this edition the authors have had the assistance of Dr. George B. Hoadley, formerly on the staff of the Massachusetts Institute of Technology, and now Assistant Professor of Electrical Engineering at the Polytechnic Institute of Brooklyn. The authors express their deep appreciation of the scholarly attainment which he brought to the task, and express their sincere thanks for his enthusiastic and conscientious efforts to produce a sound and teachable text.

WILLIAM H. TIMBIE
CAMBRIDGE, MASS.
August, 1940

VANNEVAR BUSH
WASHINGTON, D.C.

NOTE TO THE 1942 PRINTING

The 1942 printing of the third edition differs from the 1940 printing in that more material on communications has been added. The changes consist mainly of additional communication problems in some of the chapters, and in others the substitution of communication problems for former power problems.

PREFACE TO THE FIRST EDITION

This text is the outgrowth of experience in teaching the principles of electrical engineering to students of electrical engineering at the Massachusetts Institute of Technology. It aims to provide a substantial first course in the subject by presenting rigorously, and at the same time in understandable form, the really basic principles upon which modern electrical engineering rests. In furtherance of this purpose many problems and examples from current engineering practice are introduced. The book is not, however, to be mistaken for a complete condensed treatise on the entire subject. It is strictly a first course on the principles, and its study should be followed by detailed courses in direct-current and alternating-current machinery. Wherever applications of the principles are introduced, they are for the purpose of illustrating these principles and rendering them real and alive to the student.

The book has the following special features, which we believe to be desirable:

1. The subject of the magnetic circuit has been stressed. It has been the common experience of teachers of electrical engineering that students beginning the subject find this a stumbling block. Much more space than is usual has, therefore, been devoted to this matter.

2. As a basis for explanation, the modern electron theory has been freely used. It has been found that this affords the most rational means of tying together the otherwise widely divergent principles with which the electrical engineer deals.

3. The subjects of thermionic emission, conduction through gases, electrolytic conduction and certain high-frequency phenomena have been included. A knowledge of these matters is becoming more and more essential to the electrical engineer in any field.

4. The subject of the behavior of dielectrics has been approached from a standpoint which departs from the historical method of attack in order to gain clearness and unity of treatment.

5. About five hundred live problems are included for illustration, for practice in applying the principles and for the purpose of

bringing before the student useful and interesting engineering data. Some of these are purposely made of such calibre as to merit the attention of the most able students.

The book is written primarily for students of college grade and presumes a knowledge of calculus and physics. The terminology and symbols employed are those recommended by the American Institute of Electrical Engineers.

Grateful acknowledgment is extended to Professor F. S. Dellenbaugh, Jr., for oscillographs of transients, and to Mr. E. L. Bowles, Mr. L. F. Woodruff and Mr. E. L. Rose for diagrams, proofreading and the checking of problems.

W. H. T.
V. B.

CAMBRIDGE, MASSACHUSETTS
February, 1922.

CONTENTS

PRINCIPLES OF ELECTRICAL ENGINEERING

CHAPTER I

SOME FUNDAMENTAL CONSIDERATIONS

1. Energy. One of the most fundamental concepts of physics is that of energy. We find it most difficult to define, because it is so elemental that there is nothing to use as a basis for a definition. Instead, we try to understand the concept and to recognize energy whenever it is present in any one of its many forms.

We are all familiar with the energy possessed by a moving object, such as a baseball. Likewise, we know that this energy can leave the ball if conditions are right. When the ball knocks a tin can from the top of a fence post, the can acquires some of the ball's energy. When we catch the ball barehanded, we are usually aware of the energy transferred from the ball to our hands!

Energy does not need to be closely associated with any physical body; it may be cast out in the form of radiation. To us, sunshine is the most important radiant energy, because nearly all the energy which we use came originally from the sun at some time in the past.

After energy leaves the sun, about eight minutes elapse before it reaches the earth. If the sun were suddenly to cease radiating, we would be unaware of it for eight minutes after the catastrophe, because we would still be receiving the energy which was on its way to us when the sun went out.

One of the first places where we encounter quantitative relations regarding energy is in mechanics, when we study work. A force F moving through a distance D, in the direction of F, does an amount of work equal to FD. In other words, the force and the motion transfer energy from one form to another. Thus, if F lifts a weight against the force of gravity to a height D, the weight acquires energy of position, or potential energy, at the expense of the mechanical system. Likewise, if the force F is pushing against friction, the work done is the mechanical energy which is transformed into heat.

It is our belief, and it is backed by a vast quantity of experimental evidence, that energy can never be created or destroyed. We say that energy is conserved. The only thing that energy does, except fly about the universe, is to change its disguise. One instant it is associated with a moving ball. The next it is heat in the catcher's mitt.

We have come to have a good knowledge of many of the forms which energy may assume. The most common are mechanical, thermal, chemical, electrical and radiational. Close examination shows that sometimes the boundaries between some of these forms are not sharp, but for many of our problems of engineering, such a classification is handy.

One of the most interesting ideas that has come from the laboratories of the nuclear physicists in the past few years is that matter or mass can be thought of as a form of energy. Experimentally it is possible to convert mass into energy, and the experiments agree quantitatively with the theory. The possibility of using mass as a source of energy is exciting, but at present it is not of engineering significance. Whether it will always remain so is a question which the future alone can answer; so we will omit mass energy from our present discussion.

Conversion of energy from one form to another is one of the fundamental processes of engineering. Many of our machines are simply devices for this purpose. Steam boilers, turbines, generators, motors, telephones and radios are all examples of this type of machine.

In general, there are two types of conversion. For example, mechanical energy can be converted into heat energy by rubbing two pieces of wood together. Friction is the name we give to this method of conversion. It is a one-way affair, however, for the blocks of wood won't move as a result of applied heat. Such a process of conversion is said to be non-reversible. On the other hand, if we suddenly compress a gas, the temperature of the gas rises showing that mechanical energy has been converted into heat energy. This conversion can operate backwards, however, for if we allow a compressed gas to expand suddenly, its temperature falls, showing that heat energy has been converted into mechanical energy. Thus we find two types of energy conversion, one which is non-reversible and another which is reversible.

Most of this book will have as its underlying theme the means by which energy is converted to and from the electrical form. Usually, we shall speak of the **time rate** of energy conversion, which is called power.

There are two units of electrical energy in common use, the **joule** and the **kilowatt-hour.**

1 joule	= 1 watt-second	
1 joule	= 0.738 foot-pound	= 9.48×10^{-4} Btu.
1 kilowatt-hour	= 2.655×10^{6} foot-pounds	
	= 3413 Btu.	

Likewise there are two units of electrical power, the **watt** and the **kilowatt.**

1 watt	= 1 joule per second
1 watt	= 0.738 foot-pounds per second
1 kilowatt	= 1.341 horsepower.

2. Sources of Energy. Our principal sources of energy can be divided into two groups. In the first group we place all those in which the energy is held chemically. Such substances as coal, oil, natural gas, and wood belong in this source group. The energy in them is released by chemical reaction and usually appears as heat energy. In other words, we obtain the energy by making use of the chemical process of oxidation or burning. In the second group we place those sources of energy in which the energy is in the mechanical form. The energy of a waterfall, of wind, and of the tide is all mechanical energy.

Some of the energy in nature cannot be placed in either of these groups. Lightning is an example, but we do not look upon it as a source which can be tapped for our own use. It is too unreliable. Sunshine is another source of energy which cannot be placed in either group. At present, the energy in sunshine is used directly to only a slight extent in water heaters and refrigerators. Indirectly, sunshine is of vast importance in its solar form in promoting plant growth. The energy of burning coal and wood is the energy of sunshine which plants in the past have used in their growth.

Sunshine is also of great importance in causing evaporation of water. The sun provides the energy to raise the water to form clouds, and we can obtain some of this energy at waterfalls as the rain-water drains down to the ocean.

In the last analysis, we are dependent upon the sun for our whole energy supply. We have certain reserves which have been built up in the past, but these we are using up. Eventually they will be exhausted, and it will be necessary to obtain our energy directly from the sun.

Various attempts have been made to convert solar energy into such a form that it can be used by industry, but so far the results have not been generally satisfactory. At present, there is a 50-year program of research in progress, the purpose of which is to develop means for the direct use of solar energy in an economical way.

3. Uses of Energy. The ways in which we use energy are amazingly varied. Each problem presents its own particular requirements, and we often are faced with the problem of choosing among several different methods.

For example, consider the problem of house heating. Obviously, it is heat energy that we desire, but shall we burn coal, oil, gas or wood? Shall we use a hot water system, vapor system, hot air system, etc.? Among the factors which must be considered in making our decision are the cost, convenience and availability of the fuel, and the cost, reliability and effectiveness of the apparatus.

As another example consider the forming of a piece of metal. Several methods present themselves. We can machine the piece in a lathe with mechanical energy. We can cast it, using heat energy to melt the metal. We can forge it, using heat and mechanical energy together. It is the engineer's problem to decide what method to use.

It is seldom that we want energy itself as a final product. Rather do we use energy as one of several tools with which to realize our aims. In the first example above, the primary object is to keep our house comfortable in cold weather. The heat energy from the radiators is only the means to the end. If the house were well insulated much less heat energy would be needed for comfort.

Likewise in our second example, the energy involved in forming the piece of metal is only a tool which is used in the making of the finished product. Numerous similar examples can be cited.

4. The Transportation of Energy. Energy can be transported or transmitted in nearly all of its forms. The choice of which form to use is usually made on the basis of cost, convenience, and

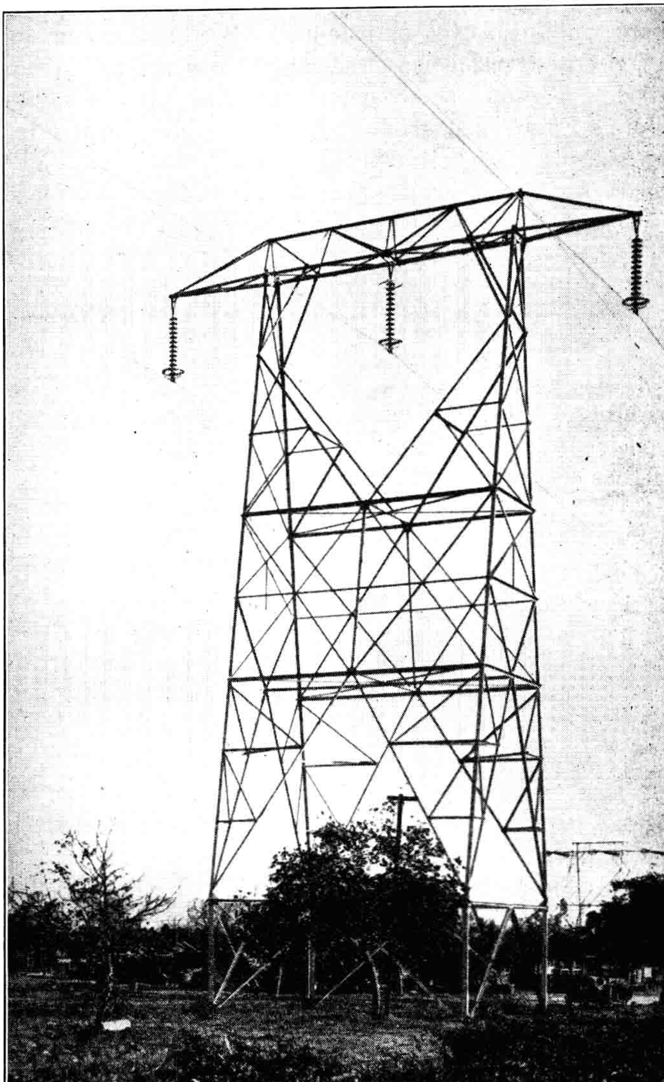

FIG. 1. One of the towers of the Southern-California-Edison 220,000-volt transmission line. *General Electric Co.*

the use to which the energy is to be put. Over very long distances, it is common to send energy by shipping coal, oil, or gas in barges, railroad cars, or pipe-lines. For distances up to 300 miles, electric transmission of energy is a competitor of the other methods. Figure 1 shows one of the towers of the Southern-California-Edison 220,000-volt line over which electric energy is transmitted more than 200 miles. The form which is adopted depends to a certain extent upon the use which is to be made of the energy. For example, gas and electricity compete keenly with each other in the field of home cooking, whereas electricity is uncontested in the field of lighting. For shorter distances, still other methods of energy transmission become important, and here again, competition between various types may be keen. As an example we may consider the problem of supplying energy to the wheels of a moving vehicle. In automobiles, the energy from the engine is transmitted to the rear wheels as mechanical energy by means of a rotating shaft. In an electric locomotive, gearing is used. In a diesel-electric locomotive, Fig. 2, a diesel engine drives an electric generator, which in turn drives electric motors which deliver energy to the wheels by means of gears.

5. The Utility of Electric Energy. Electric energy can be regulated and controlled much more easily than some other forms of energy. It has therefore come to serve in many ways other than in transmission and distribution. Our modern systems of communication, the telegraph, telephone, teletype and radio are all made possible because electric energy can be controlled so easily, and because it can be transmitted rapidly. Today we can talk by telephone to almost any part of the civilized world at a cost that is not prohibitive.

The very flexibility which makes electrical energy easy to control enables us to use electricity to measure and control other things. Temperatures can be measured by thermocouples, and additional equipment can be so arranged that these thermocouples **control** the temperature of a furnace, keeping it constant at a predetermined value. This is of vital importance in the production of many manufactured products. The world is full of electrical apparatus for doing all sorts of measurement and control jobs.

6. The Engineer. As we have remarked previously, two of the engineer's primary occupations are the transmission and the conversion of energy. The engineer is presented with a job to be done. He gathers together all the available data, then weighs

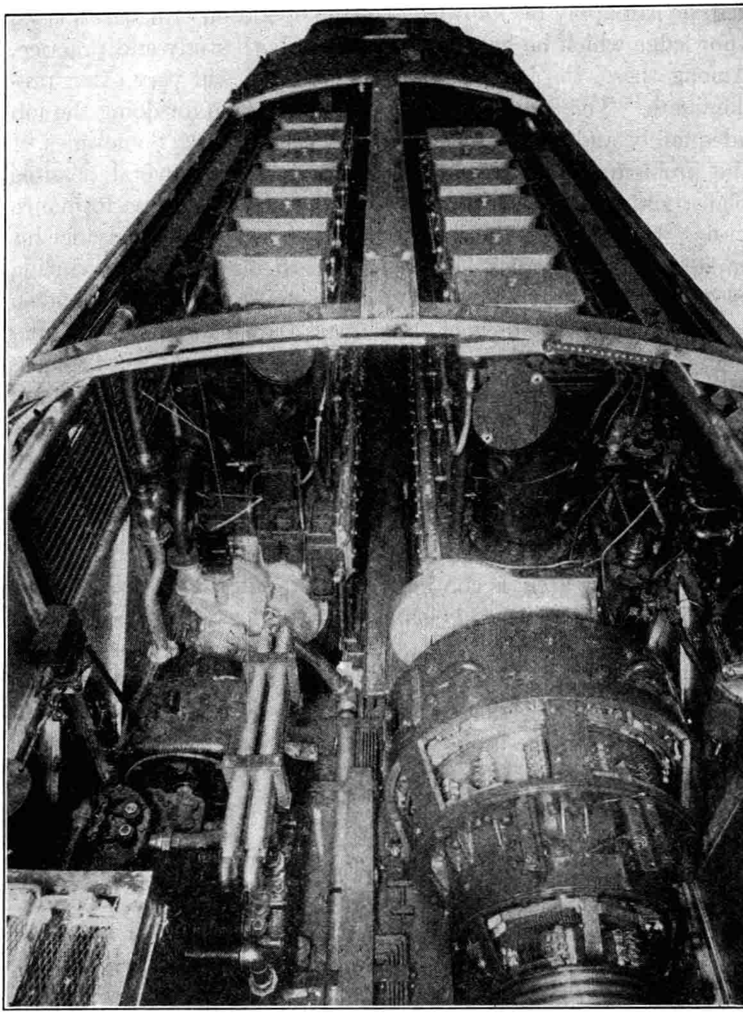

FIG. 2. An Illinois-Central R. R. diesel-electric locomotive with hatch covers removed showing arrangement of diesel engines, generator, compressor and air-brake equipment. The two Ingersoll-Rand diesel engines develop 900 hp each. *General Electric Co.*