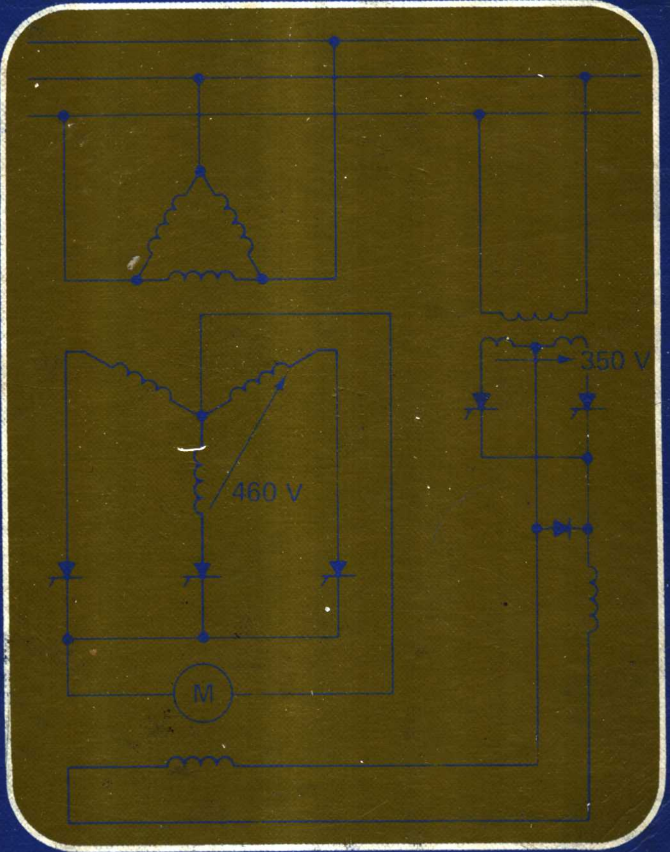
Electrical Machinery, Transformers, and Controls



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Preface

This text is designed to support a two-semester course within an electrical technology curriculum on the fundamentals of machinery and power transformers and basic concepts of control systems and power electronic circuits.

The level of the text assumes that the reader is schooled in basic electric circuit theory and in algebra and trigonometry. Since introductory circuits courses often do not include a study of three-phase power, this topic is discussed in an appendix. Further, circuits courses treat magnetism primarily from the viewpoint of inductance; to provide an adequate basis for understanding electromagnetic devices, magnetism and magnetic circuits are covered in the introductory chapter.

Despite temptation, there is no calculus in this text. Consequently, mathematical analysis generally is limited to steady-state operating conditions, but transients are discussed where they are a significant consideration in machine or system performance. The mathematical limitation is no millstone; ANSI and IEEE Test Codes applicable to equipment discussed in the text contain remarkably little calculus. A mathematical summary is included as an appendix.

The unified approach to machinery, common in engineering texts, is inappropriate at the technology level. It is highly unlikely that the idea of an induction *generator* ever entered Tesla's mind while he was developing the induction *motor*. Herein, the focus is on unique machines, but similarities are not ignored and generally are used in the transition from one to another. The stress is on deducing performance by considering the physical interactions of electricity and magnetism rather than by abstract interpretation of mathematical equations. One objective is to develop an ability to rationalize the performance of a device by analysis of the electrical and mechanical structure.

Systems are discussed to permit an appreciation of the role and performance of component equipment. The depth of the treatment necessarily is limited—whole textbooks are devoted to control systems, for example—but the presentation should adequately meet the needs of most students.

The rapid development and future potential of solid-state power electronics have made this topic a *must* in a contemporary discussion of power systems. The physics of semiconductors and the application of devices in low-power circuits are amply covered in electronics texts. In a typical electrical/electronics curriculum, the novel aspect of power electronics is the application of semiconductor devices in controlled converters—it is this that is discussed in the text. Logic circuits are important elements both in power electronics and as a replacement for many electromagnetic components in machine controls; however, because of practical limitations and a recognition that courses in logic are not uncommon in technology curriculums, this subject is generally excluded. Finally, to permit evaluation of output characteristics, particularly with delayed firing in-controlled semiconductors, some discussion of transients in sinusoidal circuits is included.

Although intended for a two-semester course, the organization of the text permits selective use in courses of lesser duration, tailored to the desired local emphasis.

A conscious effort has been made to adhere to ANSI, IEEE, and NEMA standards in terminology, definitions, symbols, testing, and so on. Similarly, problems largely reflect standardized equipment and normal machine parameters and performance.

The contributions of my wife, Helen, to the production of this text are enormous. Without her encouragement, tolerance, critical comment, and Herculean performance in producing the final manuscript, the book never would have progressed beyond a tentative project in the mind of a confirmed procrastinator.

Also in order are thanks to my colleagues at Westchester Community College for making it possible for me to concentrate upon this task.

HAROLD W. GINGRICH

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1

Basic Concepts

1-1. INTRODUCTION This book is a study of practical devices and systems all of which are functionally dependent upon interactions between electricity and magnetism. Properly exploited, electrical and magnetic phenomena allow transformation of electrical power between differing voltage–current combinations, conversion between electrical and mechanical energy, and regulation and control of electrical and mechanical system characteristics.

The explanation of the functioning and analysis of the devices in the following chapters relies upon a basic understanding of the fundamental principles of electromagnetic induction, force, and torque, and upon analytical methods appropriate to the development. This chapter highlights principles that are recurrent throughout the text.

The text assumes that the reader has a sound preparation in algebra, trigonometry, and electrical circuit theory. Regarding the latter, the modern interest in electronics has influenced circuit texts and courses to the detriment of the study of polyphase systems; since this topic is fundamental to a study of commercial and industrial power applications, the essentials are presented in Appendix A.

SECTION 1-1. UNITS

1-2. SYSTEMS OF UNITS The movement toward metrication in the United States must be recognized, but **U.S. customary units** (US) will remain for many years and cannot be ignored. Consequently, both systems are employed in this book, with the attendant requirement for interconversion.

In the fields of engineering and science, metrication has broader connotations than direct substitution of meters for yards or kilograms for pounds. An important aspect is standardization of physical units through adoption of the **International System of Units** (SI). SI defines seven base units: meter (m), kilogram (kg), second (s), ampere (A), kelvin (K), mole (mol), and candela (cd). All but the latter two are pertinent to the study of machinery.* Two supplementary units, the radian (rad) and steradian (sr) for plane and solid angles, respectively, also are specified.

All other units are derived and may or may not have special names. For example, the unit of angular velocity is radians per second (rad/s), but the force unit, the product of mass (kg) and acceleration (m/s^2) resulting in $kg \cdot m/s^2$, is termed newton (N). Derived units may be defined by combinations of base, supplementary, and previously derived units but always are traceable to base and supplementary units; for example, work or energy is the product of force and distance ($N \cdot m$) and has the special designation joule (J), which, in base units, is $kg \cdot m^2/s^2$.

The base units of fundamental electrical properties may be derived from formula relationships. In the following development, the distinction between the terms *quantity* and *unit* must be recognized. A unit is a standard, finite amount of a property in terms of which any amount of the property may be measured.

Quantity appears in equations as an indefinite amount of a property; the equation, when mathematically satisfied, interrelates specific amounts (expressed in units) of the elements appearing in it. The symbols for unit and quantity of a specific property may or may not be identical: for example, V represents both the quantity (voltage) and the unit (volts), but the quantity for power is P while the unit is W (watts). W also symbolizes the quantity, work (or energy), whose unit is joule (J); duplications of this type are common, but no confusion arises if one is alert to the distinction and notes the sense in which the symbol is used.

CURRENT. SI unit: ampere (A)

This is a base unit.

VOLTAGE. SI unit: volt (V)

$$\text{(Quantity)} \quad V = \frac{W}{Q} = \frac{W}{It}$$

---

*The kelvin is a temperature unit. In lieu of it, the degree Celsius (C), formerly termed centigrade, is permitted in SI. 1°C = 1 K.

(Unit) $$\mathrm{V} = \frac{\mathrm{J}}{\mathrm{A\cdot s}} = \frac{\mathrm{kg\cdot m^2/s^2}}{\mathrm{A\cdot s}} = \frac{\mathrm{kg\cdot m^2}}{\mathrm{A\cdot s^3}}$$

POWER. SI unit: watt (W)

(Quantity) $P = VI$

(Unit) $$\mathrm{W} = \frac{\mathrm{kg\cdot m^2}}{\mathrm{A\cdot s^3}}\cdot \mathrm{A} = \frac{\mathrm{kg\cdot m^2}}{\mathrm{s^3}}$$

RESISTANCE. SI unit: ohm (Ω)

(Quantity) $R = \dfrac{V}{I}$

(Unit) $$\Omega = \frac{\mathrm{kg\cdot m^2/A\cdot s^3}}{\mathrm{A}} = \frac{\mathrm{kg\cdot m^2}}{\mathrm{A^2\cdot s^3}}$$

Initially, some US units will seem strange when converted to SI. The kilowatt as an electrical power unit is commonplace, but a 74.6-kilowatt (not 100-horsepower) motor is not. US units will not disappear overnight but gradually will yield to SI. In technical professions, transition will be more rapid than in the public sector—pending common acceptance of SI, the technician has a continuing requirement for dual-system competency.

Fortunately, interchange between SI and US units usually requires only the application of a conversion factor; thus, 50 miles per hour is readily converted to ($50 \times 1.6 =$) 80 kilometers per hour. SI and US units and conversion factors appearing in this book are listed in Appendix B. The tabulation of US units is limited to those most commonly used in this area of study.

One problem in the US system is multiplicity of units for a single characteristic. For example, volume may be expressed in cubic yards, cubic feet, cubic inches, quarts, gallons, bushels, etc. There is no uniform numerical relationship between these units: e.g., 1 $\mathrm{yd^3} = 27\ \mathrm{ft^3}$, 1 $\mathrm{ft^3} = 1728\ \mathrm{in^3}$. In SI, volume is the cubic meter. But a cubic meter is relatively large—one cubic inch is only $1.639 \times 10^{-5}\ \mathrm{m^3}$. Commonly, working quantities are significantly larger or smaller than the SI unit. Large or small quantities are specified by standardized multiples representing 10^{3n}, where n is a positive or negative integer—e.g., 10^{+6}, 10^{-9}. Each multiple is assigned a specific name and symbol that may prefix any SI unit. For example, the prefix kilo (10^3), symbol k, appears in kilometers (km = 1000 m), kilovolts (kV = 1000 V), kilowatts (kW), and so on. The SI prefixes are tabulated in Appendix C.

A special caution applies to computations with prefixed units. Formulas are expressed in fundamental units. Thus, Ohm's law, $E = IR$, relates the fundamental unit volt to the product of the fundamental units ampere and ohm. If the current quantity were in milliamperes ($\mathrm{mA} = 10^{-3}\ \mathrm{A}$) and R in ohms, the product would be not volts but millivolts (mV)—that is, $E = (10^{-3}\ \mathrm{A})(\Omega) = 10^{-3}\ (\mathrm{A\cdot\Omega}) = 10^{-3}\ \mathrm{V}$. Similarly, the product of milliamperes and megohms is $(10^{-3}\ \mathrm{A})(10^6\Omega) = 10^{+3}\ (\mathrm{A\cdot\Omega}) =$ kilovolts (kV).

Yet another caution is in order when prefixed units are exponential. The exponent applies not only to the unit but also to the prefix. For example, $(0.001 \text{ m})^2 = (10^{-3} \text{ m})^2 = 10^{-6} \text{ m}^2$. Prefixed, the form is mm^2—that is, $(10^{-3} \text{ m})^2$—*not* μm^2, which would be $(10^{-6} \text{ m})^2$.

In converting between systems of units, rounding of the arithmetic answer is in order. How do you determine the proper rounding? There is no simple rule for universal application, but common sense and experience usually suggest the answer.

The converted unit can be no more accurate than the original quantity. Assume that an object is measured with a ruler graduated in sixteenths of an inch, and the length is $7\frac{1}{4}$ inches to the nearest graduation. Actual length may be $\frac{1}{32}$ inch greater or lesser ($\pm\frac{1}{32}$ in). One inch equals exactly 25.4 millimeters. Converting, the length is $(7\frac{1}{4} \times 25.4)$, or 184.15 mm. However, $\frac{1}{32}$ in $= (\frac{1}{32})(25.4) = 0.79375$ mm; based on the original measurement accuracy, the length is 184.15 ± 0.79375 mm. Under these circumstances, a converted length implying an accuracy greater than 184 mm is unjustifiable. However, since the actual length lies somewhere between 183 and 185 mm, rounding the answer to 180 mm sacrifices accuracy; whether or not this sacrifice is acceptable depends upon the purpose of the measurement. Four millimeters are approximately $\frac{5}{32}$ of an inch; if the purpose of the measurement were to cut a pane of glass to fit inside a molding with a $\frac{1}{4}$-in lip, 180 mm would be satisfactory, but if it were for the purpose of cutting one replacement leg for a four-legged stool, a 4-mm discrepancy would cause the stool to wobble.

In making a conversion, the converted unit—*not* the original quantity and the conversion factor—should be rounded. For the example, if the length were rounded to 7 in and the conversion factor to 25, the converted length would be 175 mm, a difference of 9 mm, or nearly $\frac{3}{8}$ in.

In analytical computations within this text, some unpredictable factors normally are involved. Further, relationships frequently are based upon simplified or idealized assumptions. There is no justification for computed answers with the 8 to 10 significant digits that commonly are provided by electronic pocket calculators. In general, slide-rule precision is appropriate. Therefore, unless there is reason for deviating, the examples and problem answers retain three significant digits or, if the first digit is one, four digits.

SECTION 1-2. MAGNETISM

1-3. MAGNETISM AND THE MAGNETIC FIELD

Michael Faraday (1791–1867) originated a concept of magnetic lines of force (also termed lines of induction) as a means of analyzing and explaining magnetic phenomena. In Fig. 1-1(a), visible lines, each representing thousands of force lines, portray typical paths around a permanent magnet. Some fundamental characteristics are apparent on the sketch.

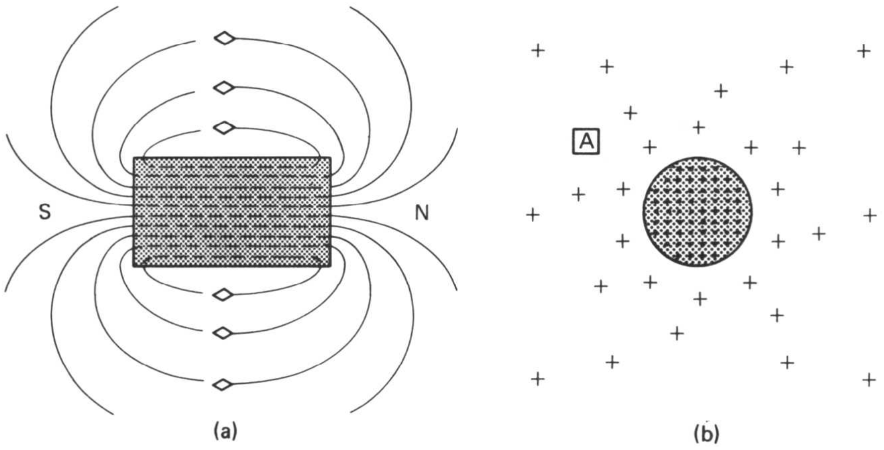


Figure 1-1 Force Lines Surrounding a Magnet

Magnetic Lines of Force Form Closed Loops. The lines exist within the body of the magnet and continue externally in order to close the loop.

Lines Are Directional. All lines emerge from one general area of the magnet, the **north** pole, and reenter at a different area, the **south** pole. Internally, the line direction is south to north; externally, north to south.

Lines Do Not Intersect. No two lines can occupy the same space or pass through a common point.

Although not graphically apparent, the following additional characteristics help explain those which can be represented.

Lines Are Mutually Repellent. Just as two like electrical charges exert mutually repellent forces, two proximate lines of induction experience forces which tend to separate them. The separating force is countered by yet another characteristic, as follows.

Lines Are Tensile. Blowing into a rubber balloon raises the internal pressure above atmospheric and forces the shape outward; this stretches the rubber, causing an increase in its elastic tensile forces. The size of the inflated balloon results from a balance between the forces of tension and pressure. Similarly, the path of a force line is fixed by a balance between the repellent forces of other lines and an inherent tensile force that causes the line to contract to the shortest permissible path.

Lines Seek Low-Reluctance Paths. Free space and most materials are difficult mediums for occupancy by force lines. However, one category of material, *ferromagnetic*, permits easy passage. Like resistance, the opposition to electrical current flow, *reluctance* is opposition to the creation of lines of force. Ferromagnetic materials have low reluctances. Thus, despite the contracting tendency, many force lines will deviate from a short, high-reluctance path and follow a longer, lower-reluctance route through a ferromagnetic body. Once the force lines are in the body, the tensile forces of the lines act to draw the body to the magnet; if the tensile forces are greater than opposing forces, the body moves. The result (Fig. 1-2) is the commonly known attraction of a magnet for certain materials.

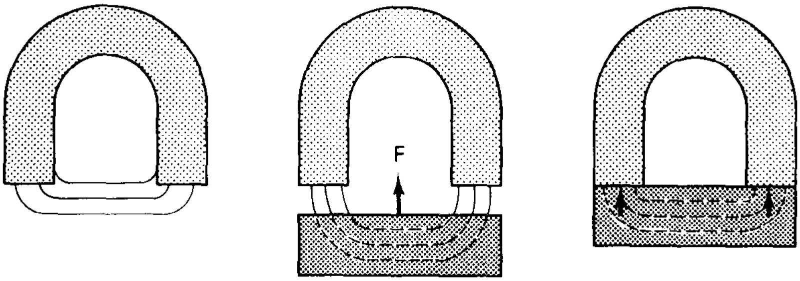


Figure 1-2 Magnetic Attraction of Iron

The general term for lines of force is *magnetic flux*, symbol Φ. The US unit is *line* or, interchangeably, *maxwell.* The SI unit is *weber* (Wb): 1 Wb $= 10^8$ lines or maxwells.

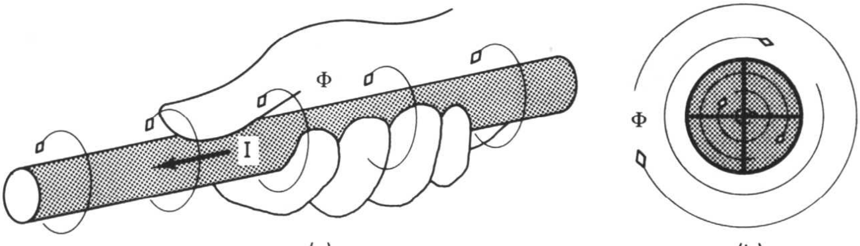
Figure 1-1(b) shows the flux through an area perpendicular to the axis of the magnet, viewed along the traverse direction of the external lines. The spacing of the crosses indicates variable density; near the body, the flux per unit cross section is large in comparison to more remote areas. Area A represents a very small area (approaching a point); let Φ represent the flux through this area. The *flux density* (B) at this site is given by the equation $\mathbf{B} = \mathbf{\Phi}/\mathbf{A}$. A common US unit of flux density is *lines/in*^{2} (or maxwells/in^2); the SI unit is the *tesla* (T)—one tesla equals one weber per square meter (Wb/m^2).

Laboratory-created densities may approach 10 T. The magnetic field of the earth is on the order of 50 μT, and practical densities in machines are on the order of 1 to 2 T.

1-4. ELECTROMAGNETISM

In 1820, Hans Christian Oersted (1777–1851) proved a direct connection between electric current and magnetic effects, thereby introducing the common study of electricity and magnetism. The evolutionary development in large measure resulted from the work of Faraday and James Clark Maxwell (1831–1879).

Oersted established the presence and direction of magnetic lines of force around any current-carrying conductor. In Fig. 1-3(a) the *right* hand grasps the conductor, with the thumb pointing in the conventional direction of current flow. The natural curl of the fingers around the conductor is in the direction of the force lines. These lines occur throughout the length, and form concentric circles both



(a) (b)

Figure 1-3 Right-Hand Rule

within and outside the conductor. Flux density is relatively large in the area close to the axis but decreases as the distance from the center of the conductor increases. Viewed in cross section, the spacing of the representative lines in Fig. 1-3(b) signifies varying external density.

Assume that a long, current-carrying conductor is formed into a coil with a number of closely packed loops [Fig. 1-4(c)]. The right-hand rule, applied to the adjacent conductors of Fig. 1-4(a), defines flux paths represented by the dashed lines. The space between the conductors would seem to have two vertical flux components, one up and the other down. But lines of force cannot occupy the same space and are mutually repellent; consequently, much of the flux will be forced into a path around both conductors as in Fig. 1-4(b). Thus, the flux created by each turn [Fig. 1-4(c)] follows a common path through the center of the coil, emerging at one end (north pole), traveling externally, and reentering at the south pole. Within the coil, the flux density is essentially constant throughout the cross section. Externally, except in the polar regions, the flux is distributed across broad

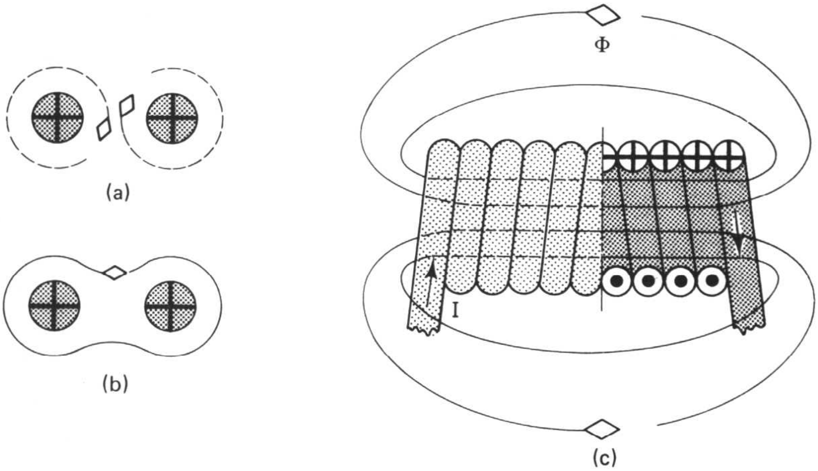


Figure 1-4 Electromagnet