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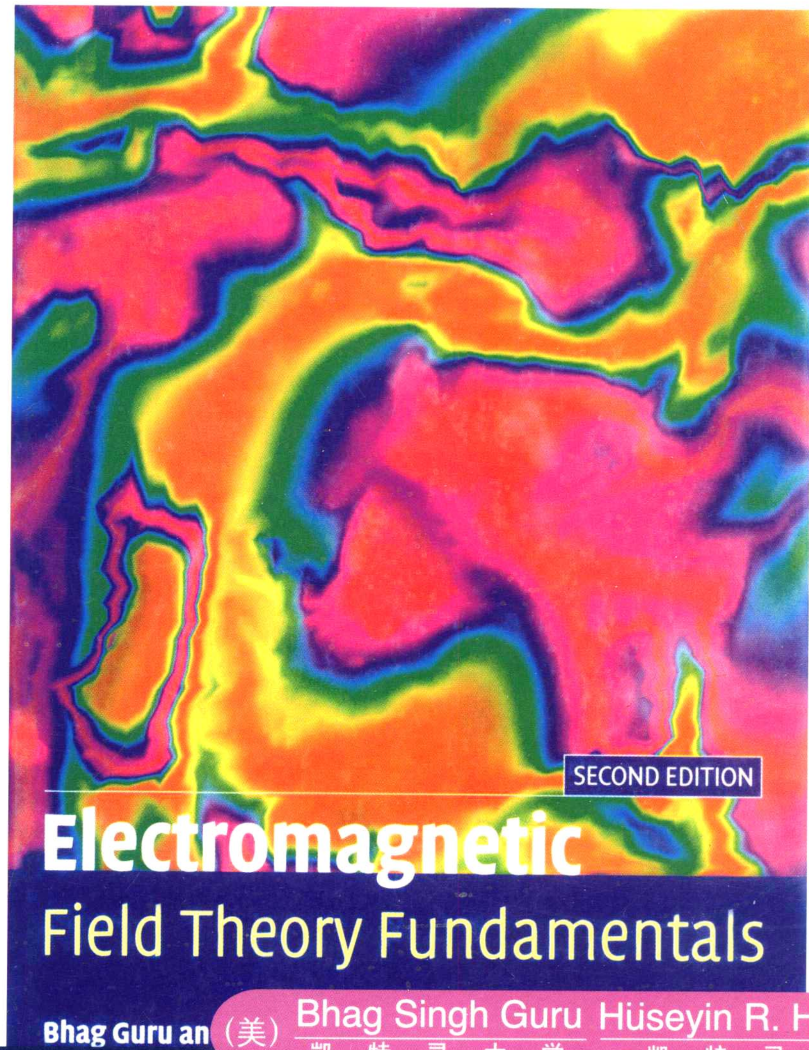

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Electromagnetic Field Theory Fundamentals

(Second Edition)

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Preface

Electromagnetic field theory has been and will continue to be one of the most important fundamental courses of the electrical engineering curriculum. It is one of the best-established general theories that provides explanations and solutions to intricate electrical engineering problems when other theories are no longer applicable.

This book is intended as a basic text for a two-semester sequence for undergraduate students desiring a fundamental comprehension of electromagnetic fields. The text can also be used for a one-semester course as long as the topics omitted neither result in any loss of continuity of the subject matter nor hamper the student's preparation for the courses that follows. This text may also serve as a reference for students preparing for an advanced course in electromagnetic fields.

The first edition of this book appeared in 1998 and was well accepted by both the students and the faculty. Among the numerous comments we received from the students, the one that transcends the others is that the book is written in simple, everyday language so that anyone can easily understand even the most sophisticated concepts of electromagnetic fields. We attribute such a favorable comment to the fact that the book was written from first-hand experience of class-room teaching. The development of this second edition also follows the same time-tested approach.

A thorough understanding of vector analysis is required to comprehend electromagnetic theory in a logical manner. Without much exaggeration, we can say that vector analysis is the backbone of the mathematical formulation of electromagnetic field theory. Therefore, a complete grasp of vector analysis is crucial to the comprehension of electromagnetic fields. In order to ensure that every reader begins with essentially the same level of understanding of vectors, we have devoted an entire chapter, Chapter 2, to the study of vector analysis. A great deal of emphasis is placed upon the coordinate transformations and various theorems.

In the development and application of electromagnetic field theory, the student is expected to recall from his/her memory various mathematical relationships. To help those who fail to recall some of the required mathematical formulas, we have included enough information in Appendix C on trigonometric identities, series, and integral calculus, etc.

A quick glance at the table of contents reveals that the text may be divided into two parts. The first part, which can be covered during the first semester for a two-semester sequence, introduces the students to static fields such as electrostatic fields (Chapter 3), magnetostatic fields (Chapter 5), and fields due to steady currents (Chapter 4). Because most of the applications of static fields involve both electric and magnetic fields, we decided to present such applications in one chapter (Chapter 6). We are also of the opinion that once the students grasp the basics of static fields, they can study the applications with a minimum of guidance. If time permits, the development of Maxwell's equations in both the time domain and the frequency (phasor) domain can be included in the first part of the course. This material is presented in Chapter 7, where the emphasis is laid upon the coexistence of time-varying electric and magnetic fields and the concept of average power density. Also included in this chapter are some of the applications of the time-varying fields in the area of electrical machines and transformers.

The rest of the book provides the subject matter for the second semester in a two-semester sequence, which deals with the propagation, transmission, and radiation of electromagnetic fields in a medium under various constraints. A chapter-by-chapter explanation follows.

The development of wave equation and its solution that provides an inkling of wave propagation are discussed in Chapter 8. Also explained in this chapter are the reflection and transmission of the waves at normal and oblique incidences. The wave may have perpendicular or parallel polarization. The wave incidence may involve an interface between the two conductors, the two dielectrics, a conductor and a dielectric, or a dielectric and a perfect conductor.

The transmission of energy along the transmission lines is covered in Chapter 9. Instead of postulating a distributed equivalent circuit for a transmission line, we used field theory to justify the use of such a model. The wave equations in terms of the voltages and the currents along the length of transmission line are then developed and their solutions are provided. In order to minimize reflections on the transmission line, impedance matching with the stubs is explained. Lattice diagrams are used to explain the transient behavior of transmission lines. Although the Smith chart provides a visual picture of what is happening along a transmission line, we still feel that it is basically a transmission-line calculator. We can now use pocket calculators and computers to obtain exact information on the line. For this reason, we have placed the Smith chart and its applications in Appendix A.

The propagation of guided waves within the rectangular cross-section of a waveguide is covered in Chapter 10. The conditions for the existence of transverse electric (TE) and transverse magnetic (TM) modes are emphasized. Power flow in a rectangular waveguide under various conditions is also analyzed. Also explained in this chapter are the necessary conditions for the existence of fields inside a cavity and the use of a cavity as a frequency meter.

The radiation of electromagnetic waves is the subject matter of Chapter 11. The wave equations in terms of potential functions are developed and their solutions are sought for various types of antennas. The concepts of near-zone and radiation fields are explained. Also discussed in this chapter are the directive gain and directivity of a transmitting antenna, receiving antenna and Friis equation, the radar operation and the Doppler effect.

Chapter 12 covers the computer-aided analysis of electromagnetic fields. Some of the commonly used methods discussed in this chapter are the finite-difference method, the finite-element method, and the method of moments. Computer programs based upon these methods are included in Appendix B.

Our aim was to write a detailed student-oriented book. The success of first edition attests that we have succeeded in our mission. The first edition has already been translated into two foreign languages: Chinese and Korean. We hope that this second edition will also be accepted both by the students and faculty with the same zeal and zest as the first. Our goal has been and still is to present the material in such a way that a student can comprehend it with a minimum of help from instructors. To this end, we have carefully placed numerous worked examples with full details in each chapter. These examples, clearly delineated from the textual matter, not only enhance appreciation of a concept or a physical law but also bridge the perceived gap, real or otherwise, between a formal theoretical development and its applications. We opine that examples are necessary for immediate reinforcement and further clarification of a topic. Near the end of each chapter, we have included some easy questions under the heading of "Exercises" whose answers depend upon the direct applications of the concepts covered in each section. We believe that these exercises will help to impart motivation, nurture confidence, and heighten the understanding of the material presented in each chapter. In addition, there are problems at the end of each chapter that are designed to offer a wide range of challenges to the student. The exercises and the problems are an important part of the text and form an integral part of the study of electromagnetic fields. We suggest that the student should use basic laws and intuitive reasoning to obtain answers to these exercises and problems. The practice of such problem-solving techniques instills not only confidence but also empowers a student to tackle more difficult, albeit real-life, problems. Each chapter ends with a summary as well as a set of review questions. Some of the important equations are included in the summary for an easy reference. The review questions are tailored to ensure that a student has taken to heart the basics of the material presented in that chapter. Once again, we have endeavored very hard to make this book as student friendly as possible and we welcome any suggestions in this regard.

Our experience points out that the students tend to view the theoretical development as an abstraction and place emphasis on some equations, treating them as "formulas". Soon frustrations set in as the students find that the so-called formulas are different, not only for different media but also for different configurations. The array of equations needed to compute just one field quantity intimidates them to the extent that they lose interest in the material. It then just another "difficult" course that they must pass to satisfy the requirements of a degree in electrical engineering. We believe that it is the instructor's responsibility to

- explain the aim of each development,
- justify the assumptions imperative to the development at hand,
- emphasize its limitations,
- highlight the influence of the medium,
- illustrate the impact of geometry on an equation, and
- point to some of its applications.

To attain these goals, instructors must use their own experiences in the subject and also emphasize other areas of application. They must also stress any new developments in the field while they are discussing the fundamentals. For example, while explaining the magnetic force between two current-carrying conductors, an instructor can discuss magnetically levitated vehicles. Likewise, an instructor can shed light upon the design of a microwave oven while discussing a cavity resonator.

When the subject matter is explained properly and the related equations are developed from the basic laws, the student then learns to

- appreciate the theoretical development,
- forsake intimidation,
- regain motivation and confidence, and
- grasp the power of reasoning to develop new ideas.

Whatever we have presented in this second edition, we have done so according to our own convictions and understanding of the subject matter. It is quite possible that while stating and explaining our points of view, we may have said something that may conflict with your views, for which we seek your candid opinion and constructive criticism. If your point of view helps sway our minds, we will surely include it in a revised edition of this book. For this reason, your input is highly valuable to us.

Acknowledgments

We are deeply grateful for all the help we received from Dr. A. Haq Qureshi during the development of the first edition of this book. His mastery of the subject and the yearning for its clear and accurate presentation had direct impact upon the success of the first edition. We are much beholden to reviewers of both editions for their invaluable suggestions and constructive criticisms. We are most appreciative of the following persons and their establishments for providing us various photographs that are reproduced in this book: Ellen Modock (Keithley Instruments, Cleveland, Ohio), Bernard Surtz (Andrew Corporation, Orlando Park, Illinois), Bruce Whitney (Detroit Edition, Detriot, Michigan), Homer Bartlett (Microstar Inc. Florida), and Jeremiah Chambers (Space Machine & Engineering Corp., Florida).

Above all, we could not have written this book without the unconditional support, active encouragement, and complete cooperation of our families. In appreciation of their immense sacrifices, this text is lovingly dedicated to them.

Contents

1

Electromagnetic field theory

1.1 Introduction

What is a field? Is it a scalar field or a vector field? What is the nature of a field? Is it a continuous or a rotational field? How is the magnetic field produced by a current-carrying coil? How does a capacitor store energy? How does a piece of wire (antenna) radiate or receive signals? How do electromagnetic fields propagate in space? What really happens when electromagnetic energy travels from one end of a hollow pipe (waveguide) to the other? The primary purpose of this text is to answer some of these questions pertaining to electromagnetic fields.

In this chapter we intend to show that the study of electromagnetic field theory is vital to understanding many phenomena that take place in electrical engineering. To do so we make use of some of the concepts and equations of other areas of electrical engineering. We aim to shed light on the origin of these concepts and equations using electromagnetic field theory.

Before we proceed any further, however, we mention that the development of science depends upon some quantities that cannot be defined precisely. We refer to these as fundamental quantities; they are **mass** (m), **length** (ℓ), **time** (t), **charge** (q), and **temperature** (T). For example, what is time? When did time begin? Likewise, what is temperature? What is hot or cold? We do have some intuitive feelings about these quantities but lack precise definitions. To measure and express each of these quantities, we need to define a system of units.

In the International System of Units (SI for short), we have adopted the units of kilogram (kg) for mass, meter (m) for length, second (s) for time, coulomb (C) for charge, and kelvin (K) for temperature. Units for all other quantities of interest are then defined in terms of these fundamental units. For example, the unit of current, the ampere (A), in terms of the fundamental units is coulombs per second (C/s). Therefore, the ampere is a derived unit. The newton (N), the unit of force, is also a derived unit; it can be expressed in terms of basic units as $1\ \text{N} = 1\ \text{kg} \cdot \text{m/s}^2$. Units for some of the quantities that we will refer to in this

Table 1.1. Derived units for some electromagnetic quantities

Symbol	Quantity	Unit	Abbreviation
Y	admittance	siemen	S
ω	angular frequency	radian/second	rad/s
C	capacitance	farad	F
ρ	charge density	coulomb/meter^3	C/m^3
G	conductance	siemen	S
σ	conductivity	siemen/meter	S/m
W	energy	joule	J
F	force	newton	N
f	frequency	hertz	Hz
Z	impedance	ohm	Ω
L	inductance	henry	H
$\mathcal{F}$	magnetomotive force	ampere-turn	A°t
μ	permeability	henry/meter	H/m
ϵ	permittivity	farad/meter	F/m
P	power	watt	W
$\mathcal{R}$	reluctance	henry^{-1}	H^{-1}

Table 1.2. Unit conversion factors

From	Multiply by	To obtain
gilbert	0.79577	ampere-turn (At)
ampere-turn/cm	2.54	ampere-turn/inch
ampere-turn/inch	39.37	ampere-turn/meter
oersted	79.577	ampere-turn/meter
line (maxwells)	1×10^{-8}	weber (Wb)
gauss (lines/cm^2)	6.4516	line/inch^2
line/inch^2	0.155×10^{-4}	Wb/m^2 (tesla)
gauss	10^{-4}	Wb/m^2
inch	2.54	centimeter (cm)
foot	30.48	centimeter
meter	100	centimeter
square inch	6.4516	square cm
ounce	28.35	gram
pound	0.4536	kilogram
pound-force	4.4482	newton
ounce-force	0.278 01	newton
newton-meter	141.62	ounce-inch
newton-meter	0.73757	pound-feet
revolution/minute	$2\pi/60$	radian/second

text are given in Tables 1.1 and 1.3. Since English units are still being used in the industry to express some field quantities, it is necessary to convert from one unit system to the other. Table 1.2 is provided for this purpose.

Table 1.3. A partial list of field quantities

Variable	Definition	Type	Unit
$\vec{\mathbf{A}}$	magnetic vector potential	vector	Wb/m
$\vec{\mathbf{B}}$	magnetic flux density	vector	Wb/m^2 (T)
$\vec{\mathbf{D}}$	electric flux density	vector	C/m^2
$\vec{\mathbf{E}}$	electric field intensity	vector	V/m
$\vec{\mathbf{F}}$	Lorentz force	vector	N
I	electric current	scalar	A
$\vec{\mathbf{J}}$	volume current density	vector	A/m^2
q	free charge	scalar	C
$\vec{\mathbf{S}}$	Poynting vector	vector	W/m^2
$\vec{\mathbf{u}}$	velocity of free charge	vector	m/s
V	electric potential	scalar	V

Table 1.4. A partial list of relationships between various field quantities

$\vec{\mathbf{D}} = \epsilon\vec{\mathbf{E}}$	permittivity (ϵ)
$\vec{\mathbf{B}} = \mu\vec{\mathbf{H}}$	permeability (μ)
$\vec{\mathbf{J}} = \sigma\vec{\mathbf{E}}$	conductivity (σ), Ohm's law
$\vec{\mathbf{F}} = q(\vec{\mathbf{E}} + \vec{\mathbf{u}} \times \vec{\mathbf{B}})$	Lorentz force equation
$\nabla \cdot \vec{\mathbf{D}} = \rho$	Gauss's law (Maxwell's equation)
$\nabla \cdot \vec{\mathbf{B}} = 0$	Gauss's law (Maxwell's equation)
$\nabla \cdot \vec{\mathbf{J}} = -\dfrac{\partial \rho}{\partial t}$	continuity equation
$\nabla \times \vec{\mathbf{E}} = -\dfrac{\partial \vec{\mathbf{B}}}{\partial t}$	Faraday's law (Maxwell's equation)
$\nabla \times \vec{\mathbf{H}} = \vec{\mathbf{J}} + \dfrac{\partial \vec{\mathbf{D}}}{\partial t}$	Ampère's law (Maxwell's equation)

1.2 Field concept

Prior to undertaking the study of electromagnetic fields we must define the concept of a **field**. When we define the behavior of a quantity in a given region in terms of a set of values, one for each point in that region, we refer to this behavior of the quantity as a field. The value at each point of a field can be either measured experimentally or predicted by carrying out certain mathematical operations on some other quantities.

From the study of other branches of science, we know that there are both scalar and vector fields. Some of the field variables we use in this text are given in Table 1.3. There also exist definite relationships between these field quantities, and some of these are given in Table 1.4.

The permittivity (ϵ) and the permeability (μ) are properties of the medium. When the medium is a vacuum or free space, their values are

$$\mu_0 = 4\pi \times 10^{-7}\ \text{H/m}$$

$$\epsilon_0 = 8.851 \times 10^{-12} \approx 10^{-9}/36\pi\ \text{F/m}$$

From the equations listed in Table 1.4, Maxwell was able to predict that electromagnetic fields propagate in a vacuum with the speed of light. That is,

$$c = (\mu_0 \epsilon_0)^{-1/2} \text{ m/s}$$

1.3 Vector analysis

Vector analysis is the language used in the study of electromagnetic fields. Without the use of vectors, the field equations would be quite unwieldy to write and onerous to remember. For example, the cross product of two vectors $\vec{\mathbf{A}}$ and $\vec{\mathbf{B}}$ can be simply written as

$$\vec{\mathbf{A}} \times \vec{\mathbf{B}} = \vec{\mathbf{C}} \tag{1.1}$$

where $\vec{\mathbf{C}}$ is another vector. When expressed in scalar form, this equation yields a set of three scalar equtions. In addition, the appearance of these scalar equations depends upon the coordinate system. In the rectangular coordinate system, the previous equation is a concise version of the following three equations:

$$A_y B_z - A_z B_y = C_x \tag{1.2a}$$

$$A_z B_x - A_x B_z = C_y \tag{1.2b}$$

$$A_x B_y - A_y B_x = C_z \tag{1.2c}$$

You can easily see that the vector equation conveys the sense of a cross product better than its three scalar counterparts. Moreover, the vector representation is independent of the coordinate system. Thus, vector analysis helps us to simplify and unify field equations.

By the time a student is required to take the first course in electromagnetic theory, he/she has had a very limited exposure to vector analysis. The student may be competent to perform such vector operations as the gradient, divergence, and curl, but may not be able to describe the significance of each operation. The knowledge of each vector operation is essential to appreciate the development of electromagnetic field theory.

Quite often, a student does not know that (a) the unit vector that transforms a scalar surface to a vector surface is always normal to the surface, (b) a thin sheet (negligible thickness) of paper has two surfaces, (c) the direction of the line integral along the boundary of a surface depends upon the direction of the unit normal to that surface, and (d) there is a difference between an open surface and a closed surface. These concepts are important, and the student must comprehend the significance of each.

There are two schools of thought on the study of vector analysis. Some authors prefer that each vector operation be introduced only when it is needed, whereas others believe that a student must gain adequate