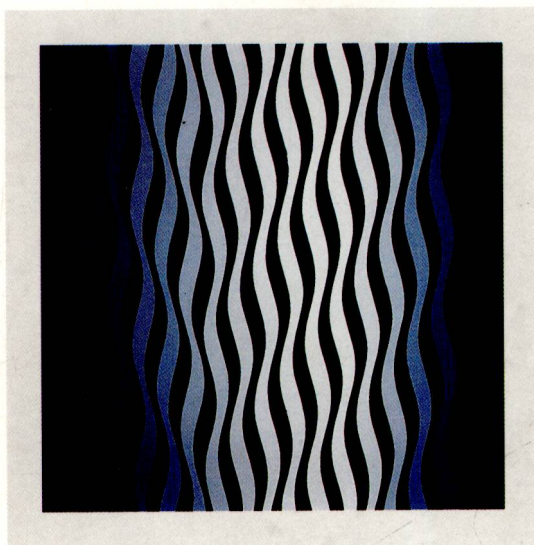




国外高校电子信息类优秀教材


工程电磁学

Engineering Electromagnetics



(英文影印版)

Kenneth R. Demarest 著

 科学出版社
www.sciencep.com



0441
D3/2

国外高校电子信息类优秀教材(英文影印版)

工 程 电 磁 学

Engineering Electromagnetics

Kenneth R. Demarest 著

科学出版社

北 京

内 容 简 介

本书为国外高校电子信息类优秀教材(英文影印版)之一。

本书基于物理方法,讲述了电磁学的理论和基本公式,包括:矢量分析,电磁源、电磁力和电磁场,自由空间中的电场,介质中的电场,电容和电能,自由空间中的磁场,介质中的磁场,磁感应系数、磁能和磁力,时分电磁场,传输线,平面波,波导,辐射和天线。书中还介绍了如何将它们应用于工程实践。

本书可作为电子工程、通信专业本科生教材,也可作为工程技术人员的参考书。

English reprint copyright ©2003 by Science Press and Pearson Education North Asia Limited.

Engineering Electromagnetics, by Kenneth R. Demarest, Copyright ©1998

ISBN 0-02-328521-4

All Rights Reserved.

Published by arrangement with the original publisher, Pearson Education, Inc., publishing as PRENTICE HALL, INC.

For sale and distribution in the People's Republic of China exclusively (except Taiwan, Hong Kong SAR and Macau SAR).

仅限于中华人民共和国境内(不包括中国香港、澳门特别行政区和中国台湾省)销售发行。

本书封面贴有 Pearson Education(培生教育出版集团)激光防伪标签。无标签者不得销售。

图字:01-2002-5986

图书在版编目(CIP)数据

工程电磁学/(美)德马雷斯特(Demarest, K. R.)著.一影印本.一北京:科学出版社,2003

(国外高校电子信息类优秀教材)

ISBN 7-03-011148-6

I.工… II.德… III.电磁学-高等学校-教材-英文 IV.O441

中国版本图书馆 CIP 数据核字(2003)第 005584 号

责任编辑:巴建芬 李 宇/封面设计:黄华斌 陈 敬/责任印制:刘秀平

科学出版社 出版

北京东黄城根北街16号

邮政编码:100717

<http://www.sciencep.com>

源海印刷有限责任公司 印刷

科学出版社发行 各地新华书店经销

*

2003年3月第 一 版 开本:787×1092 1/16

2003年3月第一次印刷 印张:43 1/4

印数:1—3 000 字数:1 001 000

定价:48.00 元

(如有印装质量问题,我社负责调换(环伟))



国外高校电子信息类优秀教材(英文影印版)

丛书编委会

(按姓氏笔画排序)

王兆安	西安交通大学	王成华	南京航空航天大学
田 良	东南大学	申功璋	北京航空航天大学
吕志伟	哈尔滨工业大学	吴 刚	中国科学技术大学
吴 澄	清华大学	宋文涛	上海交通大学
张延华	北京工业大学	李哲英	北方交通大学
李瀚荪	北京理工大学	郑大钟	清华大学
姚建铨	天津大学	赵光宙	浙江大学
郭从良	中国科学技术大学	崔一平	东南大学

Preface

I. Why I wrote this text

This book is about my favorite academic subject: electromagnetics.

The genesis of this book goes back to a student get-together I attended during the third year of my teaching career. I struck up a conversation with a good student who had taken an introductory electromagnetics course from me the previous semester. When I asked him what he remembered from the course, he very politely told me that he really couldn't remember much, except that it involved a lot of mathematics and theory. Worst of all, he seemed unaware of any way in which the material in that course would apply to his career as an electrical engineer. Apparently, he had gotten the message that, outside of "niche" areas like antennas, electromagnetics had little to do with the practice of electrical engineering.

This conversation caused me to do some serious soul searching about the way I had been teaching electromagnetics. In the end, I concluded that this student had been largely correct. While I had very accurately presented the laws of electromagnetics, I made no particular effort to integrate the material into the larger context of electrical engineering. My class in electromagnetics was probably not too different from the one taught across campus in the physics department. Given this, many of my students were

convinced that electromagnetics was relevant to their careers in electrical engineering only because they needed to pass the course in order to obtain a degree.

In reviewing a selection of electromagnetics textbooks intended for electrical engineers, I realized that the problem was more than just my own teaching style. Upon closer examination, I concluded that most of these textbooks could be divided into two classes. Textbooks in the first class tended to integrate electromagnetics nicely into engineering practice, but were often technically weak. On the other hand, textbooks in the second class typically gave solid, mathematically oriented discussions of electromagnetic theory, but little or no physical insight or engineering application.

As my teaching skills matured, I gradually found ways to convince my students that electromagnetic theory connects with all aspects of electrical engineering, while still approaching the material with the rigor needed for solving real problems. For instance, I found that students are more apt to see the relevance of electromagnetics when I remind them that the job of an electrical engineer is to constrain electric and magnetic fields so that they perform a desired task. This way of thinking is just as applicable for computer circuit designers as it is for antenna and microwave engineers.

I also found that topics that motivated the past generation of students to think seriously about electromagnetics no longer have the same resonance with the current generation. Topics like antennas and radar, while still extremely important in engineering practice, don't touch these students' lives as much as computers and consumer electronics do. Fortunately, there are a whole range of new topics that work just as well as the old ones. As an example, students quickly take notice when it is pointed out to them that the motherboard of their PC, while a digital system, is in many ways a microwave network. Even better is to show them how electrical interference between digital networks is a major safety and economic issue that can only be solved using electromagnetic techniques.

This textbook represents my vision of how to present electromagnetics to undergraduate students - one that emphasizes the physical processes and applications of electromagnetics in engineering, while at the same time presenting the material with the rigor necessary to approach real problems in engineering practice.

II. Features of This Text

Once I started writing, I discovered that a project of this magnitude appears to take on a life of its own. Although my goals for the text remained fixed, the features of the book went through a metamorphosis as the years of writing and testing in the classroom unfolded. What finally grew out of this process was a text that I feel is readable and understandable for the student, easy to integrate in the classroom, and, possibly most important, displays electromagnetics as a mainstream subject in electrical engineering.

1. This text presents electromagnetics using what most would consider a modified "traditional" or "historical" approach. After a brief overview (see point 3), static electric and magnetic fields are presented separately, followed by the time-varying case. This approach provides the greatest insight into the physical relevance of electromagnetics and allows students to grapple with electric and magnetic fields separately, before tackling the more difficult time-varying case.

2. Whenever possible, concepts and results are presented both mathematically and in plain English. My experience has shown that instructors usually prefer purely mathematical developments, but students like (and often need) word descriptions to give meaning to these developments. In addition, these physical descriptions help develop the student's engineering intuition. This is important for the students transition into engineering practice, where the problems don't look like textbook problems.
3. Chapter 3, "Sources, Forces, and Fields" provides a broad overview of the experiments and theories that led up to the definitive equations of electromagnetics—Maxwell's equations. This chapter is designed to show the basic connections between electromagnetic sources and the fields and forces they produce. The physical laws are presented in their historical order, culminating in Maxwell's equations.
4. Chapters 4–6 and 7–9 present electric and magnetic fields in parallel fashion. Each sequence starts with fields in free space, followed by material effects, and finally energy relations. This parallel construction allows students to see clearly what is similar and dissimilar about low-frequency electric and magnetic fields.
5. Graphical solution techniques are presented for both low frequency electric and magnetic fields. These techniques are useful in gaining insight into many practical problems and are also fun.
6. Unlike most traditional texts, this text presents transmission lines *before* plane waves. I have done this for two reasons. The first is that students find it easier to make the transition into propagating waves by first considering scalar voltage and current waves. Once these scalar waves are mastered, the jump into the more general case of space waves is easier. The second reason is that this choice makes it easier to introduce network-analyzer based laboratory experiments in conjunction with the last 4 chapters (transmission lines, plane waves, waveguides, and antennas and radiation).
7. Chapter 11, "Transmission Lines," covers both time-varying and frequency domain analysis. Thévenin equivalent concepts are used throughout this chapter to clearly show the student how electromagnetic and circuit theory are complementary. A great effort was made to make the time-domain section relevant to students whose primary interests are digital and computer circuits. Advanced topics in this section include microstrip transmission lines, reactive and nonlinear loads, and rise-time calculations.
8. This text covers a number of topics associated with electric and magnetic shielding, electromagnetic compatibility (EMC), and electromagnetic interference (EMI). These topics are discussed in both the static and dynamic sections of the text. My experience has shown that students very quickly see the relation between these topics and consumer electronics.
9. Chapter 13, "Waveguides," discusses both copper-based and dielectric based waveguides. This chapter includes a sizable discussion of optical fibers and systems.
10. In addition to a fundamental discussion of radiation and antenna principles, Chapter 14, "Antennas and Radiation," also presents a broad overview of the major classes of antennas encountered in engineering practice.

III. How to Use This Text

This textbook is intended for junior level electrical engineering students and can be used in either a one- or two-semester format. The following table gives suggested schedules for one- and two-semester courses.

Chapter	Title	2-Semester Lecture Hours	1-Semester Lecture Hours
1	Introduction	1	1
2	Vector Analysis	2	2
3	Electromagnetic Sources, Forces, and Fields	4	2
4	Electrostatic Fields in Free Space	5	5
5	Electrostatic Fields in Material Media	9	5
6	Capacitance and Electric Energy	3	3
7	Magnetostatic Fields in Free Space	4	4
8	Magnetostatic Fields in Material Media	5	3
9	Magnetic Inductance, Energy, and Forces	5	4
10	Time-Varying Electromagnetic Fields	4	4
11	Transmission Lines	14	6
12	Plane Waves	10	3
13	Waveguides	8	
14	Radiation and Antennas	10	
Totals		84	42

These schedules assume that students have had some previous experience with vector calculus, presumably from their calculus sequence. When this is the case, I have found that two lectures on the material in chapter 2 is a sufficient review, and students typically refer back to chapter 2 throughout the course to review various aspects of this material. For curricula where vector calculus has not yet been encountered, a longer exposure to chapter 2 would provide students with all the necessary background.

For a two-semester course sequence, I have found that there is ample time to cover nearly all the material in this text. For a one-semester course, the suggested schedule provides a more concentrated coverage of the electrostatic and magnetostatic topics, while still allowing time for 13 lectures on the most important time-varying topics.

IV. Acknowledgments

In writing this book, I have drawn from every instructor and textbook that I have encountered throughout my career as a student and a professor. Without them, I could not possibly have written this textbook. Even though the writing style that emerged is uniquely my own, I am indebted to all of them.

My greatest thanks go the students at the University of Kansas who endured the many drafts of this text in class. I was genuinely surprised by the enthusiasm they displayed for being a part of this writing process. Their comments were very insightful, and I made many changes in the manuscript in response to their comments. Although

space does not allow me to recognize all the students who made significant comments, I could not rest without recognizing Mr. Scott Fillion, who provided me with unbelievably detailed and helpful comments on the first half of the book.

I want to thank the reviewers who reviewed the manuscript of this text at various stages: Dr. Paul O. Berrett (Professor Emeritus) - Brigham Young University, Paul R. Melsaac - Cornell University, John R. Cogdell - University of Texas at Austin, Dr. Stuart A. Long - University of Houston, Walter J. Gajda, Jr. - University of Missouri - Rolla, Dennis P. Nyquist - Michigan State University, Kai Chang - Texas A & M University, Warren L. Stutzman - Virginia Polytechnic Institute and State University, Markus Zahn - Massachusetts Institute of Technology, Dr. David Rogers - North Dakota State University, Bruce McLeod - Montana State University, Jeffrey P. Mills - Illinois Institute of Technology, Robert York - University of California, Santa Barbara, Robert C. Owens - Santa Clara University, Vladimir Mitin - Wayne State University, Steven Scott Gearhart - University of Wisconsin - Madison. Their many comments caused me to rethink many aspects of the book and point me in the right direction. I appreciated their honesty and directness in telling me exactly what they did and did not like about the various manuscripts.

I also want to thank a number of colleagues and friends at the University of Kansas who assisted me in various ways during the writing of this text. Included in these are: Professors James Roberts, James Rowland and K. Sam Shanmugan, who gave me encouragement throughout this project, and Ms. Donnis Graham, who assisted in the final manuscript revisions. I would also like to thank Professor Ruth Miller at Kansas State University for several helpful discussions about teaching philosophies and electromagnetics.

Finally, I am most thankful to my wife Susan and my children, Eric and Rebecca, for standing by me during the over seven years it took to complete this text. Their concern and compassion for me during this time was greatly appreciated, and I could not have endured the process without them. I only hope I can follow through with my promise that life in the Demarest house will be easier now that this text is finally finished!

Kenneth Demarest
University of Kansas

Cylindrical Coordinates (ρ, ϕ, z)

$$\nabla f = \frac{\partial f}{\partial \rho} \hat{\mathbf{a}}_\rho + \frac{1}{\rho} \frac{\partial f}{\partial \phi} \hat{\mathbf{a}}_\phi + \frac{\partial f}{\partial z} \hat{\mathbf{a}}_z$$

$$\nabla \cdot \mathbf{A} = \frac{1}{\rho} \left[\frac{\partial}{\partial \rho} (\rho A_\rho) \right] + \frac{1}{\rho} \frac{\partial A_\phi}{\partial \phi} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \left[\frac{1}{\rho} \frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z} \right] \hat{\mathbf{a}}_\rho + \left[\frac{\partial A_\rho}{\partial z} - \frac{\partial A_z}{\partial \rho} \right] \hat{\mathbf{a}}_\phi + \frac{1}{\rho} \left[\frac{\partial}{\partial \rho} (\rho A_\phi) - \frac{\partial A_\rho}{\partial \phi} \right] \hat{\mathbf{a}}_z$$

$$\nabla^2 f = \frac{1}{\rho} \frac{\partial}{\partial \rho} \left(\rho \frac{\partial f}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2 f}{\partial \phi^2} + \frac{\partial^2 f}{\partial z^2}$$

Spherical Coordinates (r, θ, ϕ)

$$\nabla f = \frac{\partial f}{\partial r} \hat{\mathbf{a}}_r + \frac{1}{r} \frac{\partial f}{\partial \theta} \hat{\mathbf{a}}_\theta + \frac{1}{r \sin \theta} \frac{\partial f}{\partial \phi} \hat{\mathbf{a}}_\phi$$

$$\nabla \cdot \mathbf{A} = \frac{1}{r^2} \left[\frac{\partial}{\partial r} (r^2 A_r) \right] + \frac{1}{r \sin \theta} \left[\frac{\partial}{\partial \theta} (A_\theta \sin \theta) \right] + \frac{1}{r \sin \theta} \frac{\partial A_\phi}{\partial \phi}$$

$$\begin{aligned} \nabla \times \mathbf{A} = & \frac{1}{r \sin \theta} \left[\frac{\partial}{\partial \theta} (A_\phi \sin \theta) - \frac{\partial A_\theta}{\partial \phi} \right] \hat{\mathbf{a}}_r \\ & + \frac{1}{r} \left[\frac{1}{\sin \theta} \frac{\partial A_r}{\partial \phi} - \frac{\partial}{\partial r} (r A_\phi) \right] \hat{\mathbf{a}}_\theta + \frac{1}{r} \left[\frac{\partial}{\partial r} (r A_\theta) - \frac{\partial A_r}{\partial \theta} \right] \hat{\mathbf{a}}_\phi \end{aligned}$$

$$\nabla^2 f = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial f}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial f}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 f}{\partial \phi^2}$$

Vector Identities

$$(\mathbf{A} \times \mathbf{B}) \cdot \mathbf{C} = (\mathbf{B} \times \mathbf{C}) \cdot \mathbf{A} = (\mathbf{C} \times \mathbf{A}) \cdot \mathbf{B}$$

$$\mathbf{A} \times (\mathbf{B} \times \mathbf{C}) = (\mathbf{A} \cdot \mathbf{C})\mathbf{B} - (\mathbf{A} \cdot \mathbf{B})\mathbf{C}$$

$$\nabla \cdot (V\mathbf{A}) = \mathbf{A} \cdot \nabla V + V \nabla \cdot \mathbf{A}$$

$$\nabla \times (V\mathbf{A}) = \nabla V \times \mathbf{A} + V \nabla \times \mathbf{A}$$

$$\nabla \cdot (\mathbf{A} \times \mathbf{B}) = \mathbf{B} \cdot \nabla \times \mathbf{A} - \mathbf{A} \cdot \nabla \times \mathbf{B}$$

$$\nabla(\mathbf{A} \cdot \mathbf{B}) = (\mathbf{A} \cdot \nabla)\mathbf{B} + (\mathbf{B} \cdot \nabla)\mathbf{A} + \mathbf{A} \times (\nabla \times \mathbf{B}) + \mathbf{B} \times (\nabla \times \mathbf{A})$$

$$\nabla \cdot \nabla \equiv \nabla^2$$

$$\nabla \cdot (\nabla \times \mathbf{A}) = 0$$

$$\nabla \times (\nabla V) = 0$$

$$\nabla \times \nabla \times \mathbf{A} = \nabla(\nabla \cdot \mathbf{A}) - \nabla^2 \mathbf{A}$$

$$\int_V (\nabla \cdot \mathbf{A}) dv = \oint_S \mathbf{A} \cdot d\mathbf{s}$$

$$\int_S (\nabla \times \mathbf{A}) \cdot d\mathbf{s} = \oint_C \mathbf{A} \cdot d\mathbf{l}$$

$$\int_V \nabla \times \mathbf{F} dv = -\oint_S \mathbf{F} \times d\mathbf{s}$$

Gradient, Divergence, Curl, and Laplacian Operations

Cartesian Coordinates (x, y, z)

$$\nabla f = \frac{\partial f}{\partial x} \hat{\mathbf{a}}_x + \frac{\partial f}{\partial y} \hat{\mathbf{a}}_y + \frac{\partial f}{\partial z} \hat{\mathbf{a}}_z$$

$$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$$

$$\nabla \times \mathbf{A} = \left[\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} \right] \hat{\mathbf{a}}_x + \left[\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x} \right] \hat{\mathbf{a}}_y + \left[\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y} \right] \hat{\mathbf{a}}_z$$

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$$

Contents

Preface	ix
1 Background and Motivation	1
1-1 Introduction	1
1-2 A Little History	2
1-3 Engineering Applications of Electromagnetics	4
1-4 In This Text ...	5
2 Vector Analysis	7
2-1 Introduction	7
2-2 Physical Quantities and Units	7
2-3 Vector Algebra	11
2-4 Orthogonal Coordinate Systems	16
2-5 The Calculus of Scalar and Vector Fields	33
2-6 Summation	55
Problems	55

3	Electromagnetic Sources, Forces, and Fields	61
3-1	Introduction	61
3-2	Charge and Charge Density	62
3-3	Current and Current Density	63
3-4	The Law of Charge Conservation	68
3-5	Two Action-At-A-Distance Force Laws	71
3-6	The Lorentz Force Law and the Field Concept of Electromagnetics	75
3-7	Maxwell's Equation	81
3-8	Summation	84
	Problems	85
4	Electrostatic Fields in Free Space	87
4-1	Introduction	87
4-2	Maxwell's Equations for Electrostatics in Free Space	88
4-3	Coulomb's Law	90
4-4	E-Field Calculations Using Coulomb's Law	93
4-5	Field Computation Using Gauss's Law	98
4-6	Voltage and Electric Potential	107
4-7	Poisson's and Laplace's Equation	116
4-8	Summation	118
	Problems	118
5	Electrostatic Fields In Material Media	122
5-1	Introduction	122
5-2	Conductors	123
5-3	Dielectrics	132
5-4	Electrostatic Boundary Value Problems	149
5-5	Summation	174
	Problems	174
6	Capacitance and Electric Energy	179
6-1	Introduction	179
6-2	Capacitance	180
6-3	The Energy Contained in an Electrostatic Charge Distribution	195
6-4	Energy Storage in Capacitors	200
6-5	Summation	201
	Problems	202
7	Magnetostatic Fields in Free Space	205
7-1	Introduction	205

7-2	Maxwell's Equations for Magnetostatics in Free Space	206
7-3	The Biot-Savart Law and the Magnetic Vector Potential	208
7-4	Field Calculations Using Ampère's Law	218
7-5	Magnetic Potentials	227
7-6	Summation	236
	Problems	236
8	Magnetostatic Fields In Material Media	241
8-1	Introduction	241
8-2	The Hall Effect	242
8-3	Magnetic Materials	244
8-4	Magnetostatic Boundary Value Problems	260
8-5	Permanent Magnets and Magnetic Recording	265
8-6	Magnetic Circuits	268
8-7	Summation	272
	Problems	273
9	Magnetic Inductance, Energy, and Forces	277
9-1	Introduction	277
9-2	Faraday's Law of Induction	278
9-3	Inductance	290
9-4	Magnetic Forces and Torques	310
9-5	Summation	318
	Problems	319
10	Time-Varying Electromagnetic Fields	325
10-1	Introduction	325
10-2	Displacement Current	326
10-3	Maxwell's Equations for Time-Varying Fields	330
10-4	Time-Harmonic Fields	334
10-5	Boundary Conditions for Time-Varying fields	341
10-6	AC Circuit Analysis	344
10-7	Summation	346
	Problems	346
11	Transmission Lines	349
11-1	Introduction	349
11-2	TEM Modes on Transmission Lines	350

11-3	Transient Voltages and Currents On Transmission Lines	355
11-4	Time-Harmonic Waves on Transmission Lines	382
11-5	Summation	434
	Problems	434

12 Plane Waves 441

12-1	Introduction	441
12-2	Wave Equations in Simple, Source-Free Media	442
12-3	Plane Waves in Lossless Media	443
12-4	Plane Waves in Lossy Media	453
12-5	Medium Characterization	456
12-6	Power Transmission	462
12-7	Plane Wave Reflection and Transmission at Planar Boundaries: Normal Incidence	470
12-8	Plane Wave Reflection and Transmission at Planar Boundaries: Oblique Incidence	490
12-9	Summation	503
	Problems	503

13 Waveguides 508

13-1	Introduction	508
13-2	Waveguide Modes	509
13-3	Metal Waveguides	513
13-4	Dielectric Waveguides	546
13-5	Cavity Resonators	558
13-6	Summation	563
	Problems	563

14 Radiation and Antennas 567

14-1	Introduction	567
14-2	Electromagnetic Potentials	568
14-3	The Infinitesimal Dipole	573
14-4	Transmitting Antenna Parameters	582
14-5	Simple Antennas	589
14-6	Antenna Arrays	606
14-7	Properties of Receiving Antennas	616
14-8	Summation	628
	Problems	628

Appendix A: Units and Symbols 634

Appendix B: Coordinate System Relationships and Vector Identities	637
Appendix C: Fundamental Constants and Material Parameters	640
Appendix D: Transmission Line Parameters	644
Appendix E: Answers to Selected Problems	651
Selected Bibliography	657
Index	661

1

Background and Motivation

1-1 Introduction

Electromagnetics is both the oldest and most basic of all the branches of electrical engineering. Stated simply, electromagnetics deals with four questions: What is electricity, how does it behave, what can it do, and how can we control it? So fundamental are the questions that it addresses that it is not an exaggeration to say that electromagnetics is at the heart of *everything* that is done with electricity. As a result, an understanding of electromagnetics is essential in order to fully understand the operation of many (if not most) electrical devices and effects.

At its most basic level, electromagnetics concerns itself with the forces that charged particles exert upon each other. These forces are important for two reasons. The first is that they determine how electric charges and currents distribute themselves in electrical devices. The second is that it is such forces that make electricity useful to us, since they make other things move and allow us to detect the presence of charges and currents. Indeed, applications such as telecommunications, electrical machines, and computers would not be possible were it not for electromagnetic forces.

Although there are many applications where electromagnetic forces are our primary interest (as in the case of electric motors), we are usually more interested in how