

OXFORD  
HIGHER EDUCATION

# FUNDAMENTALS OF ENGINEERING ELECTROMAGNETICS

SUNIL BHOOSHAN

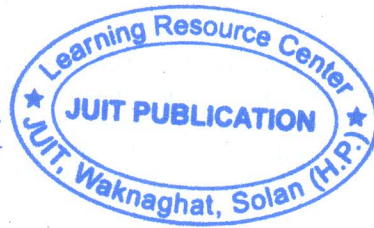


# FUNDAMENTALS OF ENGINEERING ELECTROMAGNETICS

SUNIL BHOOSHAN

*Professor and Head*

*Department of Electronics and Communication Engineering  
Jaypee University of Information Technology  
Waknaghat*



**OXFORD**  
UNIVERSITY PRESS

# OXFORD

UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide. Oxford is a registered trade mark of Oxford University Press in the UK and in certain other countries.

Published in India by  
Oxford University Press  
YMCA Library Building, 1  
Jai Singh Road, New Delhi 110001, India

© Oxford University Press 2012

The moral rights of the author/s have been asserted.

First published in 2012

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without the prior permission in writing of Oxford University Press, or as expressly permitted by law, by licence, or under terms agreed with the appropriate reprographics rights organization. Enquiries concerning reproduction outside the scope of the above should be sent to the Rights Department, Oxford University Press, at the address above.

You must not circulate this work in any other form  
and you must impose this same condition on any acquirer.

ISBN-13: 978-0-19-807794-7

ISBN-10: 0-19-807794-7

Typeset in Times New Roman  
by BeSpoke Integrated Solutions, Puducherry  
Printed in India by Rajkamal Electric Press, Kundli, Haryana

# Brief Contents

<i>Foreword</i>	v
<i>Preface</i>	vi
<i>Features of the book</i>	x
<i>Frequently Used Reference Material</i>	xix
<i>List of Symbols</i>	xxi

## Part I Introduction

1. Scalars and Vectors	3
2. Coordinate Systems and Fields	29
3. Vector Calculus	57

## Part II Electrostatics

4. The Electric Field and Gauss's Law	93
5. Energy and Potential	140
6. The Electric Field and Material Media	168
7. Laplace's and Poisson's Equations	208

## Part III Magnetostatics

8. The Steady Magnetic Field	239
9. Magnetic Forces, Inductance, and Magnetisation	280

## Part IV Time Varying Fields, Radiation, and Propagation

10. Time-Dependant Fields	315
11. Electromagnetic Waves	341
12. Transmission Lines and Waveguides	384
13. Radiation from Currents	451
14. Introduction to Antennas	488
15. Radio Wave Propagation	515

<i>Appendices</i>	553
<i>References</i>	575
<i>Index</i>	576
<i>About the Author</i>	583

# Detailed Contents

<i>Foreword</i>	v
<i>Preface</i>	vi
<i>Features of the book</i>	x
<i>Frequently Used Reference Material</i>	xix
<i>List of Symbols</i>	xxi

## Part I Introduction

<b>1. Scalars and Vectors</b>	<b>3</b>
1.1 Introduction	3
1.2 Scalars	3
1.2.1 Rules for Manipulation of Scalars	4
1.2.2 <i>Keeping Track of Calculations</i>	5
1.2.3 <i>Order of Magnitude of Calculations</i>	7
1.2.4 <i>Approximations</i>	7
1.3 Vectors	8
1.3.1 Unit Vector in General Direction	10
1.3.2 <i>Vector Addition and Subtraction</i>	10
1.3.3 <i>Dot Product or Scalar Product</i>	14
1.3.4 <i>Cross Product or Vector Product</i>	16
1.4 Units and Dimensions	21
1.4.1 Derivation of Other Units from Basic Units	22
<b>2. Coordinate Systems and Fields</b>	<b>29</b>
2.1 Introduction	29
2.2 Scalar and Vector Fields	30
2.2.1 Scalar Fields	30
2.2.2 <i>Vector Fields</i>	31
2.3 Rectangular Coordinate System	33
2.3.1 Distance Between Two Points	33
2.3.2 <i>Direction Cosines</i>	34
2.3.3 <i>Vector Equation of a Straight Line</i>	35
2.3.4 <i>Equation of a Plane</i>	38
2.4 Cylindrical Coordinate System	40
2.4.1 Equations of Surfaces and Lines in Cylindrical Coordinates	45
2.5 Spherical Coordinate System	47
<b>3. Vector Calculus</b>	<b>57</b>
3.1 Introduction	57
3.2 Differential Element of a Line	57
3.2.1 Line Integral	60
3.3 Differential Element of a Surface	64
3.3.1 Surface Integral	64
3.3.2 <i>Volume Integral</i>	67

3.4	Differential Calculus Concepts	69
3.4.1	Del or Nabla Operator	71
3.4.2	Gradient	72
3.4.3	Curl	75
3.4.4	Divergence	80
3.5	Maxwell's Equations	82
3.6	Units and Dimensions of EM Fields	83

## Part II Electrostatics

<b>4.</b>	<b>The Electric Field and Gauss's Law</b>	<b>93</b>
4.1	Introduction	93
4.2	Charge	94
4.2.1	Dirac Delta Function	95
4.3	Coulomb's Law and the Electric Field	99
4.3.1	Coulomb's Law and Superposition of Forces	102
4.3.2	Electric Field	103
4.4	Electric Field due to System of Point Charges	106
4.4.1	Electric Dipole	106
4.4.2	Electric Field Due to Any Number of Point Charges	110
4.5	Electric Field due to Continuous Charge Distributions	112
4.5.1	Infinite Line Charge	113
4.5.2	Infinite Sheet Charge	117
4.6	Electric Displacement $\psi$ and Flux Density <b>D</b>	121
4.7	Gauss's Law	122
4.8	Gauss's Law Applied to Cases of Spherical Symmetry	125
4.8.1	Gauss's Law Applied to a Point Charge	125
4.8.2	Gauss's Law Applied to a Charged Sphere	127
4.9	Gauss's Law Applied to Cases of Cylindrical Symmetry	130
4.10	Gauss's Law Applied to Cases of Rectangular Symmetry	132
<b>5.</b>	<b>Energy and Potential</b>	<b>140</b>
5.1	Potential Due to a Point Charge	140
5.2	Equipotential Surfaces	146
5.3	Potential Energy	147
5.4	Potential Due to a System of Point Charges	152
5.4.1	Far Fields for an Electric Dipole	153
5.5	Potential Due to Continuous Charge Distributions	154
<b>6.</b>	<b>The Electric Field and Material Media</b>	<b>168</b>
6.1	Current and Current Density	168
6.2	Continuity Equation	172
6.3	Conductors, Semiconductors, and Dielectrics	174
6.3.1	Conductors	174
6.3.2	Relaxation Time for Conductors	176
6.3.3	Method of Images	180
6.3.4	Semiconductors	181
6.3.5	Dielectrics	183
6.4	Capacitance	184
6.4.1	Parallel Plate Capacitor	184
6.4.2	Coaxial Line	186
6.4.3	Two Conductor Line	187
6.4.4	Capacitances of Concentric Spheres	189

6.5 Relation Between Capacitance and Resistance	190
6.6 Boundary Conditions for Electrostatic Fields	191
6.7 Energy Stored in the Electric Field	196
<b>7. Laplace's and Poisson's Equations</b>	<b>208</b>
7.1 Introduction	208
7.2 Uniqueness Theorem	209
7.3 Laplace's Equation—Applications	211
7.3.1 One-Dimensional Solutions	211
7.3.2 Two-dimensional Solutions to Laplace's Equation	217
7.3.3 Separation of Variables	220
7.3.4 Numerical Techniques	227
7.4 Poisson's Equation	229
7.4.1 One-Dimensional Solutions	229
<b>Part III Magnetostatics</b>	
<b>8. The Steady Magnetic Field</b>	<b>239</b>
8.1 Introduction	239
8.2 Biot-Savart Law	240
8.2.1 Biot-Savart Law Applied to a Tiny Filamentary Current	241
8.3 Types of Currents	243
8.3.1 Biot-Savart Law Applied to an Infinitely Long Straight Wire	244
8.3.2 Magnetic Field Lines of a Long Straight Wire	245
8.3.3 Biot-Savart Law Applied to a Short Straight Wire	246
8.4 Ampere's Law	247
8.4.1 Ampere's Law Applied to a Long Straight Wire	249
8.4.2 Ampere's Law Applied to a Wire of Radius $a$	252
8.4.3 Ampere's Law Applied to an Infinite Solenoid	254
8.4.4 Ampere's Law Applied to a Winding Around a Torus	256
8.5 The Magnetic Field	257
8.5.1 Loop of Wire Carrying a Current	257
8.5.2 Magnetic Field Due to a Current Sheet	258
8.5.3 Magnetic Field in the Interior of an Infinite Solenoid	261
8.5.4 Magnetic Field in the Interior of a Finite Solenoid	261
8.5.5 Magnetic Field on the Axis of a Rotating Charged Disk	263
8.6 Magnetic Scalar Potential	264
8.6.1 Scalar Potential in the Interior of an Infinite Solenoid	265
8.7 Vector Potential and Magnetic Flux Density	265
8.7.1 Calculation of the Vector Potential	266
8.7.2 Vector Potential of a Circular Loop	268
8.8 Biot-Savart Law-Revisited	269
8.9 Vector Potential	269
8.9.1 Vector Potential for a Current Carrying Straight Conductor	269
8.9.2 Two Current Carrying Straight Conductors	270
8.10 Far Field Approximation	271
8.10.1 Square Current Loop and Magnetic Dipole	272
<b>9. Magnetic Forces, Inductance, and Magnetisation</b>	<b>280</b>
9.1 Lorentz Force	280
9.2 Electron Moving in a Steady Magnetic Field	281

9.3 A Straight Wire Carrying a Current in a Magnetic Field	284
9.3.1 Force Between Two Current Carrying Parallel Conductors	286
9.4 Other Formulations	287
9.5 Loop Carrying a Current in a Constant Magnetic Field	287
9.6 Torque in a Loop carrying a Current in a Constant Magnetic Field	288
9.6.1 Magnetic Dipole and Torque on an Arbitrary Loop	289
9.7 Force between Two Current Elements	290
9.8 Inductance	291
9.8.1 Inductance of a Coil	292
9.8.2 Inductance of a Coaxial Line	294
9.8.3 Magnetic Energy	295
9.8.4 Inductance of a Circular Loop	297
9.8.5 Mutual Inductance	300
9.9 Magnetic Materials and Magnetic Circuits	302
9.9.1 Magnetisation	302
9.9.2 Magnetostatic Boundary Conditions	303
9.9.3 Magnetic Circuits	304

## Part IV Time Varying Fields, Radiation, and Propagation

<b>10. Time-Dependant Fields</b>	<b>315</b>
10.1 Faraday's Law	315
10.2 Maxwell Equation from Faraday's Law	319
10.3 Displacement Current Density	320
10.4 Time-dependent Maxwell's Equations	323
10.4.1 Point Form of the Equations	323
10.5 Integral Form of Maxwell's Equations	324
10.6 Fundamental Equations of Radiation and Propagation	324
10.7 Time Domain Wave Equation	325
10.8 Frequency Domain Wave Equation	330
10.8.1 Phasors	330
10.9 Wave Equation	332
<b>11. Electromagnetic Waves</b>	<b>341</b>
11.1 Introduction	341
11.2 Uniform Plane Wave	341
11.3 Electromagnetic Spectrum	347
11.4 Wave Polarisation	348
11.4.1 Circular Polarisation	348
11.4.2 Elliptical Polarisation	351
11.5 Wave Propagation in Conducting Media	353
11.5.1 Low Conductivity Materials	356
11.5.2 High Conductivity Materials	358
11.6 Boundary Conditions	360
11.7 Reflection and Refraction of Waves	364
11.7.1 Reflection from a Metal Surface	364
11.7.2 Refraction from a Dielectric Surface	367
11.8 Poynting Vector and the Flow of Power	371
11.8.1 Poynting's Theorem	371
11.8.2 Poynting Vector	373



<b>12. Transmission Lines and Waveguides</b>	<b>384</b>
12.1 Introduction	384
12.2 Time Domain Equation	386
12.3 Frequency Domain Equation	388
12.3.1 Lossy Transmission Lines and Distortion-less Lines	390
12.3.2 <i>Low-loss Transmission Lines</i>	391
12.3.3 <i>Practical Transmission Lines</i>	391
12.4 Solutions to the Transmission Line Equation	393
12.4.1 Power Considerations	394
12.4.2 Reflections from Discontinuities	395
12.4.3 Standing Wave Ratio	398
12.4.4 <i>Input Impedance anywhere along the Line</i>	402
12.4.5 <i>UHF Circuit Elements: <math>\lambda/8</math>, <math>\lambda/4</math>, and <math>\lambda/2</math> Lines</i>	403
12.4.6 <i>Propagation of Plane Waves with Transmission Line Concepts</i>	405
12.5 Transmission Line Charts	406
12.5.1 Matching a Load	411
12.5.2 <i>Single Stub Matching</i>	414
12.5.3 <i>Voltage and Currents along a Line</i>	414
12.6 Transformer Matching	416
12.7 Waveguides	421
12.8 Parallel Plate Waveguide	422
12.9 TEM Mode Waveguides	428
12.9.1 Parallel Conductor Line	428
12.9.2 <i>Coaxial Line</i>	428
12.9.3 <i>Parallel Plate Line</i>	428
12.9.4 <i>Micro-strip Line</i>	428
12.10 Rectangular Waveguide	429
12.10.1 Separation of Variables	429
12.10.2 Transverse Magnetic (TM) Modes ( $H_z = 0$ )	432
12.10.3 <i>Transverse Electric (TE) Modes (<math>E_z = 0</math>)</i>	433
12.11 Circular Waveguide	435
12.11.1 Transverse Magnetic Modes (TM) $H_z = 0$	438
12.11.2 <i>Transverse Electric Modes (TE) <math>E_z = 0</math></i>	439
12.12 Cavity Resonators	440
12.12.1 TM Modes in a Cavity ( $H_z = 0$ )	440
12.12.2 <i>TE Modes in a Cavity (<math>E_z = 0</math>)</i>	441
<b>13. Radiation from Currents</b>	<b>451</b>
13.1 Retarded Potentials	451
13.2 Wave Equation due to Charges and Currents	452
13.3 Radiation from a Current Element	455
13.4 Half-Wave Dipole Antenna	462
13.5 Far Field Approximation	468
13.5.1 Radiated Fields of a Small Current Loop	469
13.6 Basic Antenna Concepts	470
13.7 Directivity	473
13.7.1 Directivity from the Beam Pattern	475
13.7.2 <i>Directivity Using Square Degrees</i>	477
13.8 Effective Aperture and Friis Transmission Formula	478
13.9 Radar Equation	479

<b>14. Introduction to Antennas</b>	<b>488</b>
14.1 Introduction	488
14.2 Linear Antenna Arrays	489
14.3 Linear Array with Equal Currents	492
14.3.1 Array Factor	492
14.3.2 Nulls and Sidelobes	492
14.3.3 Grating Lobes	494
14.3.4 Beam Pointing Angle	495
14.4 Principle of Pattern Multiplication	498
14.5 Far Field Pattern of a Continuous Current Distribution	499
14.6 Aperture Antennas	501
14.7 Horn Antennas	504
14.7.1 Introduction	504
14.7.2 Far Fields and Patterns for Horn Antennas	504
14.7.3 Optimum Dimensions of Horn Antennas	504
14.8 Parabolic Reflector	508
14.9 Cassagrain Antenna	509
<b>15. Radio Wave Propagation</b>	<b>515</b>
15.1 Introduction	515
15.2 Ground Wave Propagation	517
15.3 Ground Reflection	518
15.3.1 Perpendicular Polarisation	519
15.3.2 Parallel Polarisation	523
15.4 Surface Wave	525
15.4.1 Surface Wave for the Vertical Dipole	525
15.4.2 Wave Tilt of the Surface Wave	528
15.4.3 Surface Wave for a Horizontal Dipole	529
15.5 Approximations for Ground Wave Propagation	530
15.6 Tropospheric Propagation	532
15.6.1 Spherical Earth Considerations	532
15.6.2 Tropospheric Waves	532
15.7 Ionospheric Propagation	538
15.7.1 Ionosphere	538
15.7.2 Plasma Oscillations	539
15.7.3 Wave Propagation in a Plasma	541
15.7.4 Low Frequency Propagation	542
15.7.5 High Frequency Propagation	543
15.7.6 Virtual Height	545
<i>Appendices</i>	
A. Coordinate Systems	555
B. Mathematical Reference	559
C. Some Key Equations	567
D. Sample Question Papers	569
References	575
Index	576
About the Author	583