

Pearson International Edition

Electromagnetics for Engineers

Fawwaz T. Ulaby

PEARSON Education

Contents

Preface 1

Int	rodu	ction 4
1-1	Histori	cal Timeline 5
	1-1.1	EM In the Classical Era 5
	1-1.2	EM in the Modern Era 6
1-2	Dimens	sions, Units, and Notation 7
1-3	The Na	ture of EM 14
	1-3.1	The Gravitational Force: A Useful Analogue 14
	1-3.2	Electric Fields 15
	1-3.3	Magnetic Fields 18
	1-3.4	Static and Dynamic Fields 19
1-4	The Ele	ectromagnetic Spectrum 21
Ve	ctor	Analysis 24
2-1	Basic I	Laws of Vector Algebra 25
	2-1.1	Equality of Two Vectors 26
	2-1.2	Vector Addition and Subtraction 27
	2-1.3	Position and Distance Vectors 27
	2-1.4	Vector Multiplication 28
	2-1.5	Scalar and Vector Triple Products 31
2-2	Orthog	onal Coordinate Systems 32
	2-2.1	Cartesian Coordinates 33
	2-2.2	Cylindrical Coordinates 33
	2-2.3	Spherical Coordinates 37
2-3	Transfo	ormations between Coordinate Systems 39
	2-3.1	Cartesian to Cylindrical Transformations 39
	2-3.2	Cartesian to Spherical Transformations 42
	2-3.3	Cylindrical to Spherical Transformations 43
	2-3.4	Distance between Two Points 43
	1-1 1-2 1-3 1-4 Ve 2-1	1-1.1 1-1.2 1-2 Dimens 1-3 The Na 1-3.1 1-3.2 1-3.3 1-3.4 1-4 The Ele Vector / 2-1 Basic I 2-1.1 2-1.2 2-1.3 2-1.4 2-1.5 2-2 Orthog 2-2.1 2-2.2 2-2.3 2-3 Transfo 2-3.1 2-3.2 2-3.3

2-4	Gradient of a Scalar Field 46	40
	2-4.1 Gradient Operator in Cylindrical and Spherical Coordinates	48
	2-4.2 Properties of the Gradient Operator 48	
2-5	Divergence of a Vector Field 50	
	2-5.1 Divergence Theorem 54	
2-6	Curl of a Vector Field 55	
	2-6.1 Vector Identities Involving the Curl 57	
	2-6.2 Stokes's Theorem 57	
2-7	Laplacian Operator 58	
	Problems 59	
Ele	ectrostatics 66	
3-1	Maxwell's Equations 67	
3-2	Charge and Current Distributions 68	
	3-2.1 Charge Densities 68	
	3-2.2 Current Density 70	
3-3	Coulomb's Law 71	
	3-3.1 Electric Field due to Multiple Point Charges 72	
	3-3.2 Electric Field due to a Charge Distribution 73	
3-4	Gauss's Law 76	
3-5	Electric Scalar Potential 79	
	3-5.1 Electric Potential as a Function of Electric Field 79	
	3-5.2 Electric Potential due to Point Charges 81	
	3-5.3 Electric Potential due to Continuous Distributions 81	
	3-5.4 Electric Field as a Function of Electric Potential 82	
	3-5.5 Poisson's Equation 83	
3-6	Electrical Properties of Materials 84	
3-7	Conductors 85	
	3-7.1 Resistance 87	
	3-7.2 Joule's Law 88	
3-8	Dielectrics 89	
3-9	Electric Boundary Conditions 94	
	3-9.1 Dielectric–Conductor Boundary 97	
	3-9.2 Conductor_Conductor Roundary 98	

5

3-10 Capacitance

3-12 Image Method 105

99 3-11 Electrostatic Potential Energy 104

	Problems 109			
Ma	ignetostatics 118			
4-1	Magnetic Forces and Torques 119			
-T 1	4-1.1 Magnetic Force on a Current-Carrying Conductor 121			
	4-1.2 Magnetic Torque on a Current-Carrying Loop 124			
4-2	The Biot–Savart Law 127			
	4-2.1 Magnetic Field due to Surface and Volume Current Distributions 128			
	4-2.2 Magnetic Field of a Magnetic Dipole 131			
4-3	Magnetic Force between Two Parallel Conductors 132			
4-4	Maxwell's Magnetostatic Equations 133			
	4-4.1 Gauss's Law for Magnetism 134			
	4-4.2 Ampère's Law 134			
4-5	-			
4-6	Magnetic Properties of Materials 140			
	4-6.1 Orbital and Spin Magnetic Moments 141			
	4-6.2 Magnetic Permeability 144			
	4-6.3 Magnetic Hysteresis of Ferromagnetic Materials 145			
4-7	Magnetic Boundary Conditions 147			
4-8	Inductance 149			
	4-8.1 Magnetic Field in a Solenoid 149			
	4-8.2 Self-inductance 152			
	4-8.3 Mutual Inductance 156			
4-9	Magnetic Energy 157			
	Problems 158			
Ma	exwell's Equations for Time-Varying Fields 166			
5-1	Faraday's Law 167			
5-2	Stationary Loop in a Time-Varying Magnetic Field 169			
5-3	The Ideal Transformer 173			
5-4	Moving Conductor in a Static Magnetic Field 174			
5-5	The Electromagnetic Generator 178			
5-6	Moving Conductor in a Time-Varying Magnetic Field 180			
5-7	Displacement Current 180			
5-8	Boundary Conditions for Electromagnetics 183			

	9 Charge–Current Continuity Relation 186 10 Electromagnetic Potentials 187 Problems 188		
Pla	ane-Wave Propagation 192		
6-1	Review of Waves and Phasors 193		
	6-1.1 Sinusoidal Wave in a Lossless Medium 194		
	6-1.2 Sinusoidal Wave in a Lossy Medium 197		
	6-1.3 Review of Complex Numbers 199		
	6-1.4 Review of Phasors 201		
6-2	Time-Harmonic Fields 205		
	6-2.1 Complex Permittivity 206		
	6-2.2 Wave Equations for a Charge-Free Medium 206		
6-3	Plane-Wave Propagation in Lossless Media 207		
	6-3.1 Uniform Plane Waves 207		
	6-3.2 General Relation between E and H 211		
6-4	Wave Polarization 212		
	6-4.1 Linear Polarization 213		
	6-4.2 Circular Polarization 214		
	6-4.3 Elliptical Polarization 216		
6-5	Plane-Wave Propagation in Lossy Media 221		
	6-5.1 Low-Loss Dielectric 223		
	6-5.2 Good Conductor 223		
6-6	Current Flow in a Good Conductor 225		
6-7	Electromagnetic Power Density 228		
	6-7.1 Plane Wave in a Lossless Medium 228		
	6-7.2 Plane Wave in a Lossy Medium 230		
	6-7.3 Decibel Scale for Power Ratios 231		
	Problems 232		
Tra	ansmission Lines 238		
7-1	General Considerations 239		
/-1	7-1.1 The Role of Wavelength 239		
	7-1.1 The Role of Wavelength 239 7-1.2 Propagation Modes 241		
7-2	Lumped-Element Model 242		
7-3	Transmission-Line Equations 247		
1-5			

7-5 The Lossless Transmission Line 251

	7-5.1	Voltage Reflection Coefficient 252		
	7-5.2	Standing Waves 255		
7-6	Input I	Impedance of the Lossless Line 259		
7-7				
	7-7.1	Short-Circuited Line 262		
	7-7.2	Open-Circuited Line 264		
	7-7.3	Application of Short-Circuit and Open-Circuit Measurements	264	
	7-7.4	Lines of Length $l = n\lambda/2$ 268		
	7-7.5	Quarter-Wave Transformer 268		
	7-7.6	Matched Transmission Line: $Z_L = Z_0$ 268		
7-8	Power :	Flow on a Lossless Transmission Line 270		
7-9	-9 The Smith Chart 271			
	7-9.1	Parametric Equations 271		
	7-9.2	Input Impedance 276		
	7-9.3	SWR, Voltage Maxima and Minima 278		
	7-9.4	Impedance to Admittance Transformations 279		
		ince Matching 285		
7-11	Transie	ents on Transmission Lines 289		
	7-11.1	Transient Response 290		
		Bounce Diagrams 293		
	Probler	ms 295		
Wa	ave F	Reflection and Transmission 304		
8-1	Wave F	Reflection and Transmission at Normal Incidence 306		
	8-1.1	Boundary between Lossless Media 306		
	8-1.2	•		
	8-1.3	-		
	8-1.4	Boundary between Lossy Media 313		
8-2	Snell's			
8-3	Fiber C	Optics 318		
8-4	Wave F	Reflection and Transmission at Oblique Incidence 320		
	8-4.1	Perpendicular Polarization 321		
	8-4.2	Parallel Polarization 325		
	8-4.3	Brewster Angle 327		
8-5	Reflect	ivity and Transmissivity 330		
	Problei	ns 334		

9	Ra	diation and Antennas 340
	9-1	Retarded Potentials 343
		9-1.1 Time-Harmonic Potentials 344
	9-2	The Short Dipole 345
		9-2.1 Far-Field Approximation 347
		9-2.2 Power Density 347
	9-3	Antenna Radiation Characteristics 349
		9-3.1 Antenna Pattern 350
		9-3.2 Beam Dimensions 351
		9-3.3 Antenna Directivity 353
		9-3.4 Antenna Gain 355
		9-3.5 Radiation Resistance 355
	9-4	Half-Wave Dipole Antenna 357
		9-4.1 Directivity of $\lambda/2$ Dipole 359
		9-4.2 Radiation Resistance of λ/2 Dipole 359
		9-4.3 Quarter-Wave Monopole Antenna 359
	9-5	Effective Area of a Receiving Antenna 360
	9-6	Friis Transmission Formula 364
		Problems 368
Α	Syr	mbols, Quantities, and Units 371
В	Ma	terial Constants of Some Common Materials 373
С	Ма	thematical Formulas 375
D	An	swers to Selected Problems 377
	Bib	liography 383
	Ind	ex