ADVANCED MODELING IN COMPUTATIONAL ELECTROMAGNETIC COMPATIBILITY

DRAGAN POLJAK, PhD
Department of Electronics
University of Split, Croatia

WILEY-INTERSCIENCE
A JOHN WILEY & SONS, INC., PUBLICATION

CONTENTS

PREFACE xv

PART I: FUNDAMENTAL CONCEPTS IN COMPUTATIONAL ELECTROMAGNETIC COMPATIBILITY 1

1. Introduction to Computational Electromagnetics and Electromagnetic Compatibility 3

1.1 Historical Note on Modeling in Electromagnetics 3
1.2 Electromagnetic Compatibility and Electromagnetic Interference 5
1.2.1 EMC Computational Models and Solution Methods 5
1.2.2 Classification of EMC Models 7
1.2.3 Summary Remarks on EMC Modeling 8
1.3 References 8

2. Fundamentals of Electromagnetic Theory 10

2.1 Differential Form of Maxwell Equations 10
2.2 Integral Form of Maxwell Equations 11
2.3 Maxwell Equations for Moving Media 14
2.4 The Continuity Equation 17
2.5 Ohm's Law 19
2.6 Conservation Law in the Electromagnetic Field 21
2.7 The Electromagnetic Wave Equations 24
2.8 Boundary Relationships for Discontinuities in Material Properties 26
2.9 The Electromagnetic Potentials 32
2.10 Boundary Relationships for Potential Functions 33
2.11 Potential Wave Equations 35
2.11.1 Coulomb Gauge 36

2.11.2 Diffusion Gauge 37
2.11.3 Lorentz Gauge 38
2.12 Retarded Potentials 40
2.13 General Boundary Conditions and Uniqueness Theorem 41
2.14 Electric and Magnetic Walls 41
2.15 The Lagrangian Form of Electromagnetic Field Laws 42
2.15.1 Lagrangian Formulation and Hamilton Variational Principle 43
2.15.2 Lagrangian Formulation and Hamilton Variational Principle in Electromagnetics 45
2.16 Complex Phasor Notation of Time-Harmonic Electromagnetic Fields 51
2.16.1 Poyinting Theorem for Complex Phasors 52
2.16.2 Complex Phasor Form of Electromagnetic Wave Equations 53
2.16.3 The Retarded Potentials for the Time-Harmonic Fields 54
2.17 Transmission Line Theory 54
2.17.1 Field Coupling Using Transmission Line Models 55
2.17.2 Derivation of Telegrapher's Equation for the Two-Wire Transmission Line 56
2.18 Plane Wave Propagation 66
2.19 Radiation 68
2.19.1 Radiation Mechanism 68
2.19.2 Hertzian Dipole 69
2.19.3 Fundamental Antenna Parameters 71
2.19.4 Linear Antennas 75
2.20 References 79

3 Introduction to Numerical Methods in Electromagnetics 80

3.1 Analytical Versus Numerical Methods 82
3.1.1 Frequency and Time Domain Modeling 82
3.2 Overview of Numerical Methods: Domain, Boundary, and Source Simulation 84
3.2.1 Modeling of Problems via the Domain Methods: FDM and FEM 84
3.2.2 Modeling of Problems via the BEM: Direct and Indirect Approach 85

3.3 The Finite Difference Method 85
3.3.1 One-Dimensional FDM 86
3.3.2 Two-Dimensional FDM 88
3.4 The Finite Element Method 91
3.4.1 Basic Concepts of FEM 91
3.4.2 One-Dimensional FEM 92
3.4.3 Two-Dimensional FEM 98
3.5 The Boundary Element Method 109
3.5.1 Integral Equation Formulation 109
3.5.2 Boundary Element Discretization 114
3.5.3 Computational Example for 2D Static Problem 121
3.6 References 122

4 Static Field Analysis 123

4.1 Electrostatic Fields 123
4.2 Magnetostatic Fields 124
4.3 Modeling of Static Field Problems 126
4.3.1 Integral Equations in Electrostatics Using Sources 126
4.3.2 Computational Example: Modeling of a Lightning Rod 129
4.4 References 135

5 Quasistatic Field Analysis 136

5.1 Introduction 136
5.2 Formulation of the Quasistatic Problem 137
5.3 Integral Equation Representation of the Helmholtz Equation 140
5.4 Computational Example 143
5.4.1 Analytical Solution of the Eddy Current Problem 144
5.4.2 Boundary Element Solution of the Eddy Current Problem 146
5.5 References 150

6 Electromagnetic Scattering Analysis 151

6.1 The Electromagnetic Wave Equations 151
6.2 Complex Phasor Form of the Wave Equations 154
6.3 Two-Dimensional Scattering from a Perfectly Conducting Cylinder of Arbitrary Cross-Section 154

6.4 Solution by the Indirect Boundary Element Method 156
6.4.1 Constant Element Case 158
6.4.2 Linear Elements Case 159
6.5 Numerical Example 159
6.6 References 162

PART II: ANALYSIS OF THIN WIRE ANTENNAS AND SCATTERERS 163

7 Wire Antennas and Scatterers: General Considerations 165

7.1 Frequency Domain Thin Wire Integral Equations 165
7.2 Time Domain Thin Wire Integral Equations 166
7.3 Modeling in the Frequency and Time Domain: Computational Aspects 167
7.4 References 168

8 Wire Antennas and Scatterers: Frequency Domain Analysis 171

8.1 Thin Wires in Free Space 171
8.1.1 Single Straight Wire in Free Space 172
8.1.2 Boundary Element Solution of Thin Wire Integral Equation 174
8.1.3 Calculation of the Radiated Electric Field and the Input Impedance of the Wire 180
8.1.4 Numerical Results for Thin Wire in Free Space 180
8.1.5 Coated Thin Wire Antenna in Free Space 181
8.1.6 The Near Field of a Coated Thin Wire Antenna 186
8.1.7 Boundary Element Procedures for Coated Wires 187
8.1.8 Numerical Results for Coated Wire 190
8.1.9 Thin Wire Loop Antenna 191
8.1.10 Boundary Element Solution of Loop Antenna Integral Equation 193
8.1.11 Numerical Results for a Loop Antenna 196
8.1.12 Thin Wire Array in Free Space: Horizontal Arrangement 196
8.1.13 Boundary Element Analysis of Horizontal Antenna Array 199
8.1.14 Radiated Electric Field of the Wire Array 201

8.1.15 Numerical Results for Horizontal Wire Array 201
8.1.16 Boundary Element Analysis of Vertical Antenna Array: Modeling of Radio Base Station Antennas 201
8.1.17 Numerical Procedures for Vertical Array 207
8.1.18 Numerical Results 209
8.2 Thin Wires Above a Lossy Half-Space 213
8.2.1 Single Straight Wire Above a Dissipative Half-Space 214
8.2.2 Loaded Antenna Above a Dissipative Half-Space 220
8.2.3 Electric Field and the Input Impedance of a Single Wire Above a Half-Space 222
8.2.4 Boundary Element Analysis for Single Wire Above a Real Ground 224
8.2.5 Treatment of Sommerfeld Integrals 227
8.2.6 Calculation of Electric Field and Input Impedance 229
8.2.7 Numerical Results for a Single Wire Above a Real Ground 233
8.2.8 Multiple Straight Wire Antennas Over a Lossy Half-Space 237
8.2.9 Electric Field of a Wire Array Above a Lossy Half-Space 239
8.2.10 Boundary Element Analysis of Wire Array Above a Lossy Ground 240
8.2.11 Near-Field Calculation for Wires Above Half-Space 241
8.2.12 Computational Examples for Wires Above a Lossy Half-Space 242
8.3 References 246

9 Wire Antennas and Scatterers: Time Domain Analysis 250

9.1 Thin Wires in Free Space 252
9.1.1 Single Wire in Free Space 252
9.1.2 Single Wire Far Field 256
9.1.3 Loaded Straight Thin Wire in Free Space 257
9.1.4 Two Coupled Identical Wires in Free Space 259
9.1.5 Measures for Postprocessing of Transient Response 263

9.1.6 Computational Procedures for Thin Wires in Free Space 265
9.1.7 Numerical Results for Thin Wires in Free Space 275
9.2 Thin Wires in a Presence of a Two-Media Configuration 290
9.2.1 Single Straight Wire Above a Real Ground 290
9.2.2 Far Field Equations 294
9.2.3 Loaded Straight Thin Wire Above a Lossy Half-Space 296
9.2.4 Two Coupled Horizontal Wires in a Two Media Configuration 300
9.2.5 Thin Wire Array Above a Real Ground 304
9.2.6 Computational Procedures for Horizontal Wires Above a Dielectric Half-Space 307
9.2.7 Computational Examples 317
9.3 References 333

PART III: COMPUTATIONAL MODELS IN ELECTROMAGNETIC COMPATIBILITY 335

10 Transmission Lines of Finite Length: General Considerations 337

10.1 Transmission Line Theory Method 338
10.2 Antenna Models of the Transmission Lines 340
10.2.1 Above-Ground Transmission Lines 341
10.2.2 Below-Ground Transmission Lines 341
10.3 References 342

11 Electromagnetic Field Coupling to Overhead Lines: Frequency Domain and Time Domain Analysis 345

11.1 Frequency Domain Analysis: Derivation of Generalized Telegrapher's Equations 345
11.2 Frequency Domain Computational Results 351
11.2.1 Single Wire Above an Imperfect Ground 351
11.2.2 Multiple Wire Transmission Line Above an Imperfect Ground 355
11.3 Time Domain Analysis 359
11.4 Time Domain Computational Examples 359

11.4.1 Single Wire Transmission Line 360
11.4.2 Two Wire Transmission Line 367
11.4.3 Three Wire Transmission Line 367
11.5 References 372

12 The Electromagnetic Field Coupling to Buried Cables: Frequency- and Time-Domain Analysis 374

12.1 The Frequency-Domain Approach 374
12.1.1 Formulation in the Frequency Domain 375
12.1.2 Numerical Solution of the Integral Equation 378
12.1.3 The Calculation of Transient Response 380
12.1.4 Numerical Results 381
12.2 Time-Domain Approach 384
12.2.1 Formulation in the Time Domain 384
12.2.2 Time-Domain Energy Measures 391
12.2.3 Time-Domain Numerical Solution Procedures 392
12.2.4 Computational Examples 395
12.3 References 403

13 Simple Grounding Systems 405

13.1 Vertical Grounding Electrode 406
13.1.1 Integral Equation Formulation for the Vertical Grounding Electrode 407
13.1.2 The Evaluation of the Input Impedance Spectrum 411
13.1.3 Numerical Procedures for Vertical Grounding Electrode 413
13.1.4 Calculation of the Transient Impedance 414
13.1.5 Numerical Results 416
13.2 Horizontal Grounding Electrode 418
13.2.1 Integral Equation Formulation for the Horizontal Electrode 420
13.2.2 The Evaluation of the Input Impedance Spectrum 425
13.2.3 Numerical Procedures for Horizontal Electrode 427
13.2.4 The Transient Impedance Calculation 428
13.2.5 Numerical Results 428
13.3 Transmission Line Method Versus Antenna Theory Approach 437
13.3.1 Transmission Line Method (TLM) Approach to Modeling of Horizontal Grounding Electrode 438

13.3.2 Computational Examples 439
13.4 Measures for Quantifying the Transient Response of Grounding Electrodes 443
13.4.1 Transient Response Assessment 443
13.4.2 Measures for Quantifying the Transient Response 444
13.4.3 Computational Examples 445
13.5 References 451

14 Human Exposure to Electromagnetic Fields 453

14.1 Environmental Risk of Electromagnetic Fields: General Considerations 453
14.1.1 Nonionizing and Ionizing Radiation 454
14.1.2 Electrosmog or Radiation Pollution at Low and High Frequencies 454
14.1.3 The Effects of Low Frequency Fields 455
14.1.4 The Effects of High Frequency Fields 456
14.1.5 Remarks on Electromagnetic Fields and Related Possible Hazard to Humans 457
14.2 Assessment of Human Exposure to Electromagnetic Fields: Frequency and Time Domain Approach 458
14.2.1 Frequency Domain Cylindrical Antenna Model 458
14.2.2 Realistic Models of the Human Body for ELF Exposures 459
14.2.3 Human Exposure to Transient Electromagnetic Fields 459
14.3 Human Exposure to Extremely Low Frequency (ELF) Electromagnetic Fields 459
14.3.1 Parasitic Antenna Representation of the Human Body 460
14.3.2 Realistic Modeling of the Human Body 467
14.4 Exposure of Humans to Transient Radiation: Cylindrical Model of the Human Body 478
14.4.1 Time Domain Model of the Human Body 479
14.4.2 Measures of the Transient Response 480
14.5 References 489

Index 493