## CONTENTS

<table>
<thead>
<tr>
<th>Preface</th>
<th>xxiii</th>
</tr>
</thead>
</table>

### PART 1  EMC THEORY 1

1. Electromagnetic Compatibility 3
   1.1 Introduction 3
   1.2 Noise and Interference 3
   1.3 Designing for Electromagnetic Compatibility 4
   1.4 Engineering Documentation and EMC 6
   1.5 United States’ EMC Regulations 6
      1.5.1 FCC Regulations 6
      1.5.2 FCC Part 15, Subpart B 8
      1.5.3 Emissions 11
      1.5.4 Administrative Procedures 14
      1.5.5 Susceptibility 17
      1.5.6 Medical Equipment 17
      1.5.7 Telecom 18
      1.5.8 Automotive 19
   1.6 Canadian EMC Requirements 19
   1.7 European Union’s EMC Requirements 20
      1.7.1 Emission Requirements 20
      1.7.2 Harmonics and Flicker 22
      1.7.3 Immunity Requirements 23
      1.7.4 Directives and Standards 23
   1.8 International Harmonization 26
   1.9 Military Standards 27
CONTENTS

1.10 Avionics 28
1.11 The Regulatory Process 30
1.12 Typical Noise Path 30
1.13 Methods of Noise Coupling 31
  1.13.1 Conductively Coupled Noise 31
  1.13.2 Common Impedance Coupling 32
  1.13.3 Electric and Magnetic Field Coupling 33
1.14 Miscellaneous Noise Sources 33
  1.14.1 Galvanic Action 33
  1.14.2 Electrolytic Action 35
  1.14.3 Triboelectric Effect 35
  1.14.4 Conductor Motion 36
1.15 Use of Network Theory 36
  Summary 38
  Problems 39
  References 41
  Further Reading 42

2. Cabling 44
  2.1 Capacitive Coupling 45
  2.2 Effect of Shield on Capacitive Coupling 48
  2.3 Inductive Coupling 52
  2.4 Mutual Inductance Calculations 54
  2.5 Effect of Shield on Magnetic Coupling 56
    2.5.1 Magnetic Coupling Between Shield and Inner Conductor 58
    2.5.2 Magnetic Coupling—Open Wire to Shielded Conductor 61
  2.6 Shielding to Prevent Magnetic Radiation 64
  2.7 Shielding a Receptor Against Magnetic Fields 67
  2.8 Common Impedance Shield Coupling 69
  2.9 Experimental Data 70
  2.10 Example of Selective Shielding 74
  2.11 Shield Transfer Impedance 75
  2.12 Coaxial Cable Versus Twisted Pair 75
4. Balancing and Filtering

4.1 Balancing
   4.1.1 Common-Mode Rejection Ratio
   4.1.2 Cable Balance
   4.1.3 System Balance
   4.1.4 Balanced Loads

4.2 Filtering
   4.2.1 Common-Mode Filters
   4.2.2 Parasitic Effects in Filters

4.3 Power Supply Decoupling
   4.3.1 Low-Frequency Analog Circuit Decoupling
   4.3.2 Amplifier Decoupling

4.4 Driving Capacitive Loads

4.5 System Bandwidth

4.6 Modulation and Coding

5. Passive Components

5.1 Capacitors
   5.1.1 Electrolytic Capacitors
   5.1.2 Film Capacitors
   5.1.3 Mica and Ceramic Capacitors
   5.1.4 Feed-Through Capacitors
   5.1.5 Paralleling Capacitors

5.2 Inductors

5.3 Transformers

5.4 Resistors
   5.4.1 Noise in Resistors
5.5 Conductors 208
  5.5.1 Inductance of Round Conductors 209
  5.5.2 Inductance of Rectangular Conductors 210
  5.5.3 Resistance of Round Conductors 211
  5.5.4 Resistance of Rectangular Conductors 213

5.6 Transmission Lines 215
  5.6.1 Characteristic Impedance 217
  5.6.2 Propagation Constant 220
  5.6.3 High-Frequency Loss 221
  5.6.4 Relationship Among $C$, $L$ and $\varepsilon_r$. 224
  5.6.5 Final Thoughts 225

5.7 Ferrites 225
  Summary 233
  Problems 234
  References 237
  Further Reading 237

6. Shielding 238
  6.1 Near Fields and Far Fields 238
  6.2 Characteristic and Wave Impedances 241
  6.3 Shielding Effectiveness 243
  6.4 Absorption Loss 245
  6.5 Reflection Loss 249
    6.5.1 Reflection Loss to Plane Waves 252
    6.5.2 Reflection Loss in the Near Field 253
    6.5.3 Electric Field Reflection Loss 254
    6.5.4 Magnetic Field Reflection Loss 255
    6.5.5 General Equations for Reflection Loss 256
    6.5.6 Multiple Reflections in Thin Shields 256
  6.6 Composite Absorption and Reflection Loss 257
    6.6.1 Plane Waves 257
    6.6.2 Electric Fields 258
    6.6.3 Magnetic Fields 259
  6.7 Summary of Shielding Equations 260
  6.8 Shielding with Magnetic Materials 260
  6.9 Experimental Data 265
CONTENTS

6.10 Apertures 267
  6.10.1 Multiple Apertures 270
  6.10.2 Seams 273
  6.10.3 Transfer Impedance 277

6.11 Waveguide Below Cutoff 280

6.12 Conductive Gaskets 282
  6.12.1 Joints of Dissimilar Metals 283
  6.12.2 Mounting of Conductive Gaskets 284

6.13 The “IDEAL” Shield 287

6.14 Conductive Windows 288
  6.14.1 Transparent Conductive Coatings 288
  6.14.2 Wire Mesh Screens 289
  6.14.3 Mounting of Windows 289

6.15 Conductive Coatings 289
  6.15.1 Conductive Paints 291
  6.15.2 Flame/Arc Spray 291
  6.15.3 Vacuum Metalizing 291
  6.15.4 Electroless Plating 292
  6.15.5 Metal Foil Linings 292
  6.15.6 Filled Plastic 293

6.16 Internal Shields 293

6.17 Cavity Resonance 295

6.18 Grounding of Shields 296
  Summary 296
  Problems 297
  References 299
  Further Reading 300

7. Contact Protection 302
  7.1 Glow Discharges 302
  7.2 Metal-Vapor or Arc Discharges 303
  7.3 AC Versus DC Circuits 305
  7.4 Contact Material 306
  7.5 Contact Rating 306
  7.6 Loads with High Inrush Currents 307
CONTENTS

7.7 Inductive Loads 308
7.8 Contact Protection Fundamentals 310
7.9 Transient Suppression for Inductive Loads 314
7.10 Contact Protection Networks for Inductive Loads 318
   7.10.1 C Network 318
   7.10.2 R–C Network 318
   7.10.3 R–C–D Network 321
7.11 Inductive Loads Controlled by a Transistor Switch 322
7.12 Resistive Load Contact Protection 323
7.13 Contact Protection Selection Guide 323
7.14 Examples 324
       Summary 325
       Problems 326
       References 327
       Further Reading 327

8. Intrinsic Noise Sources 328
8.1 Thermal Noise 328
8.2 Characteristics of Thermal Noise 332
8.3 Equivalent Noise Bandwidth 334
8.4 Shot Noise 337
8.5 Contact Noise 338
8.6 Popcorn Noise 339
8.7 Addition of Noise Voltages 340
8.8 Measuring Random Noise 341
       Summary 342
       Problems 343
       References 345
       Further Reading 345

9. Active Device Noise 346
9.1 Noise Factor 346
9.2 Measurement of Noise Factor 349
10.6 Ground Plane Current Distribution and Impedance
  10.6.1 Reference Plane Current Distribution
  10.6.2 Ground Plane Impedance
  10.6.3 Ground Plane Voltage
  10.6.4 End Effects

10.7 Digital Logic Current Flow
  10.7.1 Microstrip Line
  10.7.2 Stripline
  10.7.3 Digital Circuit Current Flow Summary

Summary
Problems
References
Further Reading

PART 2  EMC APPLICATIONS

11. Digital Circuit Power Distribution
  11.1 Power Supply Decoupling
  11.2 Transient Power Supply Currents
    11.2.1 Transient Load Current
    11.2.2 Dynamic Internal Current
    11.2.3 Fourier Spectrum of the Transient Current
    11.2.4 Total Transient Current
  11.3 Decoupling Capacitors
  11.4 Effective Decoupling Strategies
    11.4.1 Multiple Decoupling Capacitors
    11.4.2 Multiple Capacitors of the Same Value
    11.4.3 Multiple Capacitors of Two Different Values
    11.4.4 Multiple Capacitors of Many Different Values
    11.4.5 Target Impedance
    11.4.6 Embedded PCB Capacitance
    11.4.7 Power Supply Isolation
  11.5 The Effect of Decoupling on Radiated Emissions
  11.6 Decoupling Capacitor Type and Value
  11.7 Decoupling Capacitor Placement and Mounting
  11.8 Bulk Decoupling Capacitors
12. Digital Circuit Radiation

12.1 Differential-Mode Radiation
  12.1.1 Loop Area
  12.1.2 Loop Current
  12.1.3 Fourier Series
  12.1.4 Radiated Emission Envelope

12.2 Controlling Differential-Mode Radiation
  12.2.1 Board Layout
  12.2.2 Canceling Loops
  12.2.3 Dithered Clocks

12.3 Common-Mode Radiation

12.4 Controlling Common-Mode Radiation
  12.4.1 Common-Mode Voltage
  12.4.2 Cable Filtering and Shielding
  12.4.3 Separate I/O Grounds
  12.4.4 Dealing With Common-Mode Radiation Issues

Summary
Problems
References
Further Reading
13.3 Power-Line Filters
  13.3.1 Common-Mode Filtering
  13.3.2 Differential-Mode Filtering
  13.3.3 Leakage Inductance
  13.3.4 Filter Mounting
  13.3.5 Power Supplies with Integral Power-Line Filters
  13.3.6 High-Frequency Noise

13.4 Primary-to-Secondary Common-Mode Coupling

13.5 Frequency Dithering

13.6 Power Supply Instability

13.7 Magnetic Field Emissions

13.8 Variable Speed Motor Drives

13.9 Harmonic Suppression
  13.9.1 Inductive Input Filters
  13.9.2 Active Power Factor Correction
  13.9.3 AC Line Reactors

Summary

Problems

References

Further Reading

14. RF and Transient Immunity

14.1 Performance Criteria

14.2 RF Immunity
  14.2.1 The RF Environment
  14.2.2 Audio Rectification
  14.2.3 RFI Mitigation Techniques

14.3 Transient Immunity
  14.3.1 Electrostatic Discharge
  14.3.2 Electrical Fast Transient
  14.3.3 Lightning Surge
  14.3.4 Transient Suppression Networks
  14.3.5 Signal Line Suppression
  14.3.6 Protection of High-Speed Signal Lines
  14.3.7 Power Line Transient Suppression
  14.3.8 Hybrid Protection Network
14.4 Power Line Disturbances
14.4.1 Power Line Immunity Curve
Summary
Problems
References
Further Reading

15. Electrostatic Discharge
15.1 Static Generation
15.1.1 Inductive Charging
15.1.2 Energy Storage
15.2 Human Body Model
15.3 Static Discharge
15.3.1 Decay Time
15.4 ESD Protection in Equipment Design
15.5 Preventing ESD Entry
15.5.1 Metallic Enclosures
15.5.2 Input/Output Cable Treatment
15.5.3 Insulated Enclosures
15.5.4 Keyboards and Control Panels
15.6 Hardening Sensitive Circuits
15.7 ESD Grounding
15.8 Nongrounded Products
15.9 Field-Induced Upset
15.9.1 Inductive Coupling
15.9.2 Capacitive Coupling
15.10 Transient Hardened Software Design
15.10.1 Detecting Errors in Program Flow
15.10.2 Detecting Errors in Input/Output
15.10.3 Detecting Errors in Memory
15.11 Time Windows
Summary
Problems
16. PCB Layout and Stackup 622

16.1 General PCB Layout Considerations 622
16.1.1 Partitioning 622
16.1.2 Keep Out Zones 622
16.1.3 Critical Signals 623
16.1.4 System Clocks 624

16.2 PCB-to-Chassis Ground Connection 625

16.3 Return Path Discontinuities 626
16.3.1 Slots in Ground/Power Planes 627
16.3.2 Split Ground/Power Planes 628
16.3.3 Changing Reference Planes 630
16.3.4 Referencing the Top and Bottom of the Same Plane 633
16.3.5 Connectors 634
16.3.6 Ground Fill 634

16.4 PCB Layer Stackup 635
16.4.1 One- and Two-Layer Boards 636
16.4.2 Multilayer Boards 637
16.4.3 General PCB Design Procedure 653

17. Mixed-Signal PCB Layout 660

17.1 Split Ground Planes 660
17.2 Microstrip Ground Plane Current Distribution 662
17.3 Analog and Digital Ground Pins 665
17.4 When Should Split Ground Planes Be Used? 668
17.5 Mixed Signal ICs 669
17.5.1 Multi-Board Systems 671
17.6 High-Resolution A/D and D/A Converters 671
17.6.1 Stripline 673