Electromagnetic Compatibility Engineering

Henry W. Ott
Henry Ott Consultants

A JOHN WILEY & SONS, INC., PUBLICATION

CONTENTS

Preface	xxiii
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
	vii

viii **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

2.13	Braided Shields	79
2.14	Spiral Shields	81
2.15	Shield Terminations	84
2.15.1	Pigtails	84
2.15.2	Grounding of Cable Shields	88
2.16	Ribbon Cables	94
2.17	Electrically Long Cables	96
	Summary	96
	Problems	98
	References	103
	Further Reading	104
3.	Grounding	106
3.1	AC Power Distribution and Safety Grounds	107
3.1.1	Service Entrance	108
3.1.2	Branch Circuits	109
3.1.3	Noise Control	111
3.1.4	Earth Grounds	114
3.1.5	Isolated Grounds	116
3.1.6	Separately Derived Systems	118
3.1.7	Grounding Myths	119
3.2	Signal Grounds	120
3.2.1	Single-Point Ground Systems	124
3.2.2	Multipoint Ground Systems	126
3.2.3	Common Impedance Coupling	128
3.2.4	Hybrid Grounds	130
3.2.5	Chassis Grounds	131
3.3	Equipment/System Grounding	132
3.3.1	Isolated Systems	133
3.3.2	Clustered Systems	133
3.3.3	Distributed Systems	140
3.4	Ground Loops	142
3.5	Low-Frequency Analysis of Common-Mode Choke	147
3.6	High-Frequency Analysis of Common-Mode Choke	152
3.7	Single Ground Reference for a Circuit	154

x CONTENTS

Summary	155
Problems	156
References	157
Further Reading	157
4. Balancing and Filtering	158
4.1 Balancing	158
4.1.1 Common-Mode Rejection Ratio	161
4.1.2 Cable Balance	165
4.1.3 System Balance	166
4.1.4 Balanced Loads	166
4.2 Filtering	174
4.2.1 Common-Mode Filters	174
4.2.2 Parasitic Effects in Filters	177
4.3 Power Supply Decoupling	178
4.3.1 Low-Frequency Analog Circuit Decoupling	183
4.3.2 Amplifier Decoupling	185
4.4 Driving Capacitive Loads	186
4.5 System Bandwidth	188
4.6 Modulation and Coding	190
Summary	190
Problems	191
References	192
Further Reading	193
5. Passive Components	194
5.1 Capacitors	194
5.1.1 Electrolytic Capacitors	195
5.1.2 Film Capacitors	197
5.1.3 Mica and Ceramic Capacitors	198
5.1.4 Feed-Through Capacitors	200
5.1.5 Paralleling Capacitors	202
5.2 Inductors	203
5.3 Transformers	204
5.4 Resistors	206
5.4.1 Noise in Resistors	207

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 ϵ_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

xii 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

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

xiv CONTENTS

9.2.1	Single-Frequency Method	349
9.2.2	Noise Diode Method	350
9.3	Calculating S/N Ratio and Input Noise Voltage from Noise Factor	351
9.4	Noise Voltage and Current Model	353
9.5	Measurement of V_n and I_n	355
9.6	Calculating Noise Factor and S/N Ratio from V_n-I_n	356
9.7	Optimum Source Resistance	357
9.8	Noise Factor of Cascaded Stages	360
9.9	Noise Temperature	362
9.10	Bipolar Transistor Noise	364
9.10.1	Transistor Noise Factor	365
9.10.2	V_n-I_n for Transistors	367
9.11	Field-Effect Transistor Noise	368
9.11.1	FET Noise Factor	368
9.11.2	V_n-I_n Representation of FET Noise	370
9.12	Noise in Operational Amplifiers	370
9.12.1	Methods of Specifying Op-Amp Noise	373
9.12.2	Op-Amp Noise Factor	375
	Summary	375
	Problems	376
	References	377
	Further Reading	378
10.	Digital Circuit Grounding	379
10.1	Frequency Versus Time Domain	380
10.2	Analog Versus Digital Circuits	380
10.3	Digital Logic Noise	380
10.4	Internal Noise Sources	381
10.5	Digital Circuit Ground Noise	384
10.5.1	Minimizing Inductance	385
10.5.2	Mutual Inductance	386
10.5.3	Practical Digital Circuit Ground Systems	388
10.5.4	Loop Area	390

10.6	Ground Plane Current Distribution and Impedance	391
10.6.1	Reference Plane Current Distribution	392
10.6.2	Ground Plane Impedance	400
10.6.3	Ground Plane Voltage	408
10.6.4	End Effects	409
10.7	Digital Logic Current Flow	412
10.7.1	Microstrip Line	414
10.7.2	Stripline	415
10.7.3	Digital Circuit Current Flow Summary	418
	Summary	419
	Problems	420
	References	421
	Further Reading	422
PART 2	EMC APPLICATIONS	423
11.	Digital Circuit Power Distribution	425
11.1	Power Supply Decoupling	425
11.2	Transient Power Supply Currents	426
11.2.1	Transient Load Current	427
11.2.2	Dynamic Internal Current	428
11.2.3	Fourier Spectrum of the Transient Current	429
11.2.4	Total Transient Current	431
11.3	Decoupling Capacitors	431
11.4	Effective Decoupling Strategies	436
11.4.1	Multiple Decoupling Capacitors	437
11.4.2	Multiple Capacitors of the Same Value	437
11.4.3	Multiple Capacitors of Two Different Values	440
11.4.4	Multiple Capacitors of Many Different Values	444
11.4.5	Target Impedance	445
11.4.6	Embedded PCB Capacitance	447
11.4.7	Power Supply Isolation	452
11.5	The Effect of Decoupling on Radiated Emissions	454
11.6	Decoupling Capacitor Type and Value	456
11.7	Decoupling Capacitor Placement and Mounting	457
11.8	Bulk Decoupling Capacitors	459

xvi **CONTENTS**

11.9	Power Entry Filters	460
	Summary	461
	Problems	461
	References	463
	Further Reading	463
12.	Digital Circuit Radiation	464
12.1	Differential-Mode Radiation	465
	12.1.1 Loop Area	468
	12.1.2 Loop Current	468
	12.1.3 Fourier Series	468
	12.1.4 Radiated Emission Envelope	470
12.2	Controlling Differential-Mode Radiation	471
	12.2.1 Board Layout	471
	12.2.2 Canceling Loops	474
	12.2.3 Dithered Clocks	475
12.3	Common-Mode Radiation	477
12.4	Controlling Common-Mode Radiation	480
	12.4.1 Common-Mode Voltage	481
	12.4.2 Cable Filtering and Shielding	482
	12.4.3 Separate I/O Grounds	485
	12.4.4 Dealing With Common-Mode Radiation Issues	488
	Summary	488
	Problems	489
	References	490
	Further Reading	491
13.	Conducted Emissions	492
13.1	Power Line Impedance	492
	13.1.1 Line Impedance Stabilization Network	494
13.2	Switched-Mode Power Supplies	495
	13.2.1 Common-Mode Emissions	498
	13.2.2 Differential-Mode Emissions	501
	13.2.3 DC-to-DC Converters	509
	13.2.4 Rectifier Diode Noise	509

13.3	Power-Line Filters	511
13.3.1	Common-Mode Filtering	512
13.3.2	Differential-Mode Filtering	512
13.3.3	Leakage Inductance	513
13.3.4	Filter Mounting	516
13.3.5	Power Supplies with Integral Power-Line Filters	519
13.3.6	High-Frequency Noise	520
13.4	Primary-to-Secondary Common-Mode Coupling	523
13.5	Frequency Dithering	524
13.6	Power Supply Instability	524
13.7	Magnetic Field Emissions	525
13.8	Variable Speed Motor Drives	528
13.9	Harmonic Suppression	536
13.9.1	Inductive Input Filters	538
13.9.2	Active Power Factor Correction	538
13.9.3	AC Line Reactors	539
	Summary	541
	Problems	542
	References	544
	Further Reading	544
14.	RF and Transient Immunity	545
14.1	Performance Criteria	545
14.2	RF Immunity	546
14.2.1	The RF Environment	547
14.2.2	Audio Rectification	548
14.2.3	RFI Mitigation Techniques	549
14.3	Transient Immunity	557
14.3.1	Electrostatic Discharge	558
14.3.2	Electrical Fast Transient	558
14.3.3	Lightning Surge	559
14.3.4	Transient Suppression Networks	560
14.3.5	Signal Line Suppression	561
14.3.6	Protection of High-Speed Signal Lines	564
14.3.7	Power Line Transient Suppression	566
14.3.8	Hybrid Protection Network	570

xviii **CONTENTS**

14.4	Power Line Disturbances	572
14.4.1	Power Line Immunity Curve	573
	Summary	575
	Problems	576
	References	578
	Further Reading	579
15.	Electrostatic Discharge	580
15.1	Static Generation	580
15.1.1	Inductive Charging	583
15.1.2	Energy Storage	585
15.2	Human Body Model	587
15.3	Static Discharge	589
15.3.1	Decay Time	590
15.4	ESD Protection in Equipment Design	592
15.5	Preventing ESD Entry	594
15.5.1	Metallic Enclosures	595
15.5.2	Input/Output Cable Treatment	599
15.5.3	Insulated Enclosures	604
15.5.4	Keyboards and Control Panels	607
15.6	Hardening Sensitive Circuits	608
15.7	ESD Grounding	608
15.8	Nongrounded Products	609
15.9	Field-Induced Upset	610
15.9.1	Inductive Coupling	611
15.9.2	Capacitive Coupling	611
15.10	Transient Hardened Software Design	612
15.10.1	Detecting Errors in Program Flow	613
15.10.2	Detecting Errors in Input/Output	614
15.10.3	Detecting Errors in Memory	616
15.11	Time Windows	617
	Summary	617
	Problems	619

	CONTENTS	xix
References		620
Further Reading		621
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
Summary		655
Problems		657
References		658
Further Reading		658
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

xx CONTENTS

17.6.2	Asymmetric Stripline	674
17.6.3	Isolated Analog and Digital Ground Planes	675
17.7	A/D and D/A Converter Support Circuitry	676
17.7.1	Sampling Clocks	676
17.7.2	Mixed-Signal Support Circuitry	678
17.8	Vertical Isolation	679
17.9	Mixed-Signal Power Distribution	681
17.9.1	Power Distribution	681
17.9.2	Decoupling	682
17.10	The IPC Problem	684
	Summary	685
	Problems	686
	References	687
	Further Reading	687
18.	Precompliance EMC Measurements	688
18.1	Test Environment	689
18.2	Antennas Versus Probes	689
18.3	Common-Mode Currents on Cables	690
18.3.1	Test Procedure	693
18.3.2	Cautions	693
18.4	Near Field Measurements	694
18.4.1	Test Procedure	695
18.4.2	Cautions	696
18.4.3	Seams and Apertures in Enclosures	697
18.5	Noise Voltage Measurements	697
18.5.1	Balanced Differential Probe	698
18.5.2	DC to 1-GHz Probe	700
18.5.3	Cautions	700
18.6	Conducted Emission Testing	700
18.6.1	Test Procedure	702
18.6.2	Cautions	703
18.6.3	Separating C-M from D-M Noise	704
18.7	Spectrum Analyzers	707

	CONTENTS	xxi
18.7.1	Detector Functions	709
18.7.2	General Test Procedure	710
18.8	EMC Crash Cart	711
18.8.1	Mitigation Parts List	712
18.9	One-Meter Radiated Emission Measurements	713
18.9.1	Test Environment	713
18.9.2	Limits for 1-m Testing	713
18.9.3	Antennas for 1-m Testing	714
18.10	Precompliance Immunity Testing	717
18.10.1	Radiated Immunity	717
18.10.2	Conducted Immunity	720
18.10.3	Transient Immunity	721
18.11	Precompliance Power Quality Tests	723
18.11.1	Harmonics	724
18.11.2	Flicker	725
18.12	Margin	726
18.12.1	Radiated Emission Margin	726
18.12.2	Electrostatic Discharge Margin	727
	Summary	728
	Problems	729
	References	730
	Further Reading	731
APPENDIX		733
A. The Decibel		733
A.1	Properties of Logarithms	733
A.2	Using the Decibel for Other than Power Measurements	734
A.3	Power Loss or Negative Power Gain	736
A.4	Absolute Power Level	736
A.5	Summing Powers Expressed in Decibels	738
B. The Ten Best Ways to <i>Maximize</i> the Emission from Your Product		740
C. Multiple Reflections of Magnetic Fields in Thin Shields		743

D. Dipoles for Dummies	746
D.1 Basic Dipoles for Dummies	746
D.2 Intermediate Dipoles for Dummies	751
D.3 Advanced Dipoles for Dummies	756
D.3.1 Impedance of a Dipole	756
D.3.2 Dipole Resonance	756
D.3.3 Receiving Dipole	759
D.3.4 Theory of Images	759
D.3.5 Dipole Arrays	761
D.3.6 Very High-Frequency Dipoles	763
Summary	763
Further Reading	764
E. Partial Inductance	765
E.1 Inductance	765
E.2 Loop Inductance	767
E.2.1 Inductance of a Rectangular Loop	768
E.3 Partial Inductance	770
E.3.1 Partial Self-Inductance	771
E.3.2 Partial Mutual Inductance	773
E.3.3 Net Partial-Inductance	776
E.3.4 Partial Inductance Applications	776
E.3.5 Transmission Line Example	778
E.4 Ground Plane Inductance Measurement Test Setup	780
E.5 Inductance Notation	785
Summary	788
References	788
Further Reading	789
F. Answers to Problems	790
Index	825