# Contents

About the Author .......................... xxi
Preface ...................................... xxiii
Nomenclature ............................... xxv

1 Introduction .............................. 1
   1.1 Classification of Power Supplies ..... 1
   1.2 Basic Functions of Voltage Regulators . 3
   1.3 Power Relationships in DC–DC Converters . 4
   1.4 DC Transfer Functions of DC–DC Converters . 5
   1.5 Static Characteristics of DC Voltage Regulators . 6
   1.6 Dynamic Characteristics of DC Voltage Regulators . 9
   1.7 Linear Voltage Regulators
       1.7.1 Series Voltage Regulator . 13
       1.7.2 Shunt Voltage Regulator . 14
   1.8 Topologies of PWM DC–DC Converters . 16
   1.9 Relationships Among Current, Voltage, Energy, and Power . 18
   1.10 Summary ................................ 19
References .................................. 19
Review Questions ......................... 20
Problems ................................... 21

2 Buck PWM DC–DC Converter .......... 22
   2.1 Introduction ............................ 22
   2.2 DC Analysis of PWM Buck Converter for CCM . 22
       2.2.1 Circuit Description ............. 22
       2.2.2 Assumptions ................... 25
       2.2.3 Time Interval: $0 < t \leq DT$ . 25
       2.2.4 Time Interval: $DT < t \leq T$ . 26
       2.2.5 Device Stresses for CCM . 27
       2.2.6 DC Voltage Transfer Function for CCM . 27
       2.2.7 Boundary Between CCM and DCM . 29
       2.2.8 Capacitors ...................... 31
       2.2.9 Ripple Voltage in Buck Converter for CCM . 33
       2.2.10 Switching Losses with Linear MOSFET Output Capacitance . 39
       2.2.11 Switching Losses with Nonlinear MOSFET Output Capacitance . 40
       2.2.12 Power Losses and Efficiency of Buck Converter for CCM . 43
       2.2.13 DC Voltage Transfer Function of Lossy Converter for CCM . 48
       2.2.14 MOSFET Gate-Drive Power . 48
Contents

2.2.15 Gate Driver 49
2.2.16 Design of Buck Converter for CCM 50

2.3 DC Analysis of PWM Buck Converter for DCM 52
2.3.1 Time Interval: $0 < t \leq DT$ 56
2.3.2 Time Interval: $DT < t \leq (D + D_1)T$ 58
2.3.3 Time Interval: $(D + D_1)T < t \leq T$ 58
2.3.4 Device Stresses for DCM 59
2.3.5 DC Voltage Transfer Function for DCM 59
2.3.6 Maximum Inductance for DCM 62
2.3.7 Power Losses and Efficiency of Buck Converter for DCM 63
2.3.8 Design of Buck Converter for DCM 65

2.4 Buck Converter with Input Filter 68
2.5 Buck Converter with Synchronous Rectifier 68
2.6 Buck Converter with Positive Common Rail 76
2.7 Quadratic Buck Converter 76

2.8 Tapped-Inductor Buck Converters 79
2.8.1 Tapped-Inductor Common-Diode Buck Converter 79
2.8.2 Tapped-Inductor Common-Transistor Buck Converter 81
2.8.3 Watkins–Johnson Converter 82

2.9 Multiphase Buck Converter 83
2.10 Switched-Inductor Buck Converter 85
2.11 Layout 85
2.12 Summary 85
References 87
Review Questions 88
Problems 88

3 Boost PWM DC–DC Converter 90
3.1 Introduction 90
3.2 DC Analysis of PWM Boost Converter for CCM 90
3.2.1 Circuit Description 90
3.2.2 Assumptions 91
3.2.3 Time Interval: $0 < t \leq DT$ 93
3.2.4 Time Interval: $DT < t \leq T$ 94
3.2.5 DC Voltage Transfer Function for CCM 94
3.2.6 Boundary Between CCM and DCM 95
3.2.7 Ripple Voltage in Boost Converter for CCM 98
3.2.8 Power Losses and Efficiency of Boost Converter for CCM 100
3.2.9 DC Voltage Transfer Function of Lossy Boost Converter for CCM 102
3.2.10 Design of Boost Converter for CCM 103

3.3 DC Analysis of PWM Boost Converter for DCM 107
3.3.1 Time Interval: $0 < t \leq DT$ 110
3.3.2 Time Interval: $DT < t \leq (D + D_1)T$ 111
3.3.3 Time Interval: $(D + D_1)T < t \leq T$ 112
3.3.4 Device Stresses for DCM 112
3.3.5 DC Voltage Transfer Function for DCM 112
3.3.6 Maximum Inductance for DCM 117
3.3.7 Power Losses and Efficiency of Boost Converter for DCM 117
3.3.8 Design of Boost Converter for DCM 120
3.4 Bidirectional Buck and Boost Converters 127
3.5 Synchronous Boost Converter 129
3.6 Tapped-Inductor Boost Converters
3.6.1 Tapped-Inductor Common-Diode Boost Converter 131
3.6.2 Tapped-Inductor Common-Load Boost Converter 132
3.7 Duality 133
3.8 Power Factor Correction 134
3.8.1 Power Factor 134
3.8.2 Boost Power Factor Corrector 138
3.8.3 Electronic Ballasts for Fluorescent Lamps 141
3.9 Summary 141

References 142

Review Questions 143

Problems 143

4 Buck–Boost PWM DC–DC Converter 145
4.1 Introduction 145
4.2 DC Analysis of PWM Buck–Boost Converter for CCM 145
4.2.1 Circuit Description 145
4.2.2 Assumptions 146
4.2.3 Time Interval: $0 < t \leq DT$ 146
4.2.4 Time Interval: $DT < t \leq T$ 148
4.2.5 DC Voltage Transfer Function for CCM 149
4.2.6 Device Stresses for CCM 150
4.2.7 Boundary Between CCM and DCM 151
4.2.8 Ripple Voltage in Buck–Boost Converter for CCM 152
4.2.9 Power Losses and Efficiency of the Buck–Boost Converter for CCM 155
4.2.10 DC Voltage Transfer Function of Lossy Buck–Boost Converter for CCM 158
4.2.11 Design of Buck–Boost Converter for CCM 159
4.3 DC Analysis of PWM Buck–Boost Converter for DCM 162
4.3.1 Time Interval: $0 < t \leq DT$ 165
4.3.2 Time Interval: $DT < t \leq (D + D_1)T$ 166
4.3.3 Time Interval: $(D + D_1)T < t \leq T$ 167
4.3.4 Device Stresses of the Buck–Boost Converter in DCM 167
4.3.5 DC Voltage Transfer Function of the Buck–Boost Converter for DCM 167
4.3.6 Maximum Inductance for DCM 170
4.3.7 Power Losses and Efficiency of the Buck–Boost Converter in DCM 172
4.3.8 Design of Buck–Boost Converter for DCM 174
4.4 Bidirectional Buck–Boost Converter 180
4.5 Synthesis of Buck–Boost Converter 181
4.6 Synthesis of Boost–Buck (Čuk) Converter 183
4.7 Noninverting Buck–Boost Converters 184
4.7.1 Cascaded Noninverting Buck–Boost Converters 184
4.7.2 Four-Transistor Noninverting Buck–Boost Converters 184
4.8 Tapped-Inductor Buck–Boost Converters 186
4.8.1 Tapped-Inductor Common-Diode Buck–Boost Converter 186
4.8.2 Tapped-Inductor Common-Transistor Buck–Boost Converter 187
4.8.3 Tapped-Inductor Common-Load Buck–Boost Converter 188
4.8.4 Tapped-Inductor Common-Source Buck–Boost Converter 191

4.9 Summary 191

References 192

Review Questions 193

Problems 193
x Contents

4.9 Summary 192
References 192
Review Questions 193
Problems 193

5 Flyback PWM DC–DC Converter 195
5.1 Introduction 195
5.2 Transformers 196
5.3 DC Analysis of PWM Flyback Converter for CCM 197
5.3.1 Derivation of PWM Flyback Converter 197
5.3.2 Circuit Description 197
5.3.3 Assumptions 199
5.3.4 Time Interval: 0 < t ≤ DT 200
5.3.5 Time Interval: DT < t ≤ T 201
5.3.6 DC Voltage Transfer Function for CCM 203
5.3.7 Boundary Between CCM and DCM 204
5.3.8 Ripple Voltage in Flyback Converter for CCM 205
5.3.9 Power Losses and Efficiency of Flyback Converter for CCM 207
5.3.10 DC Voltage Transfer Function of Lossy Converter for CCM 210
5.3.11 Design of Flyback Converter for CCM 211
5.4 DC Analysis of PWM Flyback Converter for DCM 214
5.4.1 Time Interval: 0 < t ≤ DT 217
5.4.2 Time Interval: DT < t ≤ (D + D1)T 219
5.4.3 Time Interval: (D + D1)T < t ≤ T 220
5.4.4 DC Voltage Transfer Function for DCM 221
5.4.5 Maximum Magnetizing Inductance for DCM 222
5.4.6 Ripple Voltage in Flyback Converter for DCM 225
5.4.7 Power Losses and Efficiency of Flyback Converter for DCM 226
5.4.8 Design of Flyback Converter for DCM 228
5.5 Multiple-Output Flyback Converter 232
5.6 Bidirectional Flyback Converter 237
5.7 Ringing in Flyback Converter 237
5.8 Flyback Converter with Passive Dissipative Snubber 240
5.9 Flyback Converter with Zener Diode Voltage Clamp 240
5.10 Flyback Converter with Active Clamping 241
5.11 Two-Transistor Flyback Converter 241
5.12 Summary 243
References 244
Review Questions 244
Problems 245

6 Forward PWM DC–DC Converter 246
6.1 Introduction 246
6.2 DC Analysis of PWM Forward Converter for CCM 246
6.2.1 Derivation of Forward PWM Converter 246
6.2.2 Time Interval: 0 < t ≤ DT 248
6.2.3 Time Interval: DT < t ≤ DT + tm 251
6.2.4 Time Interval: DT + tm < t ≤ T 253
6.2.5 Maximum Duty Cycle 253
6.3 Design of Forward Converter for CCM 253
6.4 DC Analysis of PWM Forward Converter for DCM 254
6.4.1 Time Interval: 0 < t ≤ DT 256
6.4.2 Time Interval: DT < t ≤ (D + D1)T 258
6.4.3 Time Interval: (D + D1)T < t ≤ T 259
6.4.4 DC Voltage Transfer Function for DCM 260
6.4.5 Maximum Magnetizing Inductance for DCM 261
6.4.6 Ripple Voltage in Forward Converter for DCM 264
6.4.7 Power Losses and Efficiency of Forward Converter for DCM 265
6.4.8 Design of Forward Converter for DCM 267
6.5 Multiple-Output Forward Converter 271
6.6 Bidirectional Forward Converter 276
6.7 Ringing in Forward Converter 276
6.8 Forward Converter with Passive Dissipative Snubber 280
6.9 Forward Converter with Zener Diode Voltage Clamp 280
6.10 Forward Converter with Active Clamping 281
6.11 Two-Transistor Forward Converter 281
6.12 Summary 283
References 284
Review Questions 284
Problems 285
6.2.6 Device Stresses 254
6.2.7 DC Voltage Transfer Function for CCM 255
6.2.8 Boundary Between CCM and DCM 255
6.2.9 Ripple Voltage in Forward Converter for CCM 256
6.2.10 Power Losses and Efficiency of Forward Converter for CCM 258
6.2.11 DC Voltage Transfer Function of Lossy Converter for CCM 261
6.2.12 Design of Forward Converter for CCM 262
6.3 DC Analysis of PWM Forward Converter for DCM 269
6.3.1 Time Interval: 0 < t ≤ DT 269
6.3.2 Time Interval: DT < t ≤ DT + tm 272
6.3.3 Time Interval: DT + tm < t ≤ (D + D1)T 273
6.3.4 Time Interval: (D + D1)T < t ≤ T 273
6.3.5 DC Voltage Transfer Function for DCM 274
6.3.6 Maximum Inductance for DCM 277
6.3.7 Power Losses and Efficiency of Forward Converter for DCM 278
6.3.8 Design of Forward Converter for DCM 280
6.4 Multiple-Output Forward Converter 288
6.5 Forward Converter with Synchronous Rectifier 288
6.6 Forward Converters with Active Clamping 288
6.7 Two-Switch Forward Converter 290
6.8 Forward–Flyback Converter 291
6.9 Summary 292
References 293
Review Questions 293
Problems 294

7 Half-Bridge PWM DC–DC Converter 296
7.1 Introduction 296
7.2 DC Analysis of PWM Half-Bridge Converter for CCM 296
7.2.1 Circuit Description 296
7.2.2 Assumptions 299
7.2.3 Time Interval: 0 < t ≤ DT 299
7.2.4 Time Interval: DT < t ≤ T/2 301
7.2.5 Time Interval: T/2 < t ≤ T/2 + DT 303
7.2.6 Time Interval: T/2 + DT < t ≤ T 304
7.2.7 Device Stresses 304
7.2.8 DC Voltage Transfer Function of Lossless Half-Bridge Converter for CCM 304
7.2.9 Boundary Between CCM and DCM 305
7.2.10 Ripple Voltage in Half-Bridge Converter for CCM 306
7.2.11 Power Losses and Efficiency of Half-Bridge Converter for CCM 308
7.2.12 DC Voltage Transfer Function of Lossy Converter for CCM 311
7.2.13 Design of Half-Bridge Converter for CCM 312
7.3 DC Analysis of PWM Half-Bridge Converter for DCM 315
7.3.1 Time Interval: 0 < t ≤ DT 315
7.3.2 Time Interval: DT < t ≤ (D + D1)T 320
7.3.3 Time Interval: (D + D1)T < t ≤ T/2 322
7.3.4 DC Voltage Transfer Function for DCM 322
7.3.5 Maximum Inductance for DCM 326
xii Contents

7.4 Summary 326
References 327
Review Questions 327
Problems 328

8 Full-Bridge PWM DC–DC Converter 330
8.1 Introduction 330
8.2 DC Analysis of PWM Full-Bridge Converter for CCM 330
8.2.1 Circuit Description 330
8.2.2 Assumptions 332
8.2.3 Time Interval: 0 < t ≤ DT 332
8.2.4 Time Interval: DT < t ≤ T/2 334
8.2.5 Time Interval: T/2 < t ≤ T/2 + DT 336
8.2.6 Time Interval: T/2 + DT < t ≤ T 336
8.2.7 Device Stresses 337
8.2.8 DC Voltage Transfer Function of Lossless Full-Wave Converter for CCM 337
8.2.9 Boundary Between CCM and DCM 338
8.2.10 Ripple Voltage in Full-Bridge Converter for CCM 339
8.2.11 Power Losses and Efficiency of Full-Bridge Converter for CCM 340
8.2.12 DC Voltage Transfer Function of Lossy Converter for CCM 344
8.2.13 Design of Full-Bridge Converter for CCM 345
8.3 DC Analysis of PWM Full-Bridge Converter for DCM 351
8.3.1 Time Interval: 0 < t ≤ DT 351
8.3.2 Time Interval: DT < t ≤ (D + D_1)T 353
8.3.3 Time Interval: (D + D_1)T < t ≤ T/2 355
8.3.4 DC Voltage Transfer Function for DCM 356
8.3.5 Maximum Inductance for DCM 359
8.4 Phase-Controlled Full-Bridge Converter 361
8.5 Summary 362
References 362
Review Questions 362
Problems 363

9 Small-Signal Models of PWM Converters for CCM and DCM 365
9.1 Introduction 365
9.2 Assumptions 366
9.3 Averaged Model of Ideal Switching Network for CCM 366
9.4 Averaged Values of Switched Resistances 369
9.5 Model Reduction 375
9.6 Large-Signal Averaged Model for CCM 377
9.7 DC and Small-Signal Circuit Linear Models of Switching Network for CCM 381
9.7.1 Large-Signal Circuit Model of Switching Network for CCM 381
9.7.2 Linearization of Switching Network Model for CCM 384
9.8 Block Diagram of Small-signal Model of PWM DC–DC Converters 385
9.9 Family of PWM Converter Models for CCM 386
9.10 PWM Small-Signal Switch Model for CCM 389
9.11 Modeling of Ideal Switching Network for DCM 391
9.11.1 Relationships Among DC Components for DCM 391
9.11.2 Small-Signal Model of Ideal Switching Network for DCM 395
9.12  Averaged Parasitic Resistances for DCM 398
9.13  Summary 400
References 402
Review Questions 405
Problems 405

10  Small-Signal Characteristics of Buck Converter for CCM 407
10.1  Introduction 407
10.2  Small-Signal Model of the PWM Buck Converter 407
10.3  Open-Loop Transfer Functions 408
  10.3.1  Open-Loop Control-to-Output Transfer Function 409
  10.3.2  Delay in Control-to-Output Transfer Function 416
  10.3.3  Open-Loop Input-to-Output Transfer Function 418
  10.3.4  Open-Loop Input Impedance 420
  10.3.5  Open-Loop Output Impedance 423
10.4  Open-Loop Step Responses 426
  10.4.1  Open-Loop Response of Output Voltage to Step Change in Input Voltage 426
  10.4.2  Open-Loop Response of Output Voltage to Step Change in Duty Cycle 431
  10.4.3  Open-Loop Response of Output Voltage to Step Change in Load Current 433
10.5  Open-Loop DC Transfer Functions 434
10.6  Summary 436
References 436
Review Questions 437
Problems 438

11  Small-Signal Characteristics of Boost Converter for CCM 439
11.1  Introduction 439
11.2  DC Characteristics 439
11.3  Open-Loop Control-to-Output Transfer Function 440
11.4  Delay in Open-Loop Control-to-Output Transfer Function 449
11.5  Open-Loop Audio Susceptibility 451
11.6  Open-Loop Input Impedance 455
11.7  Open-Loop Output Impedance 457
11.8  Open-Loop Step Responses 461
  11.8.1  Open-Loop Response of Output Voltage to Step Change in Input Voltage 461
  11.8.2  Open-Loop Response of Output Voltage to Step Change in Duty Cycle 464
  11.8.3  Open-Loop Response of Output Voltage to Step Change in Load Current 465
11.9  Summary 467
References 467
Review Questions 468
Problems 468

12  Voltage-Mode Control of PWM Buck Converter 470
12.1  Introduction 470
12.2  Properties of Negative Feedback 471
12.3  Stability 474
12.4  Single-Loop Control of PWM Buck Converter 475
12.5  Closed-Loop Small-Signal Model of Buck Converter 478
12.6  Pulse-Width Modulator 478
xiv  Contents

12.7 Feedback Network 483
12.8 Transfer Function of Buck Converter with Modulator and Feedback Network 486
12.9 Control Circuits 489
  12.9.1 Error Amplifier 489
  12.9.2 Proportional Controller 490
  12.9.3 Integral Controller 492
  12.9.4 Proportional-Integral Controller 493
  12.9.5 Integral-Single-Lead Controller 497
  12.9.6 Loop Gain 504
  12.9.7 Closed-Loop Control-to-Output Voltage Transfer Function 504
  12.9.8 Closed-Loop Input-to-Output Transfer Function 506
  12.9.9 Closed-Loop Input Impedance 508
  12.9.10 Closed-Loop Output Impedance 509
12.10 Closed-Loop Step Responses 511
  12.10.1 Response to Step Change in Input Voltage 511
  12.10.2 Response to Step Change in Reference Voltage 513
  12.10.3 Closed-Loop Response to Step Change in Load Current 515
  12.10.4 Closed-Loop DC Transfer Functions 515
12.11 Summary 518
References 519
Review Questions 519
Problems 520

13 Voltage-Mode Control of Boost Converter 521
13.1 Introduction 521
13.2 Circuit of Boost Converter with Voltage-Mode Control 521
13.3 Transfer Function of Modulator, Boost Converter Power Stage, and Feedback Network 523
13.4 Integral-Double-Lead Controller 527
13.5 Design of Integral-Double-Lead Controller 532
13.6 Loop Gain 536
13.7 Closed-Loop Control-to-Output Voltage Transfer Function 537
13.8 Closed-Loop Audio Susceptibility 539
13.9 Closed-Loop Input Impedance 539
13.10 Closed-Loop Output Impedance 542
13.11 Closed-Loop Step Responses 544
  13.11.1 Closed-Loop Response to Step Change in Input Voltage 544
  13.11.2 Closed-Loop Response to Step Change in Reference Voltage 547
  13.11.3 Closed-Loop Response to Step Change in Load Current 548
13.12 Closed-Loop DC Transfer Functions 549
13.13 Summary 552
References 552
Review Questions 552
Problems 553

14 Current-Mode Control 554
14.1 Introduction 554
14.2 Principle of Operation of PWM Converters with Peak CMC 555
14.3 Relationship Between Duty Cycle and Inductor-Current Slopes 559
14.4 Instability of Closed-Current Loop 560
14.5 Slope Compensation

14.5.1 Analysis of Slope Compensation in Time Domain 564
14.5.2 Boundary of Slope Compensation for Buck and Buck–Boost Converters 569
14.5.3 Boundary Slope Compensation for Boost Converter 570

14.6 Sample-and-Hold Effect on Current Loop 570

14.6.1 Natural Response of Inductor Current to Small Perturbation in Closed-Current Loop 572

14.6.2 Forced Response of Inductor Current to Step Change in Control Voltage in Closed-Current Loop 575

14.6.3 Relationship Between \( s \)-Domain and \( z \)-Domain 577

14.6.4 Transfer Function of Closed-Current Loop in \( z \)-Domain 578

14.7 Closed-Loop Control Voltage-to-Inductor Current Transfer Function in \( s \)-Domain 580

14.7.1 Approximation of \( H_{ic1} \) by Rational Transfer Function 582

14.7.2 Step Responses of Closed-Inner Loop 588

14.8 Loop Gain of Current Loop 588

14.8.1 Loop Gain of Inner Loop in \( z \)-Domain 588

14.8.2 Loop Gain of Inner Loop in \( s \)-Domain 590

14.9 Gain-Crossover Frequency of Inner Loop 595

14.10 Phase Margin of Inner Loop 596

14.11 Maximum Duty Cycle for Converters Without Slope Compensation 598

14.12 Maximum Duty Cycle for Converters with Slope Compensation 600

14.13 Minimum Slope Compensation for Buck and Buck–Boost Converter 605

14.14 Minimum Slope Compensation for Boost Converter 607

14.15 Error Voltage-to-Duty Cycle Transfer Function 610

14.16 Closed-Loop Control Voltage-to-Duty Cycle Transfer Function of Current Loop 614

14.17 Alternative Representation of Current Loop 618

14.18 Current Loop with Disturbances 618

14.18.1 Modified Approximation of Current Loop 619

14.19 Voltage Loop of PWM Converters with Current-Mode Control 624

14.19.1 Control-to-Output Transfer Function for Buck Converter 624

14.19.2 Block Diagram of Power Stages of PWM Converters 627

14.19.3 Closed-Voltage Loop Transfer Function of PWM Converters with Current-Mode Control 628

14.19.4 Closed-Loop Audio Susceptibility of PWM Converters with Current-Mode Control 628

14.19.5 Closed-Loop Output Impedance of PWM Converters with Current-Mode Control 630

14.20 Feedforward Gains in PWM Converters with Current-Mode Control without Slope Compensation 631

14.21 Feedforward Gains in PWM Converters with Current-Mode Control and Slope Compensation 634

14.22 Control-to-Output Voltage Transfer Function of Inner Loop with Feedforward Gains 636

14.23 Audio-Susceptibility of Inner Loop with Feedforward Gains 637

14.24 Closed-Loop Transfer Functions with Feedforward Gains 638

14.25 Slope Compensation by Adding a Ramp to Inductor Current Waveform 638

14.26 Relationships for Constant-Frequency Current-Mode On-Time Control 639

14.27 Summary 639

References 640

Review Questions 644

Problems 644
Contents

14.28 Appendix: Sample-and-Hold Modeling 645
14.28.1 Sampler of the Control Voltage 645
14.28.2 Zero-Order Hold of Inductor Current 648
14.28.3 Approximations of $e^{sT_i}$ 650

15 Current-Mode Control of Boost Converter 653
15.1 Introduction 653
15.2 Open-Loop Small-Signal Transfer Functions 653
15.2.1 Open-Loop Duty Cycle-to-Inductor Current Transfer Function 653
15.2.2 High-Frequency Open-Loop Duty Cycle-to-Inductor Current Transfer Function 659
15.2.3 Open-Loop Input Voltage-to-Inductor Current Transfer Function 660
15.2.4 Open-Loop Inductor-to-Output Current Transfer Function 665
15.3 Open-Loop Step Responses of Inductor Current 667
15.3.1 Open-Loop Response of Inductor Current to Step Change in Input Voltage 667
15.3.2 Open-Loop Response of the Inductor Current to Step Change in the Duty Cycle 670
15.3.3 Open-Loop Response of Inductor Current to Step Change in Load Current 672
15.4 Closed-Current-Loop Transfer Functions 675
15.4.1 Forward Gain 675
15.4.2 Loop Gain of Current Loop 675
15.4.3 Closed-Loop Gain of Current Loop 675
15.4.4 Control-to-Output Transfer Function 677
15.4.5 Input Voltage-to-Duty Cycle Transfer Function 684
15.4.6 Load Current-to-Duty Cycle Transfer Function 688
15.4.7 Output Impedance of Closed-Current Loop 690
15.5 Closed-Voltage-Loop Transfer Functions 695
15.5.1 Control-to-Output Transfer Function 695
15.5.2 Control Voltage-to-Feedback Voltage Transfer Function 695
15.5.3 Loop Gain of Voltage Loop 697
15.5.4 Closed-Loop Gain of Voltage Loop 701
15.5.5 Closed-Loop Audio Susceptibility with Integral Controller 703
15.5.6 Closed-Loop Output Impedance with Integral Controller 704
15.6 Closed-Loop Step Responses 706
15.6.1 Closed-Loop Response of Output Voltage to Step Change in Input Voltage 706
15.6.2 Closed-Loop Response of Output Voltage to Step Change in Load Current 708
15.6.3 Closed-Loop Response of Output Voltage to Step Change in Reference Voltage 708
15.7 Closed-Loop DC Transfer Functions 710
15.8 Summary 711

References 711
Review Questions 712
Problems 712

16 Open-Loop Small-Signal Characteristics of PWM Boost Converter for DCM 713
16.1 Introduction 713
16.2 Small-Signal Model of Boost Converter for DCM 713
16.3 Open-Loop Control-to-Output Transfer Function 716
16.4 Open-Loop Input-to-Output Voltage Transfer Function 719
16.5 Open-Loop Input Impedance 724
16.6 Open-Loop Output Impedance 725
16.7 Step Responses of Output Voltage of Boost Converter for DCM
  16.7.1 Response of Output Voltage to Step Change in Input Voltage 728
  16.7.2 Response of Output Voltage to Step Change in Duty Cycle 730
  16.7.3 Response of Output Voltage to Step Change in Load Current 730
16.8 Open-Loop Duty Cycle-to-Inductor Current Transfer Function 731
16.9 Open-Loop Input Voltage-to-Inductor Current Transfer Function 735
16.10 Open-Loop Output Current-to-Inductor Current Transfer Function 735
16.11 Step Responses of Inductor Current of Boost Converter for DCM 738
  16.11.1 Step Response of Inductor Current to Step Change in Input Voltage 738
  16.11.2 Step Response of Inductor Current to Step Change in Duty Cycle 740
  16.11.3 Step Response of Inductor Current to Step Change in Load Current 741
16.12 DC Characteristics of Boost Converter for DCM 742
  16.12.1 DC-to-DC Voltage Transfer Function of Lossless Boost Converter for DCM 742
  16.12.2 DC-to-DC Voltage Transfer Function of Lossy Boost Converter for DCM 743
  16.12.3 Efficiency of Boost Converter for DCM 745
16.13 Summary 745

References 745
Review Questions 746
Problems 746

17 Silicon and Silicon-Carbide Power Diodes 747
17.1 Introduction 747
17.2 Electronic Power Switches 747
17.3 Atom 748
17.4 Electron and Hole Effective Mass 749
17.5 Semiconductors 750
17.6 Intrinsic Semiconductors 751
17.7 Extrinsic Semiconductors 756
  17.7.1 n-Type Semiconductor 756
  17.7.2 p-Type Semiconductor 759
  17.7.3 Maximum Operating Temperature 761
17.8 Wide Band Gap Semiconductors 762
17.9 Physical Structure of Junction Diodes 764
  17.9.1 Formation of Depletion Layer 765
  17.9.2 Charge Transport 767
17.10 Static I–V Diode Characteristic 768
17.11 Breakdown Voltage of Junction Diodes 772
  17.11.1 Depletion-Layer Width 773
  17.11.2 Electric Field Intensity Distribution 775
  17.11.3 Avalanche Breakdown Voltage 779
  17.11.4 Punch-Through Breakdown Voltage 781
  17.11.5 Edge Terminations 782
17.12 Capacitances of Junction Diodes 784
  17.12.1 Junction Capacitance 784
  17.12.2 Diffusion Capacitance 787
17.13 Reverse Recovery of pn Junction Diodes 789
  17.13.1 Qualitative Description 789
  17.13.2 Reverse Recovery in Resistive Circuits 790
17.13.3 Charge-Continuity Equation 793
17.13.4 Reverse Recovery in Inductive Circuits 796
17.14 Schottky Diodes 798
17.14.1 Static $I-V$ Characteristic of Schottky Diodes 801
17.14.2 Breakdown Voltages of Schottky Diodes 802
17.14.3 Junction Capacitance of Schottky Diodes 802
17.14.4 Switching Characteristics of Schottky Diodes 802
17.15 Solar Cells 806
17.16 Light-Emitting Diodes 809
17.17 SPICE Model of Diodes 810
17.18 Summary 811
References 815
Review Questions 816
Problems 817

18 Silicon and Silicon-Carbide Power MOSFETs 819
18.1 Introduction 819
18.2 Integrated MOSFETs 819
18.3 Physical Structure of Power MOSFETs 819
18.4 Principle of Operation of Power MOSFETs 824
18.4.1 Cutoff Region 824
18.4.2 Formation of MOSFET Channel 824
18.4.3 Linear Region 824
18.4.4 Saturation Region 825
18.4.5 Antiparallel Diode 825
18.5 Derivation of Power MOSFET Characteristics 826
18.5.1 Ohmic Region 826
18.5.2 Pinch-off Region 829
18.5.3 Channel-Length Modulation 830
18.6 Power MOSFET Characteristics 831
18.7 Mobility of Charge Carriers 833
18.7.1 Effect of Doping Concentration on Mobility 834
18.7.2 Effect of Temperature on Mobility 836
18.7.3 Effect of Electric Field on Mobility 840
18.8 Short-Channel Effects 846
18.8.1 Ohmic Region 846
18.8.2 Pinch-off Region 847
18.9 Aspect Ratio of Power MOSFETs 848
18.10 Breakdown Voltage of Power MOSFETs 850
18.11 Gate Oxide Breakdown Voltage of Power MOSFETs 852
18.12 Specific On-Resistance 852
18.13 Figures-of-Merit of Semiconductors 855
18.14 On-Resistance of Power MOSFETs 857
18.14.1 Channel Resistance 857
18.14.2 Accumulation Region Resistance 857
18.14.3 Neck Region Resistance 858
18.14.4 Drift Region Resistance 859
18.15 Capacitances of Power MOSFETs 862
18.15.1 Gate-to-Source Capacitance 862
18.15.2 Drain-to-Source Capacitance 864
18.15.3 Gate-to-Drain Capacitance 864
18.16 Switching Waveforms 875
18.17 SPICE Model of Power MOSFETs 877
18.18 IGBTs 879
18.19 Heat Sinks 880
18.20 Summary 886
References 888
Review Questions 888
Problems 889

19 Electromagnetic Compatibility 891
19.1 Introduction 891
19.2 Definition of EMI 892
19.3 Definition of EMC 892
19.4 EMI Immunity 893
19.5 EMI Susceptibility 893
19.6 Classification of EMI 895
19.7 Sources of EMI 895
19.8 Safety Standards 896
19.9 EMC Standards 896
19.10 Near Field and Far Field 897
19.11 Techniques of EMI Reduction 897
19.12 Insertion Loss 898
19.13 EMI Filters 898
19.14 Feed-Through Capacitors 900
19.15 EMI Shielding 900
19.16 Interconnections 902
19.17 Summary 903
References 903
Review Questions 903
Problems 904

A Introduction to SPICE 907

B Introduction to MATLAB® 910

C Physical Constants 915

Answers to Problems 917

Index 925