Pulse-Width Modulated DC–DC Power Converters
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To my wife Alicja
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 12
      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 ≤ DT 25
      2.2.4 Time Interval: DT < t ≤ 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 129
  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 (Ćuk) 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
5 Flyback PWM DC–DC Converter

5.1 Introduction

5.2 Transformers

5.3 DC Analysis of PWM Flyback Converter for CCM
   5.3.1 Derivation of PWM Flyback Converter
   5.3.2 Circuit Description
   5.3.3 Assumptions
   5.3.4 Time Interval: $0 < t \leq DT$
   5.3.5 Time Interval: $DT < t \leq T$
   5.3.6 DC Voltage Transfer Function for CCM
   5.3.7 Boundary Between CCM and DCM
   5.3.8 Ripple Voltage in Flyback Converter for CCM
   5.3.9 Power Losses and Efficiency of Flyback Converter for CCM
   5.3.10 DC Voltage Transfer Function of Lossy Converter for CCM
   5.3.11 Design of Flyback Converter for CCM

5.4 DC Analysis of PWM Flyback Converter for DCM
   5.4.1 Time Interval: $0 < t \leq DT$
   5.4.2 Time Interval: $DT < t \leq (D + D_1)T$
   5.4.3 Time Interval: $(D + D_1)T < t \leq T$
   5.4.4 DC Voltage Transfer Function for DCM
   5.4.5 Maximum Magnetizing Inductance for DCM
   5.4.6 Ripple Voltage in Flyback Converter for DCM
   5.4.7 Power Losses and Efficiency of Flyback Converter for DCM
   5.4.8 Design of Flyback Converter for DCM

5.5 Multiple-Output Flyback Converter

5.6 Bidirectional Flyback Converter

5.7 Ringing in Flyback Converter

5.8 Flyback Converter with Passive Dissipative Snubber

5.9 Flyback Converter with Zener Diode Voltage Clamp

5.10 Flyback Converter with Active Clamping

5.11 Two-Transistor Flyback Converter

5.12 Summary

References

6 Forward PWM DC–DC Converter

6.1 Introduction

6.2 DC Analysis of PWM Forward Converter for CCM
   6.2.1 Derivation of Forward PWM Converter
   6.2.2 Time Interval: $0 < t \leq DT$
   6.2.3 Time Interval: $DT < t \leq DT + t_m$
   6.2.4 Time Interval: $DT + t_m < t \leq T$
   6.2.5 Maximum Duty Cycle
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: \(0 < t \leq DT\) 332
8.2.4 Time Interval: \(DT < t \leq T/2\) 334
8.2.5 Time Interval: \(T/2 < t \leq T/2 + DT\) 336
8.2.6 Time Interval: \(T/2 + DT < t \leq T\) 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: \(0 < t \leq DT\) 351
8.3.2 Time Interval: \(DT < t \leq (D + D_1)T\) 353
8.3.3 Time Interval: \((D + D_1)T < t \leq T/2\) 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 Linear-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
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
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
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.5</td>
<td>Slope Compensation</td>
<td>564</td>
</tr>
<tr>
<td>14.5.1</td>
<td>Analysis of Slope Compensation in Time Domain</td>
<td>564</td>
</tr>
<tr>
<td>14.5.2</td>
<td>Boundary of Slope Compensation for Buck and Buck–Boost Converters</td>
<td>569</td>
</tr>
<tr>
<td>14.5.3</td>
<td>Boundary Slope Compensation for Boost Converter</td>
<td>570</td>
</tr>
<tr>
<td>14.6</td>
<td>Sample-and-Hold Effect on Current Loop</td>
<td>570</td>
</tr>
<tr>
<td>14.6.1</td>
<td>Natural Response of Inductor Current to Small Perturbation in Closed-Current Loop</td>
<td>572</td>
</tr>
<tr>
<td>14.6.2</td>
<td>Forced Response of Inductor Current to Step Change in Control Voltage in Closed-Current Loop</td>
<td>575</td>
</tr>
<tr>
<td>14.6.3</td>
<td>Relationship Between s-Domain and z-Domain</td>
<td>577</td>
</tr>
<tr>
<td>14.6.4</td>
<td>Transfer Function of Closed-Current Loop in z-Domain</td>
<td>578</td>
</tr>
<tr>
<td>14.7</td>
<td>Closed-Loop Control Voltage-to-Inductor Current Transfer Function in s-Domain</td>
<td>580</td>
</tr>
<tr>
<td>14.7.1</td>
<td>Approximation of $H_{icl}$ by Rational Transfer Function</td>
<td>582</td>
</tr>
<tr>
<td>14.7.2</td>
<td>Step Responses of Closed-Inner Loop</td>
<td>588</td>
</tr>
<tr>
<td>14.8</td>
<td>Loop Gain of Current Loop</td>
<td>588</td>
</tr>
<tr>
<td>14.8.1</td>
<td>Loop Gain of Inner Loop in z-Domain</td>
<td>588</td>
</tr>
<tr>
<td>14.8.2</td>
<td>Loop Gain of Inner Loop in s-Domain</td>
<td>590</td>
</tr>
<tr>
<td>14.9</td>
<td>Gain-Crossover Frequency of Inner Loop</td>
<td>595</td>
</tr>
<tr>
<td>14.10</td>
<td>Phase Margin of Inner Loop</td>
<td>596</td>
</tr>
<tr>
<td>14.11</td>
<td>Maximum Duty Cycle for Converters Without Slope Compensation</td>
<td>598</td>
</tr>
<tr>
<td>14.12</td>
<td>Maximum Duty Cycle for Converters with Slope Compensation</td>
<td>600</td>
</tr>
<tr>
<td>14.13</td>
<td>Minimum Slope Compensation for Buck and Buck–Boost Converter</td>
<td>605</td>
</tr>
<tr>
<td>14.14</td>
<td>Minimum Slope Compensation for Boost Converter</td>
<td>607</td>
</tr>
<tr>
<td>14.15</td>
<td>Error Voltage-to-Duty Cycle Transfer Function</td>
<td>610</td>
</tr>
<tr>
<td>14.16</td>
<td>Closed-Loop Control Voltage-to-Duty Cycle Transfer Function of Current Loop</td>
<td>614</td>
</tr>
<tr>
<td>14.17</td>
<td>Alternative Representation of Current Loop</td>
<td>618</td>
</tr>
<tr>
<td>14.18</td>
<td>Current Loop with Disturbances</td>
<td>618</td>
</tr>
<tr>
<td>14.18.1</td>
<td>Modified Approximation of Current Loop</td>
<td>619</td>
</tr>
<tr>
<td>14.19</td>
<td>Voltage Loop of PWM Converters with Current-Mode Control</td>
<td>624</td>
</tr>
<tr>
<td>14.19.1</td>
<td>Control-to-Output Transfer Function for Buck Converter</td>
<td>624</td>
</tr>
<tr>
<td>14.19.2</td>
<td>Block Diagram of Power Stages of PWM Converters</td>
<td>627</td>
</tr>
<tr>
<td>14.19.3</td>
<td>Closed-Voltage Loop Transfer Function of PWM Converters with Current-Mode Control</td>
<td>628</td>
</tr>
<tr>
<td>14.19.4</td>
<td>Closed-Loop Audio Susceptibility of PWM Converters with Current-Mode Control</td>
<td>628</td>
</tr>
<tr>
<td>14.19.5</td>
<td>Closed-Loop Output Impedance of PWM Converters with Current-Mode Control</td>
<td>630</td>
</tr>
<tr>
<td>14.20</td>
<td>Feedforward Gains in PWM Converters with Current-Mode Control</td>
<td>631</td>
</tr>
<tr>
<td>14.20.1</td>
<td>Feedforward Gains in PWM Converters with Current-Mode Control</td>
<td>631</td>
</tr>
<tr>
<td>14.20.1</td>
<td>Feedforward Gains in PWM Converters with Current-Mode Control and Slope Compensation</td>
<td>634</td>
</tr>
<tr>
<td>14.22</td>
<td>Control-to-Output Voltage Transfer Function of Inner Loop with Feedforward Gains</td>
<td>636</td>
</tr>
<tr>
<td>14.23</td>
<td>Audio-Susceptibility of Inner Loop with Feedforward Gains</td>
<td>637</td>
</tr>
<tr>
<td>14.24</td>
<td>Closed-Loop Transfer Functions with Feedforward Gains</td>
<td>638</td>
</tr>
<tr>
<td>14.25</td>
<td>Slope Compensation by Adding a Ramp to Inductor Current Waveform</td>
<td>638</td>
</tr>
<tr>
<td>14.26</td>
<td>Relationships for Constant-Frequency Current-Mode On-Time Control</td>
<td>639</td>
</tr>
<tr>
<td>14.27</td>
<td>Summary</td>
<td>639</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>640</td>
</tr>
<tr>
<td>Review Questions</td>
<td></td>
<td>644</td>
</tr>
<tr>
<td>Problems</td>
<td></td>
<td>644</td>
</tr>
</tbody>
</table>
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 $e^{sT}$ 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 Susceptibility 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
16.7.2 Response of Output Voltage to Step Change in Duty Cycle
16.7.3 Response of Output Voltage to Step Change in Load Current
16.8 Open-Loop Duty Cycle-to-Inductor Current Transfer Function
16.9 Open-Loop Input Voltage-to-Inductor Current Transfer Function
16.10 Open-Loop Output Current-to-Inductor Current Transfer Function
16.11 Step Responses of Inductor Current of Boost Converter for DCM
16.11.1 Step Response of Inductor Current to Step Change in Input Voltage
16.11.2 Step Response of Inductor Current to Step Change in Duty Cycle
16.11.3 Step Response of Inductor Current to Step Change in Load Current
16.12 DC Characteristics of Boost Converter for DCM
16.12.1 DC-to-DC Voltage Transfer Function of Lossless Boost Converter for DCM
16.12.2 DC-to-DC Voltage Transfer Function of Lossy Boost Converter for DCM
16.12.3 Efficiency of Boost Converter for DCM
16.13 Summary
References
Review Questions
Problems

17 Silicon and Silicon-Carbide Power Diodes
17.1 Introduction
17.2 Electronic Power Switches
17.3 Atom
17.4 Electron and Hole Effective Mass
17.5 Semiconductors
17.6 Intrinsic Semiconductors
17.7 Extrinsic Semiconductors
17.7.1 n-Type Semiconductor
17.7.2 p-Type Semiconductor
17.7.3 Maximum Operating Temperature
17.8 Wide Band Gap Semiconductors
17.9 Physical Structure of Junction Diodes
17.9.1 Formation of Depletion Layer
17.9.2 Charge Transport
17.10 Static I–V Diode Characteristic
17.11 Breakdown Voltage of Junction Diodes
17.11.1 Depletion-Layer Width
17.11.2 Electric Field Intensity Distribution
17.11.3 Avalanche Breakdown Voltage
17.11.4 Punch-Through Breakdown Voltage
17.11.5 Edge Terminations
17.12 Capacitances of Junction Diodes
17.12.1 Junction Capacitance
17.12.2 Diffusion Capacitance
17.13 Reverse Recovery of pn Junction Diodes
17.13.1 Qualitative Description
17.13.2 Reverse Recovery in Resistive Circuits
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 \textit{I}–\textit{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
<table>
<thead>
<tr>
<th>18.15.2</th>
<th>Drain-to-Source Capacitance</th>
<th>864</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.15.3</td>
<td>Gate-to-Drain Capacitance</td>
<td>864</td>
</tr>
<tr>
<td>18.16</td>
<td>Switching Waveforms</td>
<td>875</td>
</tr>
<tr>
<td>18.17</td>
<td>SPICE Model of Power MOSFETs</td>
<td>877</td>
</tr>
<tr>
<td>18.18</td>
<td>IGBTs</td>
<td>879</td>
</tr>
<tr>
<td>18.19</td>
<td>Heat Sinks</td>
<td>880</td>
</tr>
<tr>
<td>18.20</td>
<td>Summary</td>
<td>886</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>888</td>
</tr>
<tr>
<td>Review Questions</td>
<td></td>
<td>888</td>
</tr>
<tr>
<td>Problems</td>
<td>889</td>
<td></td>
</tr>
</tbody>
</table>

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

A  Introduction to SPICE  907

B  Introduction to MATLAB®  910

C  Physical Constants  915

Answers to Problems  917

Index  925
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Preface

This book is about switching-mode dc–dc power converters with pulse-width modulation (PWM) control. It is intended as a power electronics textbook at the senior and graduate levels for students majoring in electrical engineering, as well as a reference for practicing engineers in the area of power electronics. The purpose of the book is to provide foundations for semiconductor power devices, topologies of PWM switching-mode dc–dc power converters, modeling, dynamics, and controls of PWM converters. The book is devoted to energy conversion.

The first part of the book covers topologies of transformerless and isolated PWM converters, such as buck, boost, and buck–boost, flyback, forward, half-bridge, and full-bridge converters. The second part covers small-signal circuit models of PWM converters, transfer functions of PWM converter power stages, voltage-mode control, and current-mode control of PWM converters. The third part presents silicon and silicon carbide power devices.

The textbook assumes that the student is familiar with general circuit analysis techniques and electronic circuits. Complete solutions for all problems are included in the Solutions Manual, which is available from the publisher for those instructors who adopt the book for their courses.

I am pleased to express my gratitude to Dr. Nisha Kondrath and Agasthya Ayachit for MATLAB® figures, proofreading, suggestions, and critical evaluation of the manuscript.

Throughout the entire course of this project, the support provided by John Wiley & Sons was excellent. I wish to express my sincere thanks to Ella Mitchell, Associate Commissioning Editor, Electrical Engineering; Peter Mitchell, Publisher, Engineering Technology; and Richard Davis, Senior Project Editor. It has been a real pleasure working with them. Last but not least, I wish to thank my family for the support.

The author would welcome and greatly appreciate suggestions and corrections from the readers, for the improvements in the technical content as well as the presentation style.

Marian K. Kazimierczuk
Nomenclature

\( A \)  
Transfer function of forward path in negative feedback system

\( A_i \)  
Inductor-to-load current transfer function

\( A_j \)  
Cross-sectional area of junction

\( BW \)  
Bandwidth

\( C \)  
Filter capacitance

\( C_b \)  
Blocking capacitance

\( C_c \)  
Coupling capacitance

\( C_{ds} \)  
Drain–source capacitance of MOSFET

\( C_{gd} \)  
Gate–drain capacitance of MOSFET

\( C_{gs} \)  
Gate–source capacitance of MOSFET

\( C_{iss} \)  
MOSFET input capacitance at \( V_{DS} = 0 \), \( C_{iss} = C_{gs} + C_{gd} \)

\( C_{min} \)  
Minimum value of filter capacitance \( C \)

\( C_o \)  
Transistor output capacitance

\( C_{oss} \)  
MOSFET output capacitance at \( V_{GD} = 0 \), \( C_{oss} = C_{gs} + C_{ds} \)

\( C_{ox} \)  
Oxide capacitance per unit area

\( C_{rss} \)  
MOSFET transfer capacitance, \( C_{rss} = C_{gd} \)

\( c \)  
Speed of light

\( D \)  
DC component of on-duty cycle of switch

\( d \)  
AC component of on-duty cycle of switch

\( d_m \)  
Amplitude of small-signal component of on-duty cycle of switch

\( d_T \)  
Total on-duty cycle of switch

\( ESR \)  
Equivalent series resistance of capacitors and inductors

\( f_c \)  
Gain-crossover frequency

\( f_z \)  
Frequency of zero of transfer function

\( f_0 \)  
Corner frequency

\( f_p \)  
Frequency of pole of transfer function

\( f_s \)  
Switching frequency

\( f_{-180} \)  
Phase-crossover frequency

\( H_{sh} \)  
Transfer function of sampler and zero-order hold

\( i_{C_{rms}} \)  
rms value of capacitor current \( i_C \)

\( i_{pk} \)  
Magnitude of cross-conduction current

\( i_{rms} \)  
rms value of current \( i \)

\( I_D \)  
Average diode current

\( I_{DM} \)  
Peak diode current

\( I_{Drms} \)  
rms value of diode current

\( I_I \)  
DC input current of converter

\( I_L \)  
Average current through inductor \( L \)

\( I_{LB} \)  
Average current through inductor \( L \) at CCM/DCM boundary

\( I_O \)  
DC output current of converter

\( I_{O_{max}} \)  
Maximum value of dc load current \( I_O \)

\( I_{O_{min}} \)  
Minimum value of dc load current \( I_O \)
$I_{OB}$ DC output current at the boundary between CCM and DCM  
$I_{SM}$ Peak switch current  
$I_{rms}$ rms value of switch current $i_s$  
$i_s$ AC component of input current  
$i_0^0(t)$ Zero-order-hold AC component of input current  
$i_o$ AC component of load current  
$i_C$ Current through filter capacitor $C$  
$i_D$ Diode current  
$i_L$ Current through inductor $L$  
$i_O$ Total load current  
$i_S$ Switch current  
$K_i$ Input feedforward gain  
$K_o$ Output feedforward gain  
$k$ Boltzmann constant  
$L$ Inductance, Channel length  
$L_e$ Effective channel length  
$L_n$ Electron diffusion length  
$L_p$ Hole diffusion length  
$L_m$ Magnetizing inductance of transformer  
$L_{max}$ Maximum inductance $L$ for DCM operation  
$L_{min}$ Minimum inductance $L$ for CCM operation  
$L_{NR}$ Line regulation  
$L_{OR}$ Load regulation  
$M_{DC}$ DC current transfer function of converter  
$M_{VDC}$ DC voltage transfer function of converter  
$M_v$ Open-loop input-to-output voltage function of converter  
$M_{vcl}$ Closed-loop input-to-output voltage function of converter  
$M_{vi}$ Open-loop input voltage-to-inductor current transfer function  
$M_{vo}$ Open-loop input-to-output voltage function of converter at $f = 0$  
$m_e$ Mass of free electron  
$m_e^*$ Effective mass of electron  
$m_p$ Mass of hole  
$m_p^*$ Effective mass of hole  
$N_A$ Concentration of acceptors  
$N_D$ Concentration of donors  
$N_p$ Number of turns of primary winding  
$N_s$ Number of turns of secondary winding  
$n$ Transformer turns ratio, electron concentration density  
$n^+$ Electron concentration of heavily doped semiconductor by donors  
$n_i$ Intrinsic carrier concentration  
$n_n$ Majority electron concentration  
$n_p$ Minority electron concentration  
$n_{p0}$ Thermal equilibrium minority electron concentration  
$p_n$ Minority hole concentration  
$p_{n0}$ Thermal equilibrium minority hole concentration  
$p_p$ Majority hole concentration  
$PM$ Phase margin  
$P_{ton}$ Turn-on switching losses  
$P_D$ Total diode conduction loss
**Nomenclature**

- $P_{FET}$: Overall power dissipation in MOSFET (excluding gate-drive power)
- $P_G$: Gate-drive power
- $P_I$: DC input power of converter
- $P_{LS}$: Overall power dissipation of converter
- $PM$: Phase margin
- $P_O$: DC output power of converter
- $P_{RF}$: Conduction loss in diode forward resistance $R_F$
- $P_C$: Conduction loss in filter capacitor ESR
- $P_{VF}$: Conduction loss in diode offset voltage $V_F$
- $p$: Hole concentration
- $p^+$: Hole concentration of heavily doped semiconductor by acceptors
- $Q$: Quality factor
- $Q_g$: Gate charge
- $Q_F$: Forward stored charge
- $Q_{rr}$: Reverse recovery charge
- $q$: Magnitude of electron charge
- $R_{DR}$: Resistance of drift region
- $R_F$: Diode forward resistance
- $R_L$: DC load resistance
- $R_{LB}$: DC load resistance at CCM/DCM boundary
- $R_{Lmax}$: Maximum value of load resistance $R_L$
- $R_{Lmin}$: Minimum value of load resistance $R_L$
- $r_C$: Equivalent series resistance (ESR) of filter capacitor
- $t_{DS}$: On-resistance of MOSFET
- $q$: Electron charge
- $S$: Specific resistance of drift region
- $S_{max}$: Maximum percentage overshoot
- $SR$: Slew rate of op-amps
- $T$: Switching period, Loop gain
- $T_A$: Ambient temperature
- $T_c$: Voltage transfer function of controller
- $T_{cl}$: Closed-loop control-to-output transfer function
- $T_i$: Loop gain of current loop
- $T_J$: Junction temperature
- $T_m$: Transfer function of pulse-width modulator
- $T_p$: Open-loop control-to-output transfer function
- $T_{pi}$: Open-loop duty cycle-to-inductor current transfer function
- $T_{po}$: Open-loop control-to-output transfer function at $f = 0$
- $THD$: Total harmonic distortion
- $t_f$: Fall time
- $t_r$: Rise time
- $t_{rr}$: Reverse recovery time
- $V_{bi}$: Built-in potential
- $V_C$: DC component of control voltage
- $V_{cm}$: Amplitude of small-signal component of control voltage
- $V_{cpp}$: Peak-to-peak ripple voltage of the filter capacitance
- $V_E$: DC component of error voltage
- $V_t$: Gate-to-source threshold voltage
- $V_{BD}$: Breakdown voltage
Nomenclature

\( V_{BR} \)  Reverse blocking (breakdown) voltage
\( V_{DM} \)  Reverse peak voltage of diode
\( V_{DS} \)  Drain–source dc voltage of MOSFET
\( V_{DSS} \)  Drain–source breakdown voltage of MOSFETs
\( V_F \)  Diode offset voltage, dc component of feedback voltage
\( V_{GD} \)  Gate-to-drain voltage of MOSFET
\( V_{GSpp} \)  Peak-to-peak gate-to-source voltage
\( V_I \)  DC component of input voltage of converter
\( V_O \)  DC output voltage of converter
\( V_R \)  DC reference voltage
\( V_r \)  Peak-to-peak value of output ripple voltage
\( V_{rcpp} \)  Peak-to-peak ripple voltage across ESR
\( V_{SM} \)  Peak switch voltage
\( V_T \)  Thermal voltage
\( V_{Tm} \)  Peak ramp voltage of pulse-width modulator
\( v_C \)  Total control voltage
\( v_c \)  AC component of control voltage
\( v^*(t) \)  Sampled AC component of control voltage
\( v_c(j\omega) \)  Spectrum of sampled AC component of control voltage
\( v_{DS} \)  Drain–source voltage of MOSFET
\( v_E \)  Total error voltage
\( v_F \)  Total feedback voltage
\( v_e \)  AC component of error voltage
\( v_d \)  Average drift velocity
\( v_f \)  AC component of feedback voltage
\( v_L \)  Voltage across inductance \( L \)
\( v_i \)  AC component of converter input voltage
\( v_o \)  AC component of converter output voltage
\( v_{sat} \)  Saturation velocity of carriers
\( v_r \)  AC component of reference voltage
\( v_{rc} \)  Voltage across ESR of filter capacitor
\( v_{th} \)  Thermal velocity of electron
\( v_{sat} \)  Saturated average drift velocity
\( W \)  Channel width
\( W_C \)  Energy stored in capacitor
\( W_L \)  Energy stored in inductor
\( Z_i \)  Open-loop input impedance of converter
\( Z_{icl} \)  Closed-loop input impedance of converter
\( Z_o \)  Open-loop output impedance of converter
\( Z_{ocl} \)  Closed-loop output impedance of converter
\( \beta \)  Transfer function of feedback network
\( \Delta i_L \)  Peak-to-peak of inductor ripple current
\( \eta \)  Efficiency of converter
\( \theta \)  Thermal resistance
\( \mu \)  Carrier mobility
\( \mu_p \)  Mobility of holes
\( \mu_n \)  Mobility of electrons
\( \zeta \)  Damping ratio
\( \rho \)  Resistivity