

## Contents

Preface	<i>page xv</i>
Acknowledgments	xviii
<b>1 Introduction</b>	<b>1</b>
1.1 Power Electronic Circuits	1
1.2 Power Semiconductor Switches	2
1.3 Transformers	5
1.4 Nomenclature	7
1.5 Bibliographies	8
1.6 Problems	8
<b>Part I Form and Function</b>	
<b>2 Form and Function: An Overview</b>	<b>11</b>
2.1 Functions of a Power Circuit	11
2.2 AC/DC Converters	13
2.3 DC/DC Converters	18
2.4 AC/AC Converters	20
2.5 Influence of Switch Implementation	22
<b>Problems</b>	<b>24</b>
<b>3 Introduction to Rectifiers</b>	<b>27</b>
3.1 Power in Electrical Networks	27
3.2 Single-Phase Half-Wave Rectifier	29
3.3 AC-Side Reactance and Current Commutation	35
3.4 Measures and Effects of Distortion	38
3.5 Bridge Rectifiers	44
<b>Notes and Bibliography</b>	<b>49</b>
<b>Problems</b>	<b>50</b>
<b>4 Phase-Controlled Converters</b>	<b>57</b>
4.1 Single-Phase Configurations	58
4.2 Phase Control with AC-Side Reactance	64
4.3 Inversion Limits	67
	<b>vii</b>

## viii Contents

<b>Notes and Bibliography</b>	71
<b>Problems</b>	72
<b>5 Pulse-Width-Modulated DC/DC Converters</b>	76
5.1 The DC/DC Converter Topology	77
5.2 The Canonical Switching Cell	82
5.3 Direct Converter	82
5.4 Indirect Converter	89
5.5 Other PWM DC/DC Converters	92
5.6 Choice of Capacitor and Inductor Values	95
5.7 Semiconductor Device Stresses	103
5.8 Three-Level Flying-Capacitor Converter	104
5.9 Converter Operation with Discontinuous Conduction	106
<b>Notes and Bibliography</b>	108
<b>Problems</b>	109
<b>6 Switched-Capacitor and Related Converters</b>	116
6.1 Switched-Capacitor DC/DC Converter	116
6.2 Two-State Switched-Capacitor Converter	118
6.3 Switch Implementation	121
6.4 Other Switched-Capacitor DC/DC Converters	123
6.5 Other Kinds of Switched-Capacitor Converters	131
<b>Notes and Bibliography</b>	132
<b>Problems</b>	133
<b>7 Isolated Pulse-Width-Modulated DC/DC Converters</b>	136
7.1 Single-Ended Isolated Forward Converter	136
7.2 Double-Ended Isolated Forward Converter	145
7.3 Dual Active-Bridge Converter	150
7.4 Flyback Converter	153
7.5 Other PWM Isolated Converters	154
7.6 Effects of Transformer Leakage Inductance	155
7.7 Converters with Multiple Outputs	158
<b>Notes and Bibliography</b>	158
<b>Problems</b>	159
<b>8 Single-Phase Switched-Mode DC/AC Converters</b>	167
8.1 Basic Variable-Frequency Bridge Converter	167
8.2 Harmonic Reduction	172
8.3 Pulse-Width-Modulated DC/AC Converters	179
8.4 Current Control of Inverters	187

	Contents	ix
8.5	Multi-level Converters	190
8.6	Transformer-Isolated DC/AC Converters	192
8.7	Other DC/AC Converter Topologies	194
8.8	Power Balance in Single-Phase DC/AC Converters	196
8.9	Switched-Mode Rectifiers and Power Factor Correction	197
	<b>Notes and Bibliography</b>	202
	<b>Problems</b>	203
<b>9</b>	<b>Polyphase Sources and Converters</b>	207
9.1	Polyphase Sources	207
9.2	Three-Phase Sources	209
9.3	Introduction to Polyphase Rectifier Circuits	213
9.4	Phase-Controlled Three-Phase Converters	215
9.5	Commutation in Polyphase Rectifiers	216
9.6	Three-Phase Inverters	221
9.7	Space-Vector Representation and Modulation for Three-Phase Systems	229
9.8	Multi-Level Inverters	237
	<b>Notes and Bibliography</b>	242
	<b>Problems</b>	243
<b>10</b>	<b>Resonant Converters</b>	249
10.1	Review of Second-Order System Behavior	250
10.2	Quality Factor	254
10.3	Resonant Converter Analysis	256
10.4	Soft Switching of Resonant Converters	260
10.5	Resonant DC/DC Converters	264
10.6	Radio-Frequency Converters	271
	<b>Notes and Bibliography</b>	284
	<b>Problems</b>	285
<b>11</b>	<b>AC/AC Converters</b>	289
11.1	Introduction to AC/AC Converters	289
11.2	Energy Storage Requirements in a DC-Link Converter	290
11.3	The Naturally Commutated Cycloconverter	294
11.4	An Isolated High-Frequency-Link Cycloconverter	299
11.5	Solid-State Transformer	302
11.6	Matrix Converter	305
	<b>Notes and Bibliography</b>	306
	<b>Problems</b>	306

## Part II Dynamic Models and Control

<b>12 Dynamic Models and Control: An Overview</b>	313
12.1 Dynamic Behavior of Power Converters	314
12.2 Dynamic Models	322
12.3 Averaged-Circuit Models	323
12.4 Linearized Models	329
12.5 Feedback Control	332
<b>Notes and Bibliography</b>	342
<b>Problems</b>	343
<b>13 Averaged-Circuit and State-Space Models</b>	346
13.1 Averaged-Circuit Models	346
13.2 Generalizing Circuit Averaging to the Fundamental Component	350
13.3 Continuous-Time State-Space Models	354
13.4 Discrete-Time or Sampled-Data Models	365
13.5 Generalized State-Space Models	368
13.6 Models for Controllers and Interconnected Systems	372
<b>Notes and Bibliography</b>	373
<b>Problems</b>	374
<b>14 Linear Models and Feedback Control</b>	378
14.1 Linearization	378
14.2 Linearizing an Averaged-Circuit Model	379
14.3 Linearizing Continuous-Time State-Space Models	383
14.4 Analysis of Continuous-Time LTI Models	385
14.5 Piecewise LTI Models	394
14.6 Linearizing Discrete-Time Generalized State-Space Models	395
14.7 Analysis of Discrete-Time LTI Models	399
14.8 Feedback Control Design	405
14.9 Multi-Loop Control	414
14.10 State Feedback	422
14.11 Digital Control	425
<b>Notes and Bibliography</b>	428
<b>Problems</b>	429
<b>Part III Components and Devices</b>	
<b>15 Components and Devices: An Overview</b>	437
15.1 Practical Semiconductor Switches	438
15.2 Practical Energy Storage Elements	438
15.3 Semiconductor Devices	439

	Contents	xi
15.4	Capacitors	452
15.5	Inductors and Transformers	455
	<b>Problems</b>	457
<b>16</b>	<b>Review of Semiconductor Devices</b>	461
16.1	Elementary Physics of Semiconductors	461
16.2	Simple Analysis of a Diode	472
16.3	Bipolar Junction Transistor	478
16.4	MOSFET	483
16.5	The Safe Operating Area	486
	<b>Notes and Bibliography</b>	487
	<b>Problems</b>	488
<b>17</b>	<b>Power Semiconductor Devices</b>	494
17.1	Bipolar Diode	494
17.2	Switch Transitions in a pin Diode	504
17.3	The Schottky Barrier Diode	507
17.4	Power BJT	511
17.5	Power MOSFET	517
17.6	Superjunction MOSFET	523
17.7	IGBT	524
17.8	Silicon Carbide and Gallium Nitride Devices	528
17.9	Thyristor	530
17.10	Datasheet	538
	<b>Notes and Bibliography</b>	541
	<b>Problems</b>	542
<b>18</b>	<b>Introduction to Magnetics</b>	545
18.1	Inductor	546
18.2	Saturation, Hysteresis, and Residual Flux	555
18.3	Losses In Magnetic Components	557
18.4	Transformers	566
18.5	Magnetic Material Properties	575
	<b>Notes and Bibliography</b>	576
	<b>Problems</b>	577
<b>19</b>	<b>Magnetic Component Modeling</b>	582
19.1	Mathematical Representation: Inductance Matrix	582
19.2	Circuit Representations for Two-Port Transformers	584
19.3	Determining Transformer Parameters	587
19.4	Multi-Winding Model	588

xii Contents

19.5	Extending the Magnetic Circuit Model Concept	597
19.6	Physical Electric Circuit Models for Magnetic Systems	603
	<b>Notes and Bibliography</b>	607
	<b>Problems</b>	608
<b>20</b>	<b>Introduction to Magnetics Design</b>	612
20.1	Filter Inductor Design and Core Factor	613
20.2	Thermal Constraints in Magnetics Design	618
20.3	Inductor Energy Storage Limits	621
20.4	AC Magnetics Sizing and Core Area Product	624
20.5	Performance Factor for Magnetic Materials	634
20.6	An Iterative Inductor Design Algorithm	636
	<b>Notes and Bibliography</b>	638
	<b>Problems</b>	640
<b>21</b>	<b>Magnetics Loss Analysis and Design</b>	643
21.1	Magnetic Diffusion	643
21.2	Winding Loss Calculation	655
21.3	Core Loss	675
	<b>Notes and Bibliography</b>	684
	<b>Problems</b>	686
<b>Part IV Practical Considerations</b>		
<b>22</b>	<b>Practical Considerations: An Overview</b>	693
22.1	Gate and Base Drives	693
22.2	Thyristor Commutation Circuits	695
22.3	Snubbers, Clamps, and Soft Switching	697
22.4	Thermal Considerations	700
	<b>Problems</b>	701
<b>23</b>	<b>Gate and Base Drives</b>	704
23.1	MOSFET and IGBT Gate Drives	705
23.2	Bipolar Transistor Base Drives	713
23.3	Thyristor Gate Drives	716
	<b>Notes and Bibliography</b>	719
	<b>Problems</b>	719
<b>24</b>	<b>Snubber Circuits, Clamps, and Soft Switching</b>	724
24.1	Turn-Off Snubber	725
24.2	Turn-On Snubber	730

	Contents	xiii
24.3 Combined Turn-On/Turn-Off Snubber		733
24.4 Alternative Placements of the Snubber Circuit		735
24.5 Dissipation in Snubber Circuits		736
24.6 Soft Switching		739
<b>Notes and Bibliography</b>		748
<b>Problems</b>		750
<b>25 Thermal Modeling and Heat Sinking</b>		753
25.1 Static Thermal Models		754
25.2 Thermal Interfaces		758
25.3 Transient Thermal Models		762
<b>Notes and Bibliography</b>		767
<b>Problems</b>		768
<b>26 Electromagnetic Interference and Filtering</b>		771
26.1 EMI Specifications and Measurement		771
26.2 Filter Design		773
26.3 Common-Mode and Differential-Mode Variables		781
26.4 Parasitics and Circuit Layout		787
<b>Notes and Bibliography</b>		789
<b>Problems</b>		790
Index		793