CONTENTS

PREFACE xxi
ABOUT THE AUTHORS xxv
LIST OF SYMBOLS xxvii

I Introduction 1
  1.1 References 5

PART I RECTIFIERS 7

2 Class D Current-Driven Rectifiers 9
  2.1 Introduction 9
  2.2 Assumptions 10
  2.3 Class D Half-Wave Rectifier 10
      2.3.1 Circuit Operation 10
      2.3.2 Currents and Voltages 12
      2.3.3 Power Factor 13
      2.3.4 Power-Output Capability 14
      2.3.5 Efficiency 15
<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.6 Voltage Transfer Function</td>
<td>53</td>
</tr>
<tr>
<td>3.3.7 Ripple Voltage</td>
<td>55</td>
</tr>
<tr>
<td>3.4 Class D Transformer Center-Tapped Rectifier</td>
<td>56</td>
</tr>
<tr>
<td>3.4.1 Currents and Voltages</td>
<td>56</td>
</tr>
<tr>
<td>3.4.2 Power Factor</td>
<td>57</td>
</tr>
<tr>
<td>3.4.3 Efficiency</td>
<td>59</td>
</tr>
<tr>
<td>3.4.4 Input Resistance</td>
<td>60</td>
</tr>
<tr>
<td>3.4.5 Voltage Transfer Function</td>
<td>60</td>
</tr>
<tr>
<td>3.4.6 Ripple Voltage</td>
<td>61</td>
</tr>
<tr>
<td>3.5 Class D Bridge Rectifier</td>
<td>62</td>
</tr>
<tr>
<td>3.6 Synchronous Rectifiers</td>
<td>66</td>
</tr>
<tr>
<td>3.6.1 Efficiency</td>
<td>66</td>
</tr>
<tr>
<td>3.6.2 Input Resistance</td>
<td>67</td>
</tr>
<tr>
<td>3.6.3 Voltage Transfer Function</td>
<td>67</td>
</tr>
<tr>
<td>3.7 Summary</td>
<td>69</td>
</tr>
<tr>
<td>3.8 References</td>
<td>69</td>
</tr>
<tr>
<td>3.9 Review Questions</td>
<td>71</td>
</tr>
<tr>
<td>3.10 Problems</td>
<td>71</td>
</tr>
</tbody>
</table>

4 Class E Low $dv/dt$ Rectifiers                                      72

4.1 Introduction                                                      72
4.2 Low $dv/dt$ Rectifier with a Parallel Capacitor                   72
  4.2.1 Principle of Operation                                          72
  4.2.2 Assumptions                                                    74
  4.2.3 Characterization of the Rectifier at Any $D$                   75
  4.2.4 Parameters for $D = 0.5$                                       88
  4.2.5 Design Example                                                 89
4.3 Resonant Low $dv/dt$ Rectifier                                    90
  4.3.1 Circuit Description                                            90
  4.3.2 Assumptions                                                    92
  4.3.3 Characteristics                                                92
  4.3.4 Input Impedance                                                98
  4.3.5 Diode Stresses                                                 101
  4.3.6 Parameters for $D = 0.5$                                       103
  4.3.7 Design Example                                                 105
4.4 Summary                                                            106
4.5 References                                                         107
CONTENTS

4.6 Review Questions 108
4.7 Problems 108

5 Class E Low \( \frac{di}{dt} \) Rectifiers 109

5.1 Introduction 109
5.2 Low \( \frac{di}{dt} \) Rectifier with a Parallel Inductor 109
  5.2.1 Circuit Description 109
  5.2.2 Assumptions 111
  5.2.3 Component Values 112
  5.2.4 Device Stresses 115
  5.2.5 Input Impedance 115
  5.2.6 Current and Voltage Transfer Functions 122
  5.2.7 Design Example 123
5.3 Low \( \frac{di}{dt} \) Rectifier with a Series Inductor 125
  5.3.1 Principle of Operation 125
  5.3.2 Assumptions 127
  5.3.3 Component Values 128
  5.3.4 Diode Waveforms 131
  5.3.5 Peak Diode Current and Voltage 131
  5.3.6 Voltage Transfer Function 132
  5.3.7 Input Impedance 133
  5.3.8 Design Example 138
5.4 Summary 139
5.5 References 139
5.6 Review Questions 140
5.7 Problems 140

PART II INVERTERS 141

6 Class D Series-Resonant Inverter 143

6.1 Introduction 143
6.2 Circuit Description 144
6.3 Principle of Operation 146
  6.3.1 Operation Below Resonance 147
  6.3.2 Operation Above Resonance 151
6.4 Topologies of Class D Voltage-Source Inverters 152
6.5 Analysis 155
   6.5.1 Assumptions 155
   6.5.2 Series-Resonant Circuit 155
   6.5.3 Input Impedance of Series-Resonant Circuit 157
   6.5.4 Currents, Voltages, and Powers 158
   6.5.5 Current and Voltage Stresses 162
   6.5.6 Operation Under Short-Circuit and Open-Circuit Conditions 166
6.6 Voltage Transfer Function 166
6.7 Efficiency 170
   6.7.1 Conduction Losses 170
   6.7.2 Turn-On Switching Loss 170
   6.7.3 Turn-Off Switching Loss 175
6.8 Design Example 177
6.9 Class D Full-Bridge Series-Resonant Inverter 180
   6.9.1 Currents, Voltages, and Powers 180
   6.9.2 Efficiency 184
   6.9.3 Operation Under Short-Circuit and Open-Circuit Conditions 185
   6.9.4 Voltage Transfer Function 185
6.10 Relationships Among Inverters and Rectifiers 187
6.11 Summary 189
6.12 References 190
6.13 Review Questions 191
6.14 Problems 191

7 Class D Parallel-Resonant Inverter 193
7.1 Introduction 193
7.2 Principle of Operation 193
7.3 Analysis 197
   7.3.1 Assumptions 197
   7.3.2 Resonant Circuit 197
   7.3.3 Voltage Transfer Function 204
   7.3.4 Currents, Voltages, and Powers 209
   7.3.5 Efficiency 217
7.4 Short-Circuit and Open-Circuit Operation 219
7.5 Electronic Ballast for Fluorescent Lamps 223
CONTENTS

7.6 Design Example 225
7.7 Full-Bridge Parallel-Resonant Inverter 227
\hspace{1em} 7.7.1 Voltage Transfer Function 227
\hspace{1em} 7.7.2 Currents, Voltages, and Powers 228
\hspace{1em} 7.7.3 Efficiency 230
\hspace{1em} 7.7.4 Short-Circuit and Open-Circuit Operation 231
7.8 Summary 232
7.9 References 233
7.10 Review Questions 233
7.11 Problems 233

8 Class D Series-Parallel-Resonant Inverter 235

8.1 Introduction 235
8.2 Principle of Operation 235
8.3 Analysis 237
\hspace{1em} 8.3.1 Assumptions 237
\hspace{1em} 8.3.2 Resonant Circuit 238
\hspace{1em} 8.3.3 Voltage Transfer Function 242
8.4 Design Example 254
8.5 Full-Bridge Series-Parallel-Resonant Inverter 257
\hspace{1em} 8.5.1 Voltage Transfer Function 257
8.6 Summary 259
8.7 References 260
8.8 Review Questions 261
8.9 Problems 261

9 Class D CLL Resonant Inverter 262

9.1 Introduction 262
9.2 Principle of Operation 262
9.3 Analysis 264
\hspace{1em} 9.3.1 Assumptions 264
\hspace{1em} 9.3.2 Boundary Between Capacitive and Inductive Load 264
9.3.3 Voltage Transfer Function 269
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.3.4</td>
<td>Energy Parameters</td>
<td>272</td>
</tr>
<tr>
<td>9.3.5</td>
<td>Short-Circuit and Open-Circuit Operation</td>
<td>279</td>
</tr>
<tr>
<td>9.4</td>
<td>Design Example</td>
<td>282</td>
</tr>
<tr>
<td>9.5</td>
<td>Full-Bridge CLL Resonant Inverter</td>
<td>285</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Voltage Transfer Function</td>
<td>285</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Currents and Voltages</td>
<td>286</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Powers and Efficiency</td>
<td>287</td>
</tr>
<tr>
<td>9.6</td>
<td>Summary</td>
<td>287</td>
</tr>
<tr>
<td>9.7</td>
<td>References</td>
<td>288</td>
</tr>
<tr>
<td>9.8</td>
<td>Review Questions</td>
<td>288</td>
</tr>
<tr>
<td>9.9</td>
<td>Problems</td>
<td>288</td>
</tr>
<tr>
<td>10</td>
<td>Class D Current-Source-Resonant Inverter</td>
<td>290</td>
</tr>
<tr>
<td>10.1</td>
<td>Introduction</td>
<td>290</td>
</tr>
<tr>
<td>10.2</td>
<td>Principle of Operation</td>
<td>291</td>
</tr>
<tr>
<td>10.3</td>
<td>Analysis of the Parallel-Resonant Circuit</td>
<td>295</td>
</tr>
<tr>
<td>10.4</td>
<td>Analysis of the Inverter</td>
<td>297</td>
</tr>
<tr>
<td>10.4.1</td>
<td>Voltage Transfer Function</td>
<td>297</td>
</tr>
<tr>
<td>10.4.2</td>
<td>Output Power</td>
<td>302</td>
</tr>
<tr>
<td>10.4.3</td>
<td>Conduction Power Loss</td>
<td>302</td>
</tr>
<tr>
<td>10.4.4</td>
<td>Efficiency</td>
<td>305</td>
</tr>
<tr>
<td>10.5</td>
<td>Design Example</td>
<td>307</td>
</tr>
<tr>
<td>10.6</td>
<td>Summary</td>
<td>309</td>
</tr>
<tr>
<td>10.7</td>
<td>References</td>
<td>309</td>
</tr>
<tr>
<td>10.8</td>
<td>Review Questions</td>
<td>310</td>
</tr>
<tr>
<td>10.9</td>
<td>Problems</td>
<td>310</td>
</tr>
<tr>
<td>11</td>
<td>Phase-Controlled Resonant Inverters</td>
<td>311</td>
</tr>
<tr>
<td>11.1</td>
<td>Introduction</td>
<td>311</td>
</tr>
<tr>
<td>11.2</td>
<td>Phase-Controlled Current-Source Inverters</td>
<td>312</td>
</tr>
<tr>
<td>11.3</td>
<td>Phase-Controlled Voltage-Source Inverters</td>
<td>316</td>
</tr>
<tr>
<td>11.4</td>
<td>Single-Capacitor Phase-Controlled Series-Resonant Inverter</td>
<td>320</td>
</tr>
<tr>
<td>11.4.1</td>
<td>Circuit Description</td>
<td>320</td>
</tr>
<tr>
<td>11.4.2</td>
<td>Assumptions</td>
<td>321</td>
</tr>
<tr>
<td>11.4.3</td>
<td>Voltage Transfer Function</td>
<td>321</td>
</tr>
<tr>
<td>11.4.4</td>
<td>Currents</td>
<td>323</td>
</tr>
<tr>
<td>11.4.5</td>
<td>Boundary Between Capacitive and Inductive Load</td>
<td>324</td>
</tr>
<tr>
<td>11.4.6</td>
<td>Efficiency</td>
<td>327</td>
</tr>
</tbody>
</table>
CONTENTS

11.5 Design Example 328
11.6 Summary 329
11.7 References 330
11.8 Review Questions 331
11.9 Problems 332

12 Class E Zero-Voltage-Switching Resonant Inverter 334

12.1 Introduction 334
12.2 Principle of Operation 335
  12.2.1 Circuit Description 335
  12.2.2 Circuit Operation 336
  12.2.3 Optimum Operation 336
  12.2.4 Suboptimum Operation 339
12.3 Analysis 340
  12.3.1 Assumptions 340
  12.3.2 Current and Voltage Waveforms 340
  12.3.3 Voltage and Current Stresses 343
  12.3.4 Input Impedance of the Resonant Circuit 345
  12.3.5 Output Power 347
  12.3.6 Component Values 347
12.4 Parameters at $D = 0.5$ 349
12.5 Efficiency 351
12.6 Matching Resonant Circuits 354
  12.6.1 Basic Circuit 354
  12.6.2 Resonant Circuit $\pi_1 a$ 354
  12.6.3 Resonant Circuit $\pi_2 a$ 357
  12.6.4 Resonant Circuit $\pi_1 b$ 358
  12.6.5 Resonant Circuit $\pi_4 a$ 358
12.7 Design Example 359
12.8 Push-Pull Class E ZVS Inverter 362
12.9 Summary 363
12.10 References 363
12.11 Review Questions 367
12.12 Problems 368

13 Class E Zero-Current-Switching Resonant Inverter 369

13.1 Introduction 369
13.2 Circuit Description 369
CONTENTS

13.3 Principle of Operation 370
13.4 Analysis 373
  13.4.1 Steady-State Current and Voltage Waveforms 373
  13.4.2 Peak Switch Current and Voltage 376
  13.4.3 Fundamental-Frequency Components 376
13.5 Power Relationships 378
13.6 Element Values of Load Network 378
13.7 Design Example 379
13.8 Summary 380
13.9 References 381
13.10 Review Questions 381
13.11 Problems 381

14 Class DE Power Inverter 382
14.1 Introduction 382
14.2 Principle of Operation of Class DE Power Inverter 382
14.3 Analysis of Class DE Power Inverter 383
14.4 Components 393
14.5 Device Stresses 394
14.6 Design Equations 395
14.7 Maximum Operating Frequency 395
14.8 Class DE Inverter with Single Shunt Capacitor 397
14.9 Output Power 401
14.10 Cancellation of Nonlinearities of Transistor Output Capacitances 401
14.11 Summary 402
14.12 References 403
14.13 Review Questions 404
14.14 Problems 404

PART III CONVERTERS 405

15 Class D Series-Resonant Converter 407
15.1 Introduction 407
15.2 Half-Bridge Series-Resonant Converter 408
   15.2.1 Circuit Description 408
   15.2.2 Half-Bridge SRC with Half-Wave Rectifier 410
CONTENTS

15.2.3 Half-Bridge SRC with Transformer Center-Tapped Rectifier 411
15.2.4 Half-Bridge SRC with Bridge Rectifier 411
15.3 Full-Bridge Series-Resonant Converter 412
15.3.1 Full-Bridge SRC with Half-Wave Rectifier 413
15.3.2 Full-Bridge SRC with Transformer Center-Tapped Rectifier 414
15.3.3 Full-Bridge SRC with Bridge Rectifier 414
15.4 Design of Half-Bridge SRC 415
15.5 Summary 417
15.6 References 418
15.7 Review Questions 420
15.8 Problems 420

16 Class D Parallel-Resonant Converter 422
16.1 Introduction 422
16.2 Half-Bridge Parallel-Resonant Converter 422
16.2.1 Principle of Operation 422
16.2.2 Half-Bridge PRC with Half-Wave Rectifier 425
16.2.3 Half-Bridge PRC with Transformer Center-Tapped Rectifier 427
16.2.4 Half-Bridge PRC with Bridge Rectifier 427
16.3 Design of the Half-Bridge PRC 427
16.4 Full-Bridge Parallel-Resonant Converter 430
16.4.1 Full-Bridge PRC with Half-Wave Rectifier 430
16.4.2 Full-Bridge PRC with Transformer Center-Tapped Rectifier 431
16.4.3 Full-Bridge PRC with Bridge Rectifier 431
16.5 Summary 432
16.6 References 432
16.7 Review Questions 433
16.8 Problems 434

17 Class D Series-Parallel-Resonant Converter 435
17.1 Introduction 435
17.2 Circuit Description 436
17.3 Half-Bridge Series-Parallel-Resonant Converter 439
CONTENTS

17.3.1 Half-Bridge SPRC with Half-Wave Rectifier 439
17.3.2 Half-Wave SPRC with Transformer Center-Tapped Rectifier 440
17.3.3 Half-Bridge SPRC with Bridge Rectifier 440
17.4 Design of Half-Bridge SPRC 440
17.5 Full-Bridge Series-Parallel-Resonant Converter 443
17.5.1 Full-Bridge SPRC with Half-Wave Rectifier 443
17.5.2 Full-Bridge SPRC with Transformer Center-Tapped Rectifier 443
17.5.3 Full-Bridge SPRC with Bridge Rectifier 444
17.6 Summary 445
17.7 References 445
17.8 Review Questions 446
17.9 Problems 447

18 Class D CLL Resonant Converter 448
18.1 Introduction 448
18.2 Circuit Description 448
18.3 Half-Bridge CLL Resonant Converter 451
18.3.1 Half-Bridge CLL Resonant Converter with Half-Wave Rectifier 451
18.3.2 Half-Bridge CLL Resonant Converter with Transformer Center-Tapped Rectifier 452
18.3.3 Half-Bridge CLL Resonant Converter with Bridge Rectifier 452
18.4 Design of Half-Bridge CLL Resonant Converter 453
18.5 Full-Bridge CLL Resonant Converter 455
18.5.1 Full-Bridge CLL Resonant Converter with Half-Wave Rectifier 455
18.5.2 Full-Bridge CLL Resonant Converter with Transformer Center-Tapped Rectifier 456
18.5.3 Full-Bridge CLL Resonant Converter with Bridge Rectifier 456
18.6 LLC Resonant Converter 457
18.7 Summary 457
18.8 References 457
18.9 Review Questions 458
18.10 Problems 458
CONTENTS

19 Class D Current-Source-Resonant Converter 459
19.1 Introduction 459
19.2 Circuit Description 459
   19.2.1 CSRC with Half-Wave Rectifier 460
   19.2.2 CSRC with Transformer Center-Tapped Rectifier 461
   19.2.3 CSRC with Class D Bridge Rectifier 461
19.3 Design of CSRC 461
19.4 Summary 464
19.5 References 464
19.6 Review Questions 465
19.7 Problems 465

20 Class D Inverter/Class E Rectifier Resonant Converter 466
20.1 Introduction 466
20.2 Circuit Description 466
20.3 Principle of Operation 468
20.4 Rectifier Parameters for $D = 0.5$ 469
20.5 Design of Class D Inverter/Class E Resonant Converter 471
20.6 Class E ZVS Inverter/Class D Rectifier Resonant DC-DC Converter 473
20.7 Class E ZVS Inverter/Class E ZVS Rectifier Resonant DC-DC Converter 474
20.8 Summary 475
20.9 References 475
20.10 Review Questions 476
20.11 Problems 476

21 Phase-Controlled Resonant Converters 477
21.1 Introduction 477
21.2 Circuit Description of SC PC SRC 477
   21.2.1 SC PC SRC with Half-Wave Rectifier 478
   21.2.2 SC PC SRC with Transformer Center-Tapped Rectifier 479
   21.2.3 SC PC SRC with Bridge Rectifier 479
21.3 Design Example 480
21.4 Summary 482
21.5 References 482
21.6 Review Questions 484
21.7 Problems 484

22 Quasiresonant and Multiresonant DC-DC Power Converters 485

22.1 Introduction 485
22.2 Zero-Voltage-Switching Quasiresonant DC-DC Converters 488
22.3 Buck ZVS Quasiresonant DC-DC Converter 492
  22.3.1 Waveforms 492
  22.3.2 DC Voltage Transfer Function 497
  22.3.3 Voltage and Current Stresses 498
22.4 Boost ZVS Quasiresonant DC-DC Converter 501
  22.4.1 Waveforms 501
  22.4.2 DC Voltage Transfer Function 505
  22.4.3 Current and Voltage Stresses 506
22.5 Buck-Boost ZVS Quasiresonant DC-DC Converter 509
  22.5.1 Waveforms 509
  22.5.2 DC Voltage Transfer Function 513
  22.5.3 Current and Voltage Stresses 514
  22.5.4 Generalization of ZVS QR DC-DC Converters 517
22.6 Zero-Current-Switching Quasiresonant DC-DC Converters 518
22.7 Buck ZCS Quasiresonant DC-DC Converter 520
  22.7.1 Waveforms 520
  22.7.2 DC Voltage Transfer Function 524
  22.7.3 Current and Voltage Stresses 525
22.8 Boost ZCS Quasiresonant DC-DC Converter 529
  22.8.1 Waveforms 529
  22.8.2 DC Voltage Transfer Function 533
  22.8.3 Current and Voltage Stresses 535
22.9 Buck-Boost ZCS Quasiresonant DC-DC Converter 536
  22.9.1 Waveforms 536
  22.9.2 DC Voltage Transfer Function 540
  22.9.3 Current and Voltage Stresses 541
  22.9.4 Generalization of ZCS QR DC-DC Converters 544
22.10 Zero-Voltage Switching Multiresonant DC-DC Converters 545
  22.10.1 Buck Multiresonant DC-DC Converter 546
22.11 Zero-Current Switching Multiresonant DC-DC Converters 550
xx  CONTENTS

22.12 Zero-Voltage Transition PWM Converters 553
22.13 Zero-Current Transition Converters 556
22.14 Summary 558
22.15 References 561
22.16 Review Questions 563
22.17 Problems 564

23 Modeling and Control 565

23.1 Introduction 565
23.2 Modeling 566
   23.2.1 Nonlinear Model 566
   23.2.2 Small-Signal Linear Model 569
23.3 Model Reduction and Control 572
   23.3.1 Reduced Model 572
   23.3.2 Control 573
23.4 Summary 574
23.5 References 574
23.6 Review Questions 576
23.7 Problems 576

APPENDICES 577

ANSWERS TO PROBLEMS 591
INDEX 597