Contents

Preface xvii

Part I Converters 1

1 Semiconductor power devices 3
1.1 Introduction 3
1.2 High-voltage SiC power devices 4
1.2.1 Characterization of 15 kV SiC N-IGBTs 4
1.2.2 Characterization of 10 kV SiC MOSFETs 9
1.3 Low-voltage SiC devices and its characteristics 11
1.3.1 Low-voltage gate drive design 11
1.3.2 Common-mode current minimization 12
1.4 Characterization of 1,200 V, 100 A SiC MOSFET 12
1.4.1 1,200 V, 100 A SiC MOSFET device characterization without complementary device of the half-bridge module 12
1.4.2 1,200 V, 100 A SiC MOSFET device characterization with complementary device of the half-bridge module 12
1.4.3 Hard-switching characterization of 1,700 V SiC MOSFET [11] 14
1.4.4 Performance comparison of MOSFET and IGBT 16
1.4.5 Gate drive design and characterization of 1,200 V/45 A infineon SiC JFET module [12] 23
1.4.6 SiC super-junction transistor characteristics 24
1.5 Zero voltage switching characterization of 12 kV SiC [14] 25
1.5.1 ZVS turn-on characteristics 26
1.5.2 ZVS turn-off characteristics 28
1.6 All SiC-based SST 34
1.7 Summary 39
Acknowledgements 41
References 41

2 Multilevel converters 43
2.1 Introduction 43
2.2 Basic concepts of multilevel converters 43
2.2.1 One-branch converter 44
2.2.2 Two branches, “H-bridge” converter 46
2.3 Electronic switches to implement the converters 47

2.3.1 NPC converter 47
2.3.2 FC converter 49
2.3.3 CHB converter 49
2.3.4 Combined topologies 53
2.4 Three-phase multilevel converters 54
2.4.1 Phase-to-phase and phase-to-neutral voltages 55
2.4.2 Space vector representation 56
2.5 Modulation strategies for multilevel converters 60
2.5.1 Voltage levels–based algorithms 61
2.5.2 Space vector–based algorithms 69
References 72
Further reading 73

3 Multi-input converters 75
3.1 Introduction 75
3.2 Realizing multi-input converter topologies 76
3.3 Multi-port converters 87
3.3.1 Synthesis of multi-port converters by extending multi-input topologies 87
3.3.2 Multi-port converters with dc link 89
3.3.3 Ac link multi-port power converters 92
3.4 Applications of multi-port power converters 97
3.4.1 Multi-port power converters for renewable energy systems 99
3.4.2 Application of multi-input converters in micro-grids 101
3.4.3 Multi-port converters for vehicular power systems 103
3.5 Summary 106
References 106

4 Modular converters 111
4.1 Introduction 111
4.2 Modular converter topologies and description 115
4.2.1 MMCC arrangements and SM topologies 116
4.2.2 Basic modular multilevel cascade converters 121
4.3 Control strategies 125
4.3.1 Voltage-balancing control 125
4.3.2 Circulating current control 128
4.4 Modulation techniques 130
4.4.1 High switching frequency techniques 130
4.4.2 Low switching frequency techniques 132
4.5 Operational issues in MMCCs 134
4.5.1 Fault-tolerant operation 134
4.5.2 Floating DC capacitor pre-charging procedures 136
4.6 Main applications 136
Acknowledgements 138
References 138

5 Matrix converters **147**
5.1 Introduction 147
5.2 Direct matrix converter 147
5.2.1 Circuit topology 147
5.2.2 Modulation techniques 147
5.3 Indirect matrix converter 159
5.3.1 Circuit topology 161
5.3.2 Modulation techniques 162
5.4 Technological issues of MCs 165
5.5 MC versus voltage back-to-back converter 167
5.6 Summary 167
References 168

6 Soft-switching converters **169**
6.1 Resonant converters 169
6.1.1 Second-order resonant converters 169
6.1.2 Resonant converters with three or more resonating elements 178
6.2 Quasi-resonant converters 181
6.2.1 Example 1 – half-wave ZCS-QRC 183
6.2.2 Example 2 – full-wave ZCS-QRC 185
6.2.3 Example 3 – half-wave ZVS-QRC 186
6.2.4 Example 4 – full-wave ZVS-QRC 188
6.2.5 The effect of parasitic oscillations in QRCs 189
6.3 Multi-resonant converters 190
6.4 Quasi-square-wave converters 191
6.5 Other types of ZVS and ZCS converters 196
References 200

7 *Z*-source converters **205**
7.1 Introduction 205
7.1.1 General overview 205
7.1.2 Basic principles 207
7.1.3 Modeling and control 209
7.2 Categories of impedance source power converters based on conversion functionality 215
7.2.1 DC–DC converter topologies 215
7.2.2 DC–AC inverter topologies 222
7.2.3 AC–AC converter topologies 226
7.2.4 AC–DC converter topologies 227
7.3 Impedance source network topologies 227
7.3.1 Non-transformer based 229
7.3.2 With transformer or magnetic coupling 233
7.4 Conclusions 236
References 237

8 Switching power supplies **245**
8.1 Introduction 245
8.2 Non-isolated converters topologies 246
8.2.1 Buck converter 246
8.2.2 Boost converter 249
8.2.3 Buck–boost converter 251
8.2.4 Integrated buck and boost converter 252
8.2.5 Power factor correction 253
8.3 Isolated converters topologies 254
8.3.1 Flyback converter 254
8.3.2 Forward converter 255
8.3.3 Half-bridge converter 256
8.3.4 Full-bridge converter 258
8.3.5 Rectifiers 259
8.4 Parasitics in DC–DC converters 262
8.5 Continuous and discontinuous conduction modes 264
8.6 Synchronous rectification 264
8.7 Bidirectional converters 265
8.8 Interleaving 266
8.9 Control principles 268
Further reading 272

9 Smart power electronic modules **273**
9.1 History 273
9.2 Technology background 276
9.2.1 IGBT device technologies and their performance 277
9.2.2 Gate driver technology 280
9.2.3 Packaging technologies 282
9.3 Basic usage 284
9.3.1 Protection 284
9.3.2 Bootstrap power supply 285
9.3.3 Digital interface 287
9.4 Reliability 287
9.5 Variety of products 288
9.6 Future usage and emerging solutions 290
9.6.1 Grid interface with multiple power modules 290
9.6.2 Matrix converter with SPM devices 295
9.6.3 Multilevel converter with SPM devices 296
9.6.4 A different direct converter with SPM devices 298
9.7 Conclusion 306
References 306

Part II Applications **311**

10 Permanent magnet synchronous motor drives **313**
10.1 Introduction 313
10.2 Trends in sensorless control of PMSM 314

10.2.1 Key factors for sensorless controls evaluation 315
10.2.2 A glance to HF injection methods 316
10.2.3 A HF sensorless technique for IPM and PMASR motors 318
10.2.4 A HF injection method for surface-mounted permanent magnet motors 319
10.2.5 A glance to extended EMF-based methods 320
10.2.6 Sliding mode observers for the extended EMF 321
10.3 Trends in MPC of PMSM 322
10.3.1 Key factors for MPC 323
10.3.2 Direct torque and flux control 323
10.3.3 An MPC method for IPM motors 324
10.3.4 A perspective on centralised MPC-based structures 325
10.4 Some hints about energy efficiency in PMSM drives 326
10.5 Final considerations 327
Acknowledgements 328
References 328

11 Induction motor drives 333
11.1 Induction motors 333
11.2 IM model 334
11.3 Variable frequency drives 335
11.3.1 Scalar control 335
11.3.2 Field-oriented control 335
11.3.3 Direct torque control 336
11.4 DTC schemes 336
11.4.1 Space vector modulation DTC 336
11.4.2 Feedback linearization and sliding mode DTC 337
11.4.3 Intelligent DTC schemes 340
11.5 IM speed estimation with Kalman filtering 342
11.5.1 High-speed operation 343
11.5.2 Low-speed operation 344
11.5.3 Implementation considerations 346
11.6 Switched reluctance sensorless drives 348
References 349

12 Wind energy systems 351
12.1 Introduction 351
12.1.1 Overview of the wind energy technology 351
12.1.2 Types of WT rotors 352
12.1.3 Generators for WTs and standard configurations of WECSs 354
12.2 Power electronic interfaces for variable speed WTs 361
12.2.1 Conventional power electronic building blocks 363
12.2.2 Common PEC topologies for WTs 366
12.2.3 Emerging PEC topologies for WTs 369
12.2.4 PEC topologies for high power WTs 371

12.3 Control algorithms for PECs 374
12.3.1 Maximum power point tracking 375
12.3.2 Control for DC/DC boost converters 377
12.3.3 Control for IS converters 378
12.3.4 Field oriented control 380
12.3.5 Direct torque control-space vector modulated 382
12.3.6 Voltage oriented control 382
12.3.7 Direct power control-space vector modulated 384
12.3.8 Single-phase grid converter control 385
12.3.9 Control for stand-alone mode of operation 386
Acknowledgements 388
References 388

13 Photovoltaic energy systems 395
13.1 Introduction 395
13.1.1 Brief overview of photovoltaic generation 395
13.1.2 PV inverter circuit 395
13.1.3 Centralized PV plant 397
13.2 The technologies 399
13.2.1 State-of-the-art technologies 399
13.2.2 Reliability 404
13.3 The grid interface 409
13.3.1 Basic control of real and reactive power in a two-bus power system 409
13.4 The standards 414
13.4.1 Protection 417
13.4.2 Islanding 417
13.4.3 Power quality 419
13.4.4 Ancillary services 420
13.5 The field measurements 422
13.5.1 Intermittence in solar field results 422
13.5.2 LVRT test results of the 500 kW RX series 422
13.6 Summary and conclusions 423
Acknowledgements 424
References 424

14 Automotive energy systems 425
14.1 Electric vehicle batteries 425
14.1.1 Introduction 425
14.2 EV charging 440
14.2.1 Plugged charging 440
14.3 Wireless charging 456
14.3.1 Introduction 456
14.3.2 Necessity of compensation for wireless charging 458
14.3.3 Analysis of series–series topology 461
14.3.4 Analysis of series–parallel topology 461

14.3.5 Peak efficiency of series–series and series–parallel topology 462
14.3.6 Control strategies for SS and SP topology 463
14.3.7 Advantages of EV wireless charging 464
References 464

15 Shipboard power systems 469
15.1 Shipboard power system topologies 469
15.2 Shipboard propulsion drives 472
15.2.1 Voltage link systems 474
15.2.2 Current link systems 477
15.2.3 Direct AC–AC conversion – cycloconverters 478
15.3 Power quality requirements in shipboard systems 479
15.4 Harmonic mitigation in shipboard systems 483
15.4.1 Harmonic cancellation 483
15.4.2 Reactive harmonic suppressors 485
15.4.3 Active filters 489
15.4.4 Case study 492
15.5 Frequency variation and converter control 495
15.6 Concepts for future shipboard power systems 495
15.6.1 Power electronics building block 495
15.6.2 Medium voltage DC integrated power system 496
Acknowledgements 498
References 498

16 Converters in power grid 501
16.1 Introduction 501
16.2 Power converter topologies 501
16.2.1 AC–DC converters 502
16.2.2 AC phase controllers 505
16.2.3 AC pulse width modulated controllers 505
16.2.4 Modular multilevel converter 508
16.3 Application examples of power converters in power grid 512
16.3.1 Shunt compensation 512
16.3.2 Series compensation 515
16.3.3 Shunt-series compensation 521
16.3.4 Series-series compensation 523
16.3.5 High-voltage direct current transmission 524
16.3.6 Low-frequency high-voltage ac transmission 526
16.3.7 Solid-state power transformer 528
16.4 Summary 529
References 530

17 Distributed generation and microgrids 535
17.1 Introduction 535
17.2 Distribution generators 536

17.2.1 Examples of DGs 536
17.2.2 Technical impacts due to DG 541
17.2.3 IEEE1547 544
17.3 Microgrid 545
17.3.1 DC and AC microgrids 546
17.3.2 Stand-alone microgrids 546
17.3.3 Grid-tied microgrids 546
17.3.4 Centralized control 547
17.3.5 Conventional droop control method 547
17.3.6 Local control 550
17.3.7 Multifunctionalities 551
References 553

18 Uninterruptible power supplies 557
18.1 Introduction 557
18.2 Topologies 557
18.2.1 On-line UPS systems 557
18.2.2 Off-Line UPS 558
18.2.3 Line-interactive UPS 560
18.2.4 Delta conversion UPS 561
18.2.5 Tri-mode UPS 561
18.2.6 Rotary UPS 562
18.2.7 Hybrid static and rotary UPS 563
18.2.8 Flywheels 564
18.2.9 DC UPS for pulse load with power leveling 565
18.2.10 Redundant bus 566
18.3 Controls for UPS systems 566
18.4 Applications 571
18.4.1 Desktop personal computers 572
18.4.2 Industrial systems 572
18.4.3 Data centers 572
18.4.4 Medical equipment 572
References 573

19 Wireless power transfer 577
19.1 Introduction 577
19.2 Basic principles and two fundamental concepts of WPT 579
19.2.1 Basic principles 579
19.2.2 Two fundamental concepts 580
19.3 Different forms of WPT systems 582
19.3.1 Two-coil systems 582
19.3.2 Three-coil systems 583
19.3.3 Four-coil systems 584
19.3.4 WPT systems with relay and domino resonators 585

19.4 Power electronics and control 585
19.4.1 Series and parallel tuned primary and secondary circuits 586
19.4.2 Practical circuit topologies 588
19.4.3 Control 592
19.5 Safety regulations 594
19.5.1 Electromagnetic compatibility 594
19.5.2 Human exposure 595
19.6 Conclusion 597
Acknowledgements 597
References 597

20 Advanced control of power electronic systems 601
20.1 Introduction 601
20.2 Brief overview of historic advanced nonlinear controllers for PES applications 601
20.3 Switching SBC [9–11] 604
20.3.1 SBC for standalone PES 604
20.3.2 SBC for networked PESs 610
Acknowledgements 617
References 617

Index 619