

Contents

Preface	17
About the Author	23

Chapter 1	Introduction	25
1.1	Applications of Power Electronics	26
1.2	History of Power Electronics	28
1.3	Types of Power Electronic Circuits	30
1.4	Design of Power Electronics Equipment	34
1.5	Determining the Root-Mean-Square Values of Waveforms	35
1.6	Peripheral Effects	36
1.7	Characteristics and Specifications of Switches	39
1.7.1	Ideal Characteristics	39
1.7.2	Characteristics of Practical Devices	40
1.7.3	Switch Specifications	42
1.8	Power Semiconductor Devices	43
1.9	Control Characteristics of Power Devices	49
1.10	Device Choices	49
1.11	Power Modules	53
1.12	Intelligent Modules	53
1.13	Power Electronics Journals and Conferences	55
	Summary	56
	References	56
	Review Questions	57
	Problems	57

PART I Power Diodes and Rectifiers 59

Chapter 2	Power Diodes and Switched RLC Circuits	59
2.1	Introduction	60
2.2	Semiconductor Basics	60
2.3	Diode Characteristics	62

2.4	Reverse Recovery Characteristics	65
2.5	Power Diode Types	68
2.5.1	General-Purpose Diodes	68
2.5.2	Fast-Recovery Diodes	69
2.5.3	Schottky Diodes	70
2.6	Silicon Carbide Diodes	70
2.7	Silicon Carbide Schottky Diodes	71
2.8	SPICE Diode Model	72
2.9	Series-Connected Diodes	73
2.10	Parallel-Connected Diodes	77
2.11	Diode Switched RC Load	78
2.12	Diode Switched RL Load	80
2.13	Diode Switched LC Load	82
2.14	Diode Switched RLC Load	85
2.15	Frewheeling Diodes with Switched RL Load	89
2.16	Recovery of Trapped Energy with a Diode	92
	Summary	96
	References	96
	Review Questions	97
	Problems	97

Chapter 3 Diode Rectifiers 103

3.1	Introduction	104
3.2	Performance Parameters	104
3.3	Single-Phase Full-Wave Rectifiers	106
3.4	Single-Phase Full-Wave Rectifier with RL Load	109
3.5	Single-Phase Full-Wave Rectifier with a Highly Inductive Load	116
3.6	Multiphase Star Rectifiers	118
3.7	Three-Phase Bridge Rectifiers	122
3.8	Three-Phase Bridge Rectifier with RL Load	126
3.9	Three-Phase Rectifier with a Highly Inductive Load	130
3.10	Comparisons of Diode Rectifiers	132
3.11	Rectifier Circuit Design	132
3.12	Output Voltage with LC Filter	144
3.13	Effects of Source and Load Inductances	148
3.14	Practical Considerations for Selecting Inductors and Capacitors	151
3.14.1	AC Film Capacitors	151
3.14.2	Ceramic Capacitors	152
3.14.3	Aluminum Electrolytic Capacitors	152
3.14.4	Solid Tantalum Capacitors	153
3.14.5	Supercapacitors	153
	Summary	153
	References	153
	Review Questions	154
	Problems	154

PART II Power Transistors and DC–DC Converters 158**Chapter 4 Power Transistors 158**

4.1	Introduction	159
4.2	Silicon Carbide Transistors	160
4.3	Power MOSFETs	161
4.3.1	Steady-State Characteristics	164
4.3.2	Switching Characteristics	167
4.3.3	Silicon Carbide MOSFETs	169
4.4	COOLMOS	171
4.5	Junction Field-Effect Transistors (JFETs)	173
4.5.1	Operation and Characteristics of JFETs	173
4.5.2	Silicon Carbide JFET Structures	177
4.6	Bipolar Junction Transistors	180
4.6.1	Steady-State Characteristics	181
4.6.2	Switching Characteristics	185
4.6.3	Switching Limits	192
4.6.4	Silicon Carbide BJTs	193
4.7	IGBTs	194
4.7.1	Silicon Carbide IGBTs	197
4.8	SITs	198
4.9	Comparisons of Transistors	199
4.10	Power Derating of Power Transistors	199
4.11	di/dt and dv/dt Limitations	203
4.12	Series and Parallel Operation	206
4.13	SPICE Models	208
4.13.1	BJT SPICE Model	208
4.13.2	MOSFET SPICE Model	210
4.13.3	IGBT SPICE Model	211
4.14	MOSFET Gate Drive	213
4.15	JFET Gate Drives	215
4.16	BJT Base Drive	216
4.17	Isolation of Gate and Base Drives	221
4.17.1	Pulse Transformers	223
4.17.2	Optocouplers	223
4.18	GATE-DRIVE ICs	224
	Summary	226
	References	227
	Review Questions	230
	Problems	232

Chapter 5 DC–DC Converters 234

5.1	Introduction	235
5.2	Performance Parameters of DC–DC Converters	235
5.3	Principle of Step-Down Operation	236
5.3.1	Generation of Duty Cycle	240

5.4	Step-Down Converter with RL Load	241
5.5	Principle of Step-Up Operation	246
5.6	Step-Up Converter with a Resistive Load	249
5.7	Frequency Limiting Parameters	251
5.8	Converter Classification	252
5.9	Switching-Mode Regulators	256
5.9.1	Buck Regulators	257
5.9.2	Boost Regulators	261
5.9.3	Buck–Boost Regulators	265
5.9.4	Cúk Regulators	269
5.9.5	Limitations of Single-Stage Conversion	275
5.10	Comparison of Regulators	276
5.11	Multiooutput Boost Converter	277
5.12	Diode Rectifier-Fed Boost Converter	280
5.13	Averaging Models of Converters	282
5.14	State–Space Analysis of Regulators	288
5.15	Design Considerations for Input Filter and Converters	292
5.16	Drive IC for Converters	297
	Summary	299
	References	301
	Review Questions	303
	Problems	303

PART III Inverters 306

Chapter 6 DC–AC Converters 306

6.1	Introduction	307
6.2	Performance Parameters	307
6.3	Principle of Operation	309
6.4	Single-Phase Bridge Inverters	313
6.5	Three-Phase Inverters	319
6.5.1	180-Degree Conduction	320
6.5.2	120-Degree Conduction	327
6.6	Voltage Control of Single-Phase Inverters	330
6.6.1	Multiple-Pulse-Width Modulation	330
6.6.2	Sinusoidal Pulse-Width Modulation	333
6.6.3	Modified Sinusoidal Pulse-Width Modulation	336
6.6.4	Phase-Displacement Control	339
6.7	Voltage Control of Three-Phase Inverters	340
6.7.1	Sinusoidal PWM	341
6.7.2	60-Degree PWM	344
6.7.3	Third-Harmonic PWM	344
6.7.4	Space Vector Modulation	347
6.7.5	Comparison of PWM Techniques	359
6.8	Harmonic Reductions	359
6.9	Current-Source Inverters	364

6.10	Variable DC-Link Inverter	366
6.11	Boost Inverter	368
6.12	Inverter Circuit Design	373
	Summary	378
	References	378
	Review Questions	380
	Problems	380
Chapter 7	Resonant Pulse Inverters	385
7.1	Introduction	386
7.2	Series Resonant Inverters	386
	7.2.1 Series Resonant Inverters with Unidirectional Switches	387
	7.2.2 Series Resonant Inverters with Bidirectional Switches	396
7.3	Frequency Response of Series Resonant Inverters	402
	7.3.1 Frequency Response for Series Loaded	402
	7.3.2 Frequency Response for Parallel Loaded	405
	7.3.3 Frequency Response for Series-Parallel Loaded	407
7.4	Parallel Resonant Inverters	408
7.5	Voltage Control of Resonant Inverters	412
7.6	Class E Resonant Inverter	414
7.7	Class E Resonant Rectifier	418
7.8	Zero-Current-Switching Resonant Converters	422
	7.8.1 <i>L</i> -Type ZCS Resonant Converter	423
	7.8.2 <i>M</i> -Type ZCS Resonant Converter	426
7.9	Zero-Voltage-Switching Resonant Converters	426
7.10	Comparisons Between ZCS and ZVS Resonant Converters	430
7.11	Two-Quadrant ZVS Resonant Converters	431
7.12	Resonant DC-Link Inverters	433
	Summary	437
	References	438
	Review Questions	438
	Problems	439
Chapter 8	Multilevel Inverters	441
8.1	Introduction	441
8.2	Multilevel Concept	442
8.3	Types of Multilevel Inverters	444
8.4	Diode-Clamped Multilevel Inverter	444
	8.4.1 Principle of Operation	445
	8.4.2 Features of Diode-Clamped Inverter	446
	8.4.3 Improved Diode-Clamped Inverter	448
8.5	Flying-Capacitors Multilevel Inverter	450
	8.5.1 Principle of Operation	450
	8.5.2 Features of Flying-Capacitors Inverter	452

8.6	Cascaded Multilevel Inverter	453
8.6.1	Principle of Operation	453
8.6.2	Features of Cascaded Inverter	455
8.7	Applications	457
8.7.1	Reactive Power Compensation	457
8.7.2	Back-to-Back Intertie	459
8.7.3	Adjustable Speed Drives	459
8.8	Switching Device Currents	460
8.9	DC-Link Capacitor Voltage Balancing	461
8.10	Features of Multilevel Inverters	462
8.11	Comparisons of Multilevel Converters	463
	Summary	464
	References	464
	Review Questions	465
	Problems	465

PART IV Thyristors and Thyristorized Converters 467

Chapter 9 Thyristors 467

9.1	Introduction	467
9.2	Thyristor Characteristics	468
9.3	Two-Transistor Model of Thyristor	471
9.4	Thyristor Turn-On	473
9.5	Thyristor Turn-Off	475
9.6	Thyristor Types	477
9.6.1	Phase-Controlled Thyristors	471
9.6.2	Bidirectional Phase-Controlled Thyristors	478
9.6.3	Fast-Switching Asymmetrical Thyristors	479
9.6.4	Light-Activated Silicon-Controlled Rectifiers	480
9.6.5	Bidirectional Triode Thyristors	480
9.6.6	Reverse-Conducting Thyristors	481
9.6.7	Gate Turn-off Thyristors	481
9.6.8	FET-Controlled Thyristors	486
9.6.9	MTOs	487
9.6.10	ETOs	488
9.6.11	IGCTs	489
9.6.12	MCTs	490
9.6.13	SITHs	493
9.6.14	Comparisons of Thyristors	494
9.7	Series Operation of Thyristors	499
9.8	Parallel Operation of Thyristors	502
9.9	di/dt Protection	503
9.10	dv/dt Protection	504
9.11	SPICE Thyristor Model	506
9.11.1	Thyristor SPICE Model	506
9.11.2	GTO SPICE Model	508

9.11.3	MCT SPICE Model	510
9.11.4	SITH SPICE Model	510
9.12	DIACs	510
9.13	Thyristor Firing Circuits	513
9.14	Unijunction Transistor	516
9.15	Programmable Unijunction Transistor	518
	Summary	520
	References	521
	Review Questions	524
	Problems	525
Chapter 10	Controlled Rectifiers	527
10.1	Introduction	528
10.2	Single-Phase Full Converters	528
10.2.1	Single-Phase Full Converter with RL Load	532
10.3	Single-Phase Dual Converters	535
10.4	Three-Phase Full Converters	538
10.4.1	Three-Phase Full Converter with RL Load	542
10.5	Three-Phase Dual Converters	544
10.6	Pulse-Width-Modulation Control	547
10.6.1	PWM Control	548
10.6.2	Single-Phase Sinusoidal PWM	550
10.6.3	Three-Phase PWM Rectifier	551
10.7	Single-Phase Series Converters	555
10.8	Twelve-Pulse Converters	558
10.9	Design of Converter Circuits	560
10.10	Effects of Load and Source Inductances	566
	Summary	568
	References	568
	Review Questions	570
	Problems	570
Chapter 11	AC Voltage Controllers	576
11.1	Introduction	577
11.2	Performance Parameters of AC Voltage Controllers	578
11.3	Single-Phase Full-Wave Controllers with Resistive Loads	579
11.4	Single-Phase Full-Wave Controllers with Inductive Loads	583
11.5	Three-Phase Full-Wave Controllers	587
11.6	Three-Phase Full-Wave Delta-Connected Controllers	592
11.7	Single-Phase Transformer Connection Changers	596
11.8	Cycloconverters	601
11.8.1	Single-Phase Cycloconverters	601
11.8.2	Three-Phase Cycloconverters	604
11.8.3	Reduction of Output Harmonics	605
11.9	AC Voltage Controllers with PWM Control	608

11.10	Matrix Converter	610	
11.11	Design of AC Voltage-Controller Circuits	612	
11.12	Effects of Source and Load Inductances	620	
	Summary	621	
	References	621	
	Review Questions	622	
	Problems	622	
PART V Power Electronics Applications and Protections			626
Chapter 12 Flexible AC Transmission Systems			626
12.1	Introduction	627	
12.2	Principle of Power Transmission	628	
12.3	Principle of Shunt Compensation	630	
12.4	Shunt Compensators	632	
	12.4.1 Thyristor-Controlled Reactor	632	
	12.4.2 Thyristor-Switched Capacitor	633	
	12.4.3 Static VAR Compensator	636	
	12.4.4 Advanced Static VAR Compensator	637	
12.5	Principle of Series Compensation	639	
12.6	Series Compensators	641	
	12.6.1 Thyristor-Switched Series Capacitor	641	
	12.6.2 Thyristor-Controlled Series Capacitor	643	
	12.6.3 Forced-Commutation-Controlled Series Capacitor	644	
	12.6.4 Series Static VAR Compensator	645	
	12.6.5 Advanced SSVC	645	
12.7	Principle of Phase-Angle Compensation	648	
12.8	Phase-Angle Compensator	651	
12.9	Unified Power Flow Controller	652	
12.10	Comparisons of Compensators	653	
	Summary	655	
	References	655	
	Review Questions	656	
	Problems	656	
Chapter 13 Power Supplies			658
13.1	Introduction	659	
13.2	Dc Power Supplies	659	
	13.2.1 Switched-Mode Dc Power Supplies	660	
	13.2.2 Flyback Converter	660	
	13.2.3 Forward Converter	664	
	13.2.4 Push-Pull Converter	669	
	13.2.5 Half-Bridge Converter	671	
	13.2.6 Full-Bridge Converter	674	
	13.2.7 Resonant Dc Power Supplies	677	
	13.2.8 Bidirectional Power Supplies	679	

13.3	Ac Power Supplies	679
13.3.1	Switched-Mode Ac Power Supplies	681
13.3.2	Resonant Ac Power Supplies	681
13.3.3	Bidirectional Ac Power Supplies	682
13.4	Multistage Conversions	683
13.5	Control Circuits	684
13.6	Magnetic Design Considerations	688
13.6.1	Transformer Design	688
13.6.2	Dc Inductor	692
13.6.3	Magnetic Saturation	693
	Summary	694
	References	694
	Review Questions	695
	Problems	695
Chapter 14	Dc Drives	699
14.1	Introduction	699
14.2	Basic Characteristics of Dc Motors	701
14.2.1	Separately Excited Dc Motor	701
14.2.2	Series-Excited Dc Motor	704
14.2.3	Gear Ratio	706
14.3	Operating Modes	708
14.4	Single-Phase Drives	710
14.4.1	Single-Phase Semiconverter Drives	712
14.4.2	Single-Phase Full-Converter Drives	713
14.4.3	Single-Phase Dual-Converter Drives	714
14.5	Three-Phase Drives	718
14.5.1	Three-Phase Semiconverter Drives	718
14.5.2	Three-Phase Full-Converter Drives	718
14.5.3	Three-Phase Dual-Converter Drives	719
14.6	Dc-Dc Converter Drives	722
14.6.1	Principle of Power Control	722
14.6.2	Principle of Regenerative Brake Control	724
14.6.3	Principle of Rheostatic Brake Control	727
14.6.4	Principle of Combined Regenerative and Rheostatic Brake Control	728
14.6.5	Two- and Four-Quadrant Dc-dc Converter Drives	729
14.6.6	Multiphase Dc-dc Converters	730
14.7	Closed-Loop Control of Dc Drives	733
14.7.1	Open-Loop Transfer Function	733
14.7.2	Open-Loop Transfer Function of Separately Excited Motors	734
14.7.3	Open-Loop Transfer Function of Series Excited Motors	737
14.7.4	Converter Control Models	739
14.7.5	Closed-Loop Transfer Function	741
14.7.6	Closed-Loop Current Control	744

14.7.7	Design of Current Controller	748
14.7.8	Design of Speed Controller	749
14.7.9	Dc–dc Converter-Fed Drive	753
14.7.10	Phase-Locked-Loop Control	754
14.7.11	Microcomputer Control of Dc Drives	756
	Summary	758
	References	758
	Review Questions	759
	Problems	760

Chapter 15 Ac Drives 764

15.1	Introduction	765
15.2	Induction Motor Drives	765
15.2.1	Performance Characteristics	767
15.2.2	Torque–Speed Characteristics	769
15.2.3	Stator Voltage Control	774
15.2.4	Rotor Voltage Control	778
15.2.5	Frequency Control	787
15.2.6	Voltage and Frequency Control	789
15.2.7	Current Control	794
15.2.8	Constant Slip-Speed Control	799
15.2.9	Voltage, Current, and Frequency Control	800
15.3	Closed-Loop Control of Induction Motors	802
15.4	Dimensioning the Control Variables	806
15.5	Vector Controls	808
15.5.1	Basic Principle of Vector Control	808
15.5.2	Direct and Quadrature-Axis Transformation	810
15.5.3	Indirect Vector Control	815
15.5.4	Direct Vector Control	819
15.6	Synchronous Motor Drives	821
15.6.1	Cylindrical Rotor Motors	822
15.6.2	Salient-Pole Motors	825
15.6.3	Reluctance Motors	826
15.6.4	Switched Reluctance Motors	827
15.6.5	Permanent-Magnet Motors	839
15.6.6	Closed-Loop Control of Synchronous Motors	832
15.6.7	Brushless Dc and Ac Motor Drives	834
15.7	Design of Speed Controller for PMSM Drives	836
15.7.1	System Block Diagram	836
15.7.2	Current Loop	838
15.7.3	Speed Controller	839
15.8	Stepper Motor Control	842
15.8.1	Variable-Reluctance Stepper Motors	842
15.8.2	Permanent-Magnet Stepper Motors	845
15.9	Linear Induction Motors	849
15.10	High-Voltage IC for Motor Drives	852
	Summary	857

References	858
Review Questions	859
Problems	860
Chapter 16	Introduction to Renewable Energy 864
16.1	Introduction 865
16.2	Energy and Power 866
16.3	Renewable Energy Generation System 867
16.3.1	Turbine 868
16.3.2	Thermal Cycle 869
16.4	Solar Energy Systems 871
16.4.1	Solar Energy 871
16.4.2	Photovoltaic 874
16.4.3	Photovoltaic Cells 874
16.4.4	PV Models 875
16.4.5	Photovoltaic Systems 881
16.5	Wind Energy 884
16.5.1	Wind Turbines 884
16.5.2	Turbine Power 885
16.5.3	Speed and Pitch Control 888
16.5.4	Power Curve 889
16.5.5	Wind Energy Systems 890
16.5.6	Doubly Fed Induction Generators 893
16.5.7	Squirrel-Cage Induction Generators 894
16.5.8	Synchronous Generators 895
16.5.9	Permanent-Magnet Synchronous Generators 896
16.5.10	Switched Reluctance Generator 897
16.5.11	Comparisons of the Wind Turbine Power Configurations 897
16.6	Ocean Energy 898
16.6.1	Wave Energy 898
16.6.2	Mechanism of Wave Generation 899
16.6.3	Wave Power 900
16.6.4	Tidal Energy 903
16.6.5	Ocean Thermal Energy Conversion 905
16.7	Hydropower Energy 906
16.7.1	Large-Scale Hydropower 906
16.7.2	Small-Scale Hydropower 907
16.8	Fuel Cells 910
16.8.1	Hydrogen Generation and Fuel Cells 911
16.8.2	Types of Fuel Cells 912
16.8.3	Polymer Electrolyte Membrane Fuel Cells (PEMFC) 913
16.8.4	Direct-Methanol Fuel Cells (DMFC) 914
16.8.5	Alkaline Fuel Cells (AFC) 916
16.8.6	Phosphoric Acid Fuel Cells (PAFC) 917
16.8.7	Molten Carbonate Fuel Cells (MCFC) 918
16.8.8	Solid Oxide Fuel Cells (SOFC) 919
16.8.9	Thermal and Electrical Processes of Fuel Cells 920

16.9	Geothermal Energy	924
16.10	Biomass Energy	924
	Summary	925
	References	925
	Review Questions	926
	Problems	927
Chapter 17	Protections of Devices and Circuits	931
17.1	Introduction	931
17.2	Cooling and Heat Sinks	932
17.3	Thermal Modeling of Power Switching Devices	937
	17.3.1 Electrical Equivalent Thermal Model	938
	17.3.2 Mathematical Thermal Equivalent Circuit	940
	17.3.3 Coupling of Electrical and Thermal Components	941
17.4	Snubber Circuits	943
17.5	Reverse Recovery Transients	944
17.6	Supply- and Load-Side Transients	950
17.7	Voltage Protection by Selenium Diodes and Metaloxide Varistors	953
17.8	Current Protections	955
	17.8.1 Fusing	955
	17.8.2 Fault Current with Ac Source	958
	17.8.3 Fault Current with Dc Source	960
17.9	Electromagnetic Interference	963
	17.9.1 Sources of EMI	964
	17.9.2 Minimizing EMI Generation	964
	17.9.3 EMI Shielding	965
	17.9.4 EMI Standards	965
	Summary	966
	References	967
	Review Questions	967
	Problems	968
Appendix A	Three-Phase Circuits	971
Appendix B	Magnetic Circuits	975
Appendix C	Switching Functions of Converters	983
Appendix D	DC Transient Analysis	989
Appendix E	Fourier Analysis	993
Appendix F	Reference Frame Transformation	996
Bibliography		1000
Answers to Selected Problems		1003
Index		1014