
Contents

Preface	xix
1 Introduction	1
1.1 Introduction to Power Processing	1
1.2 Several Applications of Power Electronics	7
1.3 Elements of Power Electronics	9
References	
I Converters in Equilibrium	11
2 Principles of Steady State Converter Analysis	13
2.1 Introduction	13
2.2 Inductor Volt-Second Balance, Capacitor Charge Balance, and the Small-Ripple Approximation	15
2.3 Boost Converter Example	22
2.4 Ćuk Converter Example	27
2.5 Estimating the Output Voltage Ripple in Converters Containing Two-Pole Low-Pass Filters	31
2.6 Summary of Key Points	34
References	34
Problems	35
3 Steady-State Equivalent Circuit Modeling, Losses, and Efficiency	39
3.1 The DC Transformer Model	39
3.2 Inclusion of Inductor Copper Loss	42
3.3 Construction of Equivalent Circuit Model	45

3.3.1	Inductor Voltage Equation	46
3.3.2	Capacitor Current Equation	46
3.3.3	Complete Circuit Model	47
3.3.4	Efficiency	48
3.4	How to Obtain the Input Port of the Model	50
3.5	Example: Inclusion of Semiconductor Conduction Losses in the Boost Converter Model	52
3.6	Summary of Key Points	56
References		56
Problems		57
Switch Realization		63
4.1	Switch Applications	65
4.1.1	Single-Quadrant Switches	65
4.1.2	Current-Bidirectional Two-Quadrant Switches	67
4.1.3	Voltage-Bidirectional Two-Quadrant Switches	71
4.1.4	Four-Quadrant Switches	72
4.1.5	Synchronous Rectifiers	73
4.2	A Brief Survey of Power Semiconductor Devices	74
4.2.1	Power Diodes	75
4.2.2	Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)	78
4.2.3	Bipolar Junction Transistor (BJT)	81
4.2.4	Insulated Gate Bipolar Transistor (IGBT)	86
4.2.5	Thyristors (SCR, GTO, MCT)	88
4.3	Switching Loss	92
4.3.1	Transistor Switching with Clamped Inductive Load	93
4.3.2	Diode Recovered Charge	96
4.3.3	Device Capacitances, and Leakage, Package, and Stray Inductances	98
4.3.4	Efficiency vs. Switching Frequency	100
4.4	Summary of Key Points	101
References		102
Problems		103
The Discontinuous Conduction Mode		107
5.1	Origin of the Discontinuous Conduction Mode, and Mode Boundary	108
5.2	Analysis of the Conversion Ratio $M(D,K)$	112
5.3	Boost Converter Example	117
5.4	Summary of Results and Key Points	124
Problems		126
Converter Circuits		131
6.1	Circuit Manipulations	132
6.1.1	Inversion of Source and Load	132
6.1.2	Cascade Connection of Converters	134
6.1.3	Rotation of Three-Terminal Cell	137

6.1.4	Differential Connection of the Load	138
6.2	A Short List of Converters	143
6.3	Transformer Isolation	146
6.3.1	Full-Bridge and Half-Bridge Isolated Buck Converters	149
6.3.2	Forward Converter	154
6.3.3	Push-Pull Isolated Buck Converter	159
6.3.4	Flyback Converter	161
6.3.5	Boost-Derived Isolated Converters	165
6.3.6	Isolated Versions of the SEPIC and the Ćuk Converter	168
6.4	Converter Evaluation and Design	171
6.4.1	Switch Stress and Utilization	171
6.4.2	Design Using Computer Spreadsheet	174
6.5	Summary of Key Points	177
References		177
Problems		179
II Converter Dynamics and Control		185
7 AC Equivalent Circuit Modeling		187
7.1	Introduction	187
7.2	The Basic AC Modeling Approach	192
7.2.1	Averaging the Inductor Waveforms	193
7.2.2	Discussion of the Averaging Approximation	194
7.2.3	Averaging the Capacitor Waveforms	196
7.2.4	The Average Input Current	197
7.2.5	Perturbation and Linearization	197
7.2.6	Construction of the Small-Signal Equivalent Circuit Model	201
7.2.7	Discussion of the Perturbation and Linearization Step	202
7.2.8	Results for Several Basic Converters	204
7.2.9	Example: A Nonideal Flyback Converter	204
7.3	State-Space Averaging	213
7.3.1	The State Equations of a Network	213
7.3.2	The Basic State-Space Averaged Model	216
7.3.3	Discussion of the State-Space Averaging Result	217
7.3.4	Example: State-Space Averaging of a Nonideal Buck-Boost Converter	221
7.4	Circuit Averaging and Averaged Switch Modeling	226
7.4.1	Obtaining a Time-Invariant Circuit	228
7.4.2	Circuit Averaging	229
7.4.3	Perturbation and Linearization	232
7.4.4	Switch Networks	235
7.4.5	Example: Averaged Switch Modeling of Conduction Losses	242
7.4.6	Example: Averaged Switch Modeling of Switching Losses	244
7.5	The Canonical Circuit Model	247
7.5.1	Development of the Canonical Circuit Model	248

7.5.2	Example: Manipulation of the Buck-Boost Converter Model into Canonical Form	250
7.5.3	Canonical Circuit Parameter Values for Some Common Converters	252
7.6	Modeling the Pulse-Width Modulator	253
7.7	Summary of Key Points	256
References		257
Problems		258
Converter Transfer Functions		265
8.1	Review of Bode Plots	267
8.1.1	Single Pole Response	269
8.1.2	Single Zero Response	275
8.1.3	Right Half-Plane Zero	276
8.1.4	Frequency Inversion	277
8.1.5	Combinations	278
8.1.6	Quadratic Pole Response: Resonance	282
8.1.7	The Low- Q Approximation	287
8.1.8	Approximate Roots of an Arbitrary-Degree Polynomial	289
8.2	Analysis of Converter Transfer Functions	293
8.2.1	Example: Transfer Functions of the Buck-Boost Converter	294
8.2.2	Transfer Functions of Some Basic CCM Converters	300
8.2.3	Physical Origins of the RHP Zero in Converters	300
8.3	Graphical Construction of Impedances and Transfer Functions	302
8.3.1	Series Impedances: Addition of Asymptotes	303
8.3.2	Series Resonant Circuit Example	305
8.3.3	Parallel Impedances: Inverse Addition of Asymptotes	308
8.3.4	Parallel Resonant Circuit Example	309
8.3.5	Voltage Divider Transfer Functions: Division of Asymptotes	311
8.4	Graphical Construction of Converter Transfer Functions	313
8.5	Measurement of AC Transfer Functions and Impedances	317
8.6	Summary of Key Points	321
References		322
Problems		322
Controller Design		331
9.1	Introduction	331
9.2	Effect of Negative Feedback on the Network Transfer Functions	334
9.2.1	Feedback Reduces the Transfer Functions from Disturbances to the Output	335
9.2.2	Feedback Causes the Transfer Function from the Reference Input to the Output to be Insensitive to Variations in the Gains in the Forward Path of the Loop	337
9.3	Construction of the Important Quantities $1/(1+T)$ and $T/(1+T)$ and the Closed-Loop Transfer Functions	337
9.4	Stability	340

9.4.1	The Phase Margin Test	341
9.4.2	The Relationship Between Phase Margin and Closed-Loop Damping Factor	342
9.4.3	Transient Response vs. Damping Factor	346
9.5	Regulator Design	347
9.5.1	Lead (PD) Compensator	348
9.5.2	Lag (PI) Compensator	351
9.5.3	Combined (PID) Compensator	353
9.5.4	Design Example	354
9.6	Measurement of Loop Gains	362
9.6.1	Voltage Injection	364
9.6.2	Current Injection	367
9.6.3	Measurement of Unstable Systems	368
9.7	Summary of Key Points	369
References		369
Problems		369
10 Input Filter Design		377
10.1	Introduction	377
10.1.1	Conducted EMI	377
10.1.2	The Input Filter Design Problem	379
10.2	Effect of an Input Filter on Converter Transfer Functions	381
10.2.1	Discussion	382
10.2.2	Impedance Inequalities	384
10.3	Buck Converter Example	385
10.3.1	Effect of Undamped Input Filter	385
10.3.2	Damping the Input Filter	391
10.4	Design of a Damped Input Filter	392
10.4.1	R_f-C_b Parallel Damping	395
10.4.2	R_f-L_b Parallel Damping	396
10.4.3	R_f-L_b Series Damping	398
10.4.4	Cascading Filter Sections	398
10.4.5	Example: Two Stage Input Filter	400
10.5	Summary of Key Points	403
References		405
Problems		406
11 AC and DC Equivalent Circuit Modeling of the Discontinuous Conduction Mode		409
11.1	DCM Averaged Switch Model	410
11.2	Small-Signal AC Modeling of the DCM Switch Network	420
11.2.1	Example: Control-to-Output Frequency Response of a DCM Boost Converter	428
11.2.2	Example: Control-to-Output Frequency Responses of a CCM/DCM SEPIC	429

11.3	High-Frequency Dynamics of Converters in DCM	431
11.4	Summary of Key Points	434
References		434
Problems		435
12	Current Programmed Control	439
12.1	Oscillation for $D > 0.5$	441
12.2	A Simple First-Order Model	449
12.2.1	Simple Model via Algebraic Approach: Buck–Boost Example	450
12.2.2	Averaged Switch Modeling	454
12.3	A More Accurate Model	459
12.3.1	Current-Programmed Controller Model	459
12.3.2	Solution of the CPM Transfer Functions	462
12.3.3	Discussion	465
12.3.4	Current-Programmed Transfer Functions of the CCM Buck Converter	466
12.3.5	Results for Basic Converters	469
12.3.6	Quantitative Effects of Current-Programmed Control on the Converter Transfer Functions	471
12.4	Discontinuous Conduction Mode	473
12.5	Summary of Key Points	480
References		481
Problems		482
III	Magnetics	489
13	Basic Magnetics Theory	491
13.1	Review of Basic Magnetics	491
13.1.1	Basic Relationships	491
13.1.2	Magnetic Circuits	498
13.2	Transformer Modeling	501
13.2.1	The Ideal Transformer	502
13.2.2	The Magnetizing Inductance	502
13.2.3	Leakage Inductances	504
13.3	Loss Mechanisms in Magnetic Devices	506
13.3.1	Core Loss	506
13.3.2	Low-Frequency Copper Loss	508
13.4	Eddy Currents in Winding Conductors	508
13.4.1	Introduction to the Skin and Proximity Effects	508
13.4.2	Leakage Flux in Windings	512
13.4.3	Foil Windings and Layers	514
13.4.4	Power Loss in a Layer	515
13.4.5	Example: Power Loss in a Transformer Winding	518
13.4.6	Interleaving the Windings	520
13.4.7	PWM Waveform Harmonics	522

13.5	Several Types of Magnetic Devices, Their B – H Loops, and Core vs. Copper Loss	525
13.5.1	Filter Inductor	525
13.5.2	AC Inductor	527
13.5.3	Transformer	528
13.5.4	Coupled Inductor	529
13.5.5	Flyback Transformer	530
13.6	Summary of Key Points	531
References		532
Problems		533
14	Inductor Design	539
14.1	Filter Inductor Design Constraints	539
14.1.1	Maximum Flux Density	541
14.1.2	Inductance	542
14.1.3	Winding Area	542
14.1.4	Winding Resistance	543
14.1.5	The Core Geometrical Constant K_g	543
14.2	A Step-by-Step Procedure	544
14.3	Multiple-Winding Magnetics Design via the K_g Method	545
14.3.1	Window Area Allocation	545
14.3.2	Coupled Inductor Design Constraints	550
14.3.3	Design Procedure	552
14.4	Examples	554
14.4.1	Coupled Inductor for a Two-Output Forward Converter	554
14.4.2	CCM Flyback Transformer	557
14.5	Summary of Key Points	562
References		562
Problems		563
15	Transformer Design	565
15.1	Transformer Design: Basic Constraints	565
15.1.1	Core Loss	566
15.1.2	Flux Density	566
15.1.3	Copper Loss	567
15.1.4	Total Power Loss vs. ΔB	568
15.1.5	Optimum Flux Density	569
15.2	A Step-by-Step Transformer Design Procedure	570
15.3	Examples	573
15.3.1	Example 1: Single-Output Isolated Ćuk Converter	573
15.3.2	Example 2: Multiple-Output Full-Bridge Buck Converter	576
15.4	AC Inductor Design	580
15.4.1	Outline of Derivation	580
15.4.2	Step-by-Step AC Inductor Design Procedure	582

15.5	Summary	583
	References	583
	Problems	584
IV	Modern Rectifiers and Power System Harmonics	587
16	Power and Harmonics in Nonsinusoidal Systems	589
16.1	Average Power	590
16.2	Root-Mean-Square (RMS) Value of a Waveform	593
16.3	Power Factor	594
16.3.1	Linear Resistive Load, Nonsinusoidal Voltage	594
16.3.2	Nonlinear Dynamic Load, Sinusoidal Voltage	595
16.4	Power Phasors in Sinusoidal Systems	598
16.5	Harmonic Currents in Three-Phase Systems	599
16.5.1	Harmonic Currents in Three-Phase Four-Wire Networks	599
16.5.2	Harmonic Currents in Three-Phase Three-Wire Networks	601
16.5.3	Harmonic Current Flow in Power Factor Correction Capacitors	602
16.6	AC Line Current Harmonic Standards	603
16.6.1	International Electrotechnical Commission Standard 1000	603
16.6.2	IEEE/ANSI Standard 519	604
	Bibliography	605
	Problems	605
17	Line-Commutated Rectifiers	609
17.1	The Single-Phase Full-Wave Rectifier	609
17.1.1	Continuous Conduction Mode	610
17.1.2	Discontinuous Conduction Mode	611
17.1.3	Behavior when C is Large	612
17.1.4	Minimizing THD when C is Small	613
17.2	The Three-Phase Bridge Rectifier	615
17.2.1	Continuous Conduction Mode	615
17.2.2	Discontinuous Conduction Mode	616
17.3	Phase Control	617
17.3.1	Inverter Mode	619
17.3.2	Harmonics and Power Factor	619
17.3.3	Commutation	620
17.4	Harmonic Trap Filters	622
17.5	Transformer Connections	628
17.6	Summary	630
	References	631
	Problems	632
18	Pulse-Width Modulated Rectifiers	637
18.1	Properties of the Ideal Rectifier	638

18.2	Realization of a Near-Ideal Rectifier	640
18.2.1	CCM Boost Converter	642
18.2.2	DCM Flyback Converter	646
18.3	Control of the Current Waveform	648
18.3.1	Average Current Control	648
18.3.2	Current Programmed Control	654
18.3.3	Critical Conduction Mode and Hysteretic Control	657
18.3.4	Nonlinear Carrier Control	659
18.4	Single-Phase Converter Systems Incorporating Ideal Rectifiers	663
18.4.1	Energy Storage	663
18.4.2	Modeling the Outer Low-Bandwidth Control System	668
18.5	RMS Values of Rectifier Waveforms	673
18.5.1	Boost Rectifier Example	674
18.5.2	Comparison of Single-Phase Rectifier Topologies	676
18.6	Modeling Losses and Efficiency in CCM High-Quality Rectifiers	678
18.6.1	Expression for Controller Duty Cycle $d(t)$	679
18.6.2	Expression for the DC Load Current	681
18.6.3	Solution for Converter Efficiency η	683
18.6.4	Design Example	684
18.7	Ideal Three-Phase Rectifiers	685
18.8	Summary of Key Points	691
	References	692
	Problems	696

V Resonant Converters **703**

19	Resonant Conversion	705
19.1	Sinusoidal Analysis of Resonant Converters	709
19.1.1	Controlled Switch Network Model	710
19.1.2	Modeling the Rectifier and Capacitive Filter Networks	711
19.1.3	Resonant Tank Network	713
19.1.4	Solution of Converter Voltage Conversion Ratio $M = V/V_g$	714
19.2	Examples	715
19.2.1	Series Resonant DC-DC Converter Example	715
19.2.2	Subharmonic Modes of the Series Resonant Converter	717
19.2.3	Parallel Resonant DC-DC Converter Example	718
19.3	Soft Switching	721
19.3.1	Operation of the Full Bridge Below Resonance: Zero-Current Switching	722
19.3.2	Operation of the Full Bridge Above Resonance: Zero-Voltage Switching	723
19.4	Load-Dependent Properties of Resonant Converters	726
19.4.1	Inverter Output Characteristics	727
19.4.2	Dependence of Transistor Current on Load	729
19.4.3	Dependence of the ZVS/ZCS Boundary on Load Resistance	734

19.4.4	Another Example	737
19.5	Exact Characteristics of the Series and Parallel Resonant Converters	740
19.5.1	Series Resonant Converter	740
19.5.2	Parallel Resonant Converter	748
19.6	Summary of Key Points	752
	References	752
	Problems	755
20	Soft Switching	761
20.1	Soft-Switching Mechanisms of Semiconductor Devices	762
20.1.1	Diode Switching	763
20.1.2	MOSFET Switching	765
20.1.3	IGBT Switching	768
20.2	The Zero-Current-Switching Quasi-Resonant Switch Cell	770
20.2.1	Waveforms of the Half-Wave ZCS Quasi-Resonant Switch Cell	774
20.2.2	The Average Terminal Waveforms	779
20.2.3	The Full-Wave ZCS Quasi-Resonant Switch Cell	781
20.3	Resonant Switch Topologies	783
20.3.1	The Zero-Voltage-Switching Quasi-Resonant Switch	784
20.3.2	The Zero-Voltage-Switching Multi-Resonant Switch	787
20.3.3	Quasi-Square-Wave Resonant Switches	790
20.4	Soft Switching in PWM Converters	791
20.4.1	The Zero-Voltage Transition Full-Bridge Converter	794
20.4.2	The Auxiliary Switch Approach	796
20.4.3	Auxiliary Resonant Commutated Pole	797
20.5	Summary of Key Points	798
	References	800
	Problems	803
Appendices		803
Appendix A RMS Values of Commonly-Observed Converter Waveforms		805
A.1	Some Common Waveforms	805
A.2	General Piecewise Waveform	809
Appendix B Simulation of Converters		813
B.1	Averaged Switch Models for Continuous Conduction Mode	815
B.1.1	Basic CCM Averaged Switch Model	815
B.1.2	CCM Subcircuit Model that Includes Switch Conduction Losses	816
B.1.3	Example: SEPIC DC Conversion Ratio and Efficiency	818
B.1.4	Example: Transient Response of a Buck-Boost Converter	819
B.2	Combined CCM/DCM Averaged Switch Model	822
B.2.1	Example: SEPIC Frequency Responses	825
B.2.2	Example: Loop Gain and Closed-Loop Responses of a Buck Voltage Regulator	827

B.2.3	Example: DCM Boost Rectifier	832
B.3	Current Programmed Control	834
B.3.1	Current Programmed Mode Model for Simulation	834
B.3.2	Example: Frequency Responses of a Buck Converter with Current Programmed Control	837
	References	840
Appendix C Middlebrook's Extra Element Theorem		843
C.1	Basic Result	843
C.2	Derivation	846
C.3	Discussion	849
C.4	Examples	850
C.4.1	A Simple Transfer Function	850
C.4.2	An Unmodeled Element	855
C.4.3	Addition of an Input Filter to a Converter	857
C.4.4	Dependence of Transistor Current on Load in a Resonant Inverter	859
	References	861
Appendix D Magnetics Design Tables		863
D.1	Pot Core Data	864
D.2	EE Core Data	865
D.3	EC Core Data	866
D.4	ETD Core Data	866
D.5	PQ Core Data	867
D.6	American Wire Gauge Data	868
	References	869
Index		871