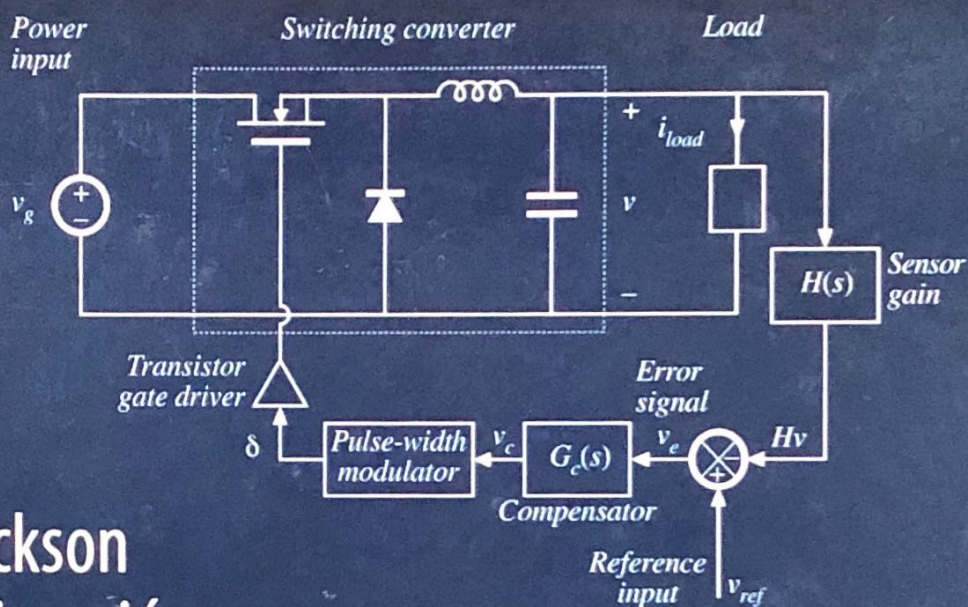




Robert W. Erickson
Dragan Maksimović

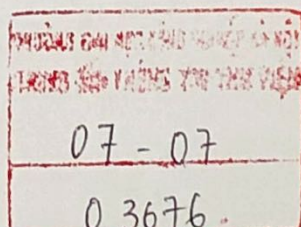
Fundamentals of Power Electronics

Third Edition

Robert W. Erickson • Dragan Maksimović

Fundamentals of Power Electronics

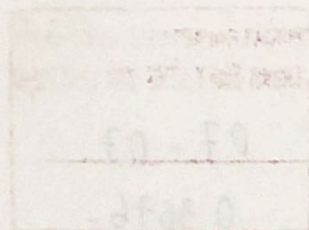
Third Edition



 Springer

Robert W. Erickson
Department of Electrical, Computer,
and Energy Engineering
University of Colorado Boulder
Boulder, CO, USA

Dragan Maksimović
Department of Electrical, Computer,
and Energy Engineering
University of Colorado Boulder
Boulder, CO, USA



ISBN 978-3-030-43879-1 ISBN 978-3-030-43881-4 (eBook)
<https://doi.org/10.1007/978-3-030-43881-4>

1st edition: © Springer Science+Business Media Dordrecht 1997

2nd edition: © Kluwer Academic Publishers 2001

© Springer Nature Switzerland AG 2020

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

*Dedicated to
Linda, William, and Richard
Lidija, Filip, Nikola, and Stevan*

The purpose of this book and its companion volume was to provide an accessible, yet comprehensive, survey of the history and development of the field of international law. The book is intended to be a useful resource for students and scholars alike, and to provide a foundation for further study and research. The book is organized into two main parts: the first part covers the history and development of international law, and the second part covers the current state of the field and its future prospects. The book is written in a clear and concise style, and is intended to be accessible to a wide range of readers.

In writing this book, I have been greatly assisted by the many people who have provided me with support and encouragement. I am particularly grateful to my family, and to my colleagues and friends who have provided me with valuable feedback and suggestions. I am also grateful to the many people who have provided me with access to the many resources and materials that I have used in writing this book. I hope that this book will be a useful resource for many people, and that it will provide a foundation for further study and research in the field of international law.

The book is organized into two main parts: the first part covers the history and development of international law, and the second part covers the current state of the field and its future prospects. The first part is organized into three main sections: the first section covers the history of international law from its origins to the present day; the second section covers the development of international law from its origins to the present day; and the third section covers the current state of the field and its future prospects. The second part is organized into two main sections: the first section covers the current state of the field and its future prospects, and the second section covers the current state of the field and its future prospects. The book is written in a clear and concise style, and is intended to be accessible to a wide range of readers.

The book is written in a clear and concise style, and is intended to be accessible to a wide range of readers. The book is organized into two main parts: the first part covers the history and development of international law, and the second part covers the current state of the field and its future prospects. The first part is organized into three main sections: the first section covers the history of international law from its origins to the present day; the second section covers the development of international law from its origins to the present day; and the third section covers the current state of the field and its future prospects. The second part is organized into two main sections: the first section covers the current state of the field and its future prospects, and the second section covers the current state of the field and its future prospects.

The book is written in a clear and concise style, and is intended to be accessible to a wide range of readers. The book is organized into two main parts: the first part covers the history and development of international law, and the second part covers the current state of the field and its future prospects. The first part is organized into three main sections: the first section covers the history of international law from its origins to the present day; the second section covers the development of international law from its origins to the present day; and the third section covers the current state of the field and its future prospects. The second part is organized into two main sections: the first section covers the current state of the field and its future prospects, and the second section covers the current state of the field and its future prospects.

Contents

1	Introduction	1
1.1	Introduction to Power Processing	1
1.2	Several Applications of Power Electronics	8
1.3	Elements of Power Electronics	10

Part I Converters in Equilibrium

2	Principles of Steady-State Converter Analysis	15
2.1	Introduction	15
2.2	Volt-Second and Charge Balance, Small-Ripple Approximation	18
2.3	Boost Converter Example	24
2.4	Ćuk Converter Example	30
2.5	Estimating the Output Voltage Ripple in Converters Containing Two-Pole Low-Pass Filters	35
2.6	Summary of Key Points	37
	Problems	38
3	Steady-State Equivalent Circuit Modeling, Losses, and Efficiency	43
3.1	The DC Transformer Model	43
3.2	Inclusion of Inductor Copper Loss	46
3.3	Construction of Equivalent Circuit Model	49
3.3.1	Inductor Voltage Equation	50
3.3.2	Capacitor Current Equation	50
3.3.3	Complete Circuit Model	51
3.3.4	Efficiency	52
3.4	How to Obtain the Input Port of the Model	54
3.5	Example: Inclusion of Semiconductor Conduction Losses in the Boost Converter Model	56
3.6	Summary of Key Points	60
	Problems	61

4	Switch Realization	67
4.1	Switch Applications	69
4.1.1	Single-Quadrant Switches	69
4.1.2	Current-Bidirectional Two-Quadrant Switches	72
4.1.3	Voltage-Bidirectional Two-Quadrant Switches	75
4.1.4	Four-Quadrant Switches	76
4.1.5	Synchronous Rectifiers	78
4.2	Introduction to Power Semiconductors	79
4.2.1	Breakdown Voltage, Forward Voltage, and Switching Speed	79
4.2.2	Transistor Switching Loss with Clamped Inductive Load	80
4.3	The Power Diode	82
4.3.1	Introduction to Power Diodes	82
4.3.2	Discussion: Power Diodes	87
4.3.3	Modeling Diode-Induced Switching Loss	90
4.3.4	Boost Converter Example	94
4.4	Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)	99
4.4.1	Introduction to the Power MOSFET	99
4.4.2	Wide-Bandgap FETs	103
4.4.3	MOSFET Gate Drivers	107
4.5	Minority-Carrier Transistors	111
4.5.1	Bipolar Junction Transistor (BJT)	111
4.5.2	Insulated-Gate Bipolar Transistor (IGBT)	115
4.5.3	Thyristors (SCR, GTO)	119
4.6	Additional Sources of Switching Loss	122
4.6.1	Device Capacitances, and Leakage, Package, and Stray Inductances	122
4.6.2	Inducing Switching Loss in Other Elements	124
4.6.3	Efficiency vs. Switching Frequency	126
4.7	Summary of Key Points	126
	Problems	128
5	The Discontinuous Conduction Mode	135
5.1	Origin of the Discontinuous Conduction Mode, and Mode Boundary	135
5.2	Analysis of the Conversion Ratio $M(D, K)$	140
5.3	Boost Converter Example	145
5.4	Summary of Results and Key Points	152
	Problems	154
6	Converter Circuits	163
6.1	Circuit Manipulations	164
6.1.1	Inversion of Source and Load	164
6.1.2	Cascade Connection of Converters	166
6.1.3	Rotation of Three-Terminal Cell	169
6.1.4	Differential Connection of the Load	170
6.2	A Short List of Converters	174
6.3	Transformer Isolation	178
6.3.1	Full-Bridge and Half-Bridge Isolated Buck Converters	181
6.3.2	Forward Converter	187

6.3.3	Push-Pull Isolated Buck Converter	192
6.3.4	Flyback Converter	194
6.3.5	Boost-Derived Isolated Converters	198
6.3.6	Isolated Versions of the SEPIC and the Ćuk Converter	201
6.4	Summary of Key Points	203
	Problems	205

Part II Converter Dynamics and Control

7	AC Equivalent Circuit Modeling	215
7.1	Introduction	215
7.2	The Basic AC Modeling Approach	220
7.2.1	Averaging the Inductor and Capacitor Waveforms	221
7.2.2	The Average Inductor Voltage and the Small-Ripple Approximation...	222
7.2.3	Discussion of the Averaging Approximation	223
7.2.4	Averaging the Capacitor Waveforms	225
7.2.5	The Average Input Current	226
7.2.6	Perturbation and Linearization	227
7.2.7	Construction of the Small-Signal Equivalent Circuit Model	230
7.2.8	Discussion of the Perturbation and Linearization Step	232
7.2.9	Results for Several Basic Converters	233
7.2.10	Example: A Nonideal Flyback Converter	234
7.3	Modeling the Pulse-Width Modulator	242
7.4	The Canonical Circuit Model	245
7.4.1	Development of the Canonical Circuit Model	245
7.4.2	Example: Manipulation of the Buck-Boost Converter Model into Canonical Form	248
7.4.3	Canonical Circuit Parameter Values for Some Common Converters ...	250
7.5	State-Space Averaging	251
7.5.1	The State Equations of a Network	252
7.5.2	The Basic State-Space Averaged Model	255
7.5.3	Discussion of the State-Space Averaging Result	256
7.5.4	Example: State-Space Averaging of a Nonideal Buck-Boost Converter	259
7.5.5	Example: State-Space Averaging of a Boost Converter with ESR	264
7.6	Summary of Key Points	271
	Problems	272
8	Converter Transfer Functions	277
8.1	Review of Bode Plots	279
8.1.1	Single-Pole Response	281
8.1.2	Single Zero Response	287
8.1.3	Right Half-Plane Zero	288
8.1.4	Frequency Inversion	289
8.1.5	Combinations	290
8.1.6	Quadratic Pole Response: Resonance	294
8.1.7	The Low- Q Approximation	298

8.1.8	The High- Q Approximation	301
8.1.9	Approximate Roots of an Arbitrary-Degree Polynomial	304
8.2	Analysis of Converter Transfer Functions	309
8.2.1	Example: Transfer Functions of the Buck-Boost Converter	309
8.2.2	Transfer Functions of Some Basic CCM Converters	315
8.2.3	Physical Origins of the RHP Zero in Converters	316
8.3	Graphical Construction of Impedances and Transfer Functions	317
8.3.1	Series Impedances: Addition of Asymptotes	318
8.3.2	Series Resonant Circuit Example	320
8.3.3	Parallel Impedances: Inverse Addition of Asymptotes	322
8.3.4	Parallel Resonant Circuit Example	323
8.3.5	Voltage Divider Transfer Functions: Division of Asymptotes	325
8.4	Graphical Construction of Converter Transfer Functions	327
8.5	Measurement of AC Transfer Functions and Impedances	332
8.6	Summary of Key Points	336
	Problems	337
9	Controller Design	347
9.1	Introduction	347
9.2	Effect of Negative Feedback on the Network Transfer Functions	350
9.2.1	Feedback Reduces the Transfer Functions from Disturbances to the Output	351
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	353
9.3	Construction of $1/(1 + T)$ and $T/(1 + T)$	353
9.4	Stability	358
9.4.1	The Phase Margin Test	359
9.4.2	The Nyquist Stability Criterion	360
9.4.3	The Relationship Between Phase Margin and Closed-Loop Damping Factor	370
9.4.4	Transient Response vs. Damping Factor	373
9.4.5	Load Step Response vs. Damping Factor	375
9.5	Regulator Design	376
9.5.1	Lead (PD) compensator	377
9.5.2	Lag (PI) Compensator	380
9.5.3	Combined (PID) Compensator	382
9.5.4	Design Example	383
9.6	Measurement of Loop Gains	392
9.6.1	Voltage Injection	394
9.6.2	Current Injection	396
9.6.3	Measurement of Unstable Systems	397
9.7	Summary of Key Points	398
	Problems	399

Part III Magnetics

10 Basic Magnetism Theory	409
10.1 Review of Basic Magnetism	409
10.1.1 Basic Relationships	409
10.1.2 Magnetic Circuits	415
10.2 Transformer Modeling	418
10.2.1 The Ideal Transformer	419
10.2.2 The Magnetizing Inductance	420
10.2.3 Leakage Inductances	421
10.3 Loss Mechanisms in Magnetic Devices	423
10.3.1 Core Loss	423
10.3.2 Low-Frequency Copper Loss	426
10.4 Eddy Currents in Winding Conductors	426
10.4.1 Introduction to the Skin and Proximity Effects	426
10.4.2 Leakage Flux in Windings	431
10.4.3 Foil Windings and Layers	432
10.4.4 Power Loss in a Layer	434
10.4.5 Example: Power Loss in a Transformer Winding	436
10.4.6 Interleaving the Windings	438
10.4.7 PWM Waveform Harmonics	441
10.5 Several Types of Magnetic Devices, Their B - H Loops, and Core vs. Copper Loss	444
10.5.1 Filter Inductor	444
10.5.2 AC Inductor	446
10.5.3 Transformer	447
10.5.4 Coupled Inductor	448
10.5.5 Flyback Transformer	449
10.6 Summary of Key Points	450
Problems	451
11 Inductor Design	459
11.1 Filter Inductor Design Constraints	459
11.1.1 Maximum Flux Density	461
11.1.2 Inductance	462
11.1.3 Winding Area	462
11.1.4 Winding Resistance	463
11.1.5 The Core Geometrical Constant K_g	463
11.2 The K_g Method: A First-Pass Design	464
11.3 Multiple-Winding Magnetism Design via the K_g Method	465
11.3.1 Window Area Allocation	465
11.3.2 Coupled Inductor Design Constraints	470
11.3.3 First-Pass Design Procedure	472
11.4 Examples	474
11.4.1 Coupled Inductor for a Two-Output Forward Converter	474

11.4.2 CCM Flyback Transformer	476
11.5 Summary of Key Points	481
Problems	482
12 Transformer Design	485
12.1 Transformer Design: Basic Constraints	486
12.1.1 Core Loss	486
12.1.2 Flux Density	487
12.1.3 Copper Loss	488
12.1.4 Total Power Loss vs. ΔB	488
12.1.5 Optimum Flux Density	490
12.2 A First-Pass Transformer Design Procedure	490
12.2.1 Procedure	492
12.3 Examples	492
12.3.1 Example 1: Single-Output Isolated Ćuk Converter	496
12.3.2 Example 2: Multiple-Output Full-Bridge Buck Converter	499
12.4 AC Inductor Design	500
12.4.1 Outline of Derivation	501
12.4.2 First-Pass AC Inductor Design Procedure	502
12.5 Summary	502
Problems	502

Part IV Advanced Modeling, Analysis, and Control Techniques

13 Techniques of Design-Oriented Analysis: The Feedback Theorem	509
13.1 Introduction to Part IV	509
13.2 The Feedback Theorem	510
13.2.1 Basic Result	510
13.2.2 Derivation	513
13.3 Example: Op Amp PD Compensator Circuit	519
13.4 Example: Closed-Loop Regulator	528
13.5 Summary of Key Points	540
Problems	540
14 Circuit Averaging, Averaged Switch Modeling, and Simulation	547
14.1 Circuit Averaging and Averaged Switch Modeling	548
14.1.1 Obtaining a Time-Invariant Circuit	550
14.1.2 Circuit Averaging	550
14.1.3 Perturbation and Linearization	552
14.1.4 Indirect Power	555
14.2 Additional Configurations of Switch Networks	558
14.3 Simulation of Averaged Circuit Models	566
14.3.1 Simulation Model of the Ideal CCM Averaged Switch Network	568
14.3.2 Averaged Switch Modeling and Simulation of Conduction Losses	569
14.3.3 Inclusion of Switch Conduction Losses in Simulations	571
14.3.4 Example: SEPIC DC Conversion Ratio and Efficiency	572

14.3.5 Example: Transient Response of a Buck–Boost Converter	575
14.4 Summary of Key Points	579
Problems	580
15 Equivalent Circuit Modeling of the Discontinuous Conduction Mode	585
15.1 Introduction to DCM Converter Dynamics	586
15.2 DCM Averaged Switch Model	589
15.3 Small-Signal AC Modeling of the DCM Switch Network	600
15.3.1 Example: Control-to-Output Frequency Response of a DCM Boost Converter	607
15.4 Combined CCM/DCM Averaged Switch Simulation Model	608
15.4.1 Example: CCM/DCM SEPIC Frequency Responses	611
15.4.2 Example: Loop Gain and Closed-Loop Responses of a Buck Voltage Regulator	614
15.5 High-Frequency Dynamics of Converters in DCM	618
15.6 Summary of Key Points	622
Problems	622
16 Techniques of Design-Oriented Analysis: Extra Element Theorems	625
16.1 Extra Element Theorem	625
16.1.1 Basic Result	626
16.1.2 Derivation	628
16.1.3 Discussion	631
16.2 EET Examples	632
16.2.1 A Simple Transfer Function	632
16.2.2 An Unmodeled Element	637
16.2.3 SEPIC Example	640
16.2.4 Damping the SEPIC Internal Resonances	644
16.3 The n -Extra Element Theorem	648
16.3.1 Introduction to the n -EET	649
16.3.2 Procedure for DC-Referenced Functions	653
16.4 n -EET Examples	654
16.4.1 Two-Section L – C Filter	654
16.4.2 Bridge-T Filter Example	658
16.5 Frequency Inversion	661
16.5.1 Example: Damped Input Filter	662
16.5.2 Other Special Cases	668
Problems	669
17 Input Filter Design	675
17.1 Introduction	675
17.1.1 Conducted EMI	675
17.1.2 The Input Filter Design Problem	676
17.2 Effect of an Input Filter on Converter Transfer Functions	679
17.2.1 Modified Transfer Functions	679
17.2.2 Discussion	682
17.2.3 Impedance Inequalities	684

17.3 Buck Converter Example	685
17.3.1 Effect of Undamped Input Filter	686
17.3.2 Damping the Input Filter	691
17.4 Design of a Damped Input Filter	693
17.4.1 R_f - C_b Parallel Damping	694
17.4.2 R_f - L_b Parallel Damping	696
17.4.3 R_f - L_b Series Damping	698
17.4.4 Cascading Filter Sections	699
17.4.5 Example: Two Stage Input Filter	700
17.5 Stability Criteria	704
17.5.1 Modified Phase Margin	706
17.5.2 Closed-Loop Input Impedance	711
17.5.3 Discussion	720
17.6 Summary of Key Points	720
Problems	721
18 Current-Programmed Control	725
18.1 A Simple First-Order Model	728
18.1.1 Simple Model via Algebraic Approach: Buck-Boost Example	729
18.1.2 Averaged Switch Modeling	733
18.2 Oscillation for $D > 0.5$	738
18.3 A More Accurate Model	746
18.3.1 Current-Programmed Controller Model	746
18.3.2 Small-Signal Averaged Model	748
18.4 Current-Programmed Transfer Functions	752
18.4.1 Discussion	754
18.4.2 Current-Programmed Transfer Functions of the CCM Buck Converter ..	755
18.4.3 Results for Basic Converters	758
18.4.4 Addition of an Input Filter to a Current-Programmed Converter	760
18.5 Simulation of CPM Controlled Converters	763
18.5.1 Simulation Model for CPM Controlled Converters in CCM	764
18.5.2 Combined CCM/DCM Simulation Model	765
18.5.3 Simulation Example: Frequency Responses of a Buck Converter with Current-Programmed Control	766
18.6 Voltage Feedback Loop Around a Current-Programmed Converter	769
18.6.1 System Model	769
18.6.2 Design Example	770
18.7 High-Frequency Dynamics of Current-Programmed Converters	772
18.7.1 Sampled-Data Model	773
18.7.2 First-Order Approximation	776
18.7.3 Second-Order Approximation	778
18.8 Discontinuous Conduction Mode	779
18.9 Average Current-Mode Control	786
18.9.1 System Model and Transfer Functions	788
18.9.2 Design Example: ACM Controlled Boost Converter	791
18.10 Summary of Key Points	798
Problems	799

19 Digital Control of Switched-Mode Power Converters	805
19.1 Digital Control Loop	806
19.1.1 A/D and DPWM Quantization	807
19.1.2 Sampling and Delays in the Control Loop	810
19.2 Introduction to Discrete-Time Systems	812
19.2.1 Integration in Continuous Time and in Discrete Time	812
19.2.2 z -Transform and Frequency Responses of Discrete-Time Systems	814
19.2.3 Continuous Time to Discrete Time Mapping	817
19.3 Discrete-Time Compensator Design	822
19.3.1 Design Procedure	823
19.3.2 Design Example	824
19.4 Digital Controller Implementation	827
19.4.1 Discrete-Time Compensator Realization	828
19.4.2 Quantization Effects, Digital Pulse-Width Modulators and A/D Converters	830
19.5 Summary of Key Points	838
Problems	838

Part V Modern Rectifiers and Power System Harmonics

20 Power and Harmonics in Nonsinusoidal Systems	849
20.1 Average Power	850
20.2 Root-Mean-Square (RMS) Value of a Waveform	853
20.3 Power Factor	854
20.3.1 Linear Resistive Load, Nonsinusoidal Voltage	854
20.3.2 Nonlinear Dynamic Load, Sinusoidal Voltage	855
20.4 Power Phasors in Sinusoidal Systems	858
20.5 Harmonic Currents in Three-Phase Systems	859
20.5.1 Harmonic Currents in Three-Phase Four-Wire Networks	859
20.5.2 Harmonic Currents in Three-Phase Three-Wire Networks	861
20.5.3 Harmonic Current Flow in Power Factor Correction Capacitors	862
Problems	863
21 Pulse-Width Modulated Rectifiers	867
21.1 Properties of the Ideal Rectifier	868
21.2 Realization of a Near-Ideal Rectifier	870
21.2.1 CCM Boost Converter	872
21.2.2 Simulation Example: DCM Boost Rectifier	876
21.2.3 DCM Flyback Converter	878
21.3 Control of the Current Waveform	880
21.3.1 Average Current Control	881
21.3.2 Current-Programmed Control	886
21.3.3 Critical Conduction Mode and Hysteretic Control	889
21.3.4 Nonlinear Carrier Control	892
21.4 Single-Phase Converter Systems Incorporating Ideal Rectifiers	895
21.4.1 Energy Storage	895

21.4.2 Modeling the Outer Low-Bandwidth Control System	900
21.5 RMS Values of Rectifier Waveforms	905
21.5.1 Boost Rectifier Example	906
21.5.2 Comparison of Single-Phase Rectifier Topologies	908
21.6 Modeling Losses and Efficiency in CCM High-Quality Rectifiers	910
21.6.1 Expression for Controller Duty Cycle $d(t)$	913
21.6.2 Expression for the DC Load Current	913
21.6.3 Solution for Converter Efficiency η	915
21.6.4 Design Example	916
21.7 Ideal Three-Phase Rectifiers	917
21.8 Summary of Key Points	923
Problems	925

Part VI Resonant Converters

22 Resonant Conversion	933
22.1 Sinusoidal Analysis of Resonant Converters	938
22.1.1 Controlled Switch Network Model	938
22.1.2 Modeling the Rectifier and Capacitive Filter Networks	940
22.1.3 Resonant Tank Network	942
22.1.4 Solution of Converter Voltage Conversion Ratio $M = V/V_g$	943
22.2 Examples	944
22.2.1 Series Resonant DC-DC Converter Example	944
22.2.2 Subharmonic Modes of the Series Resonant Converter	946
22.2.3 Parallel Resonant DC-DC Converter Example	947
22.3 Soft Switching	951
22.3.1 Operation of the Full Bridge Below Resonance: Zero-Current Switching	951
22.3.2 Operation of the Full-Bridge Above Resonance: Zero-Voltage Switching	954
22.4 Load-Dependent Properties of Resonant Converters	957
22.4.1 Inverter Output Characteristics	958
22.4.2 Dependence of Transistor Current on Load	960
22.4.3 Dependence of the ZVS/ZCS Boundary on Load Resistance	965
22.4.4 Another Example	967
22.4.5 LLC Example	972
22.4.6 Results for Basic Tank Networks	973
22.5 Exact Characteristics of the Series and Parallel Resonant Converters	976
22.5.1 Series Resonant Converter	977
22.5.2 Parallel Resonant Converter	983
22.6 Summary of Key Points	988
Problems	988

23 Soft Switching	995
23.1 Soft-Switching Mechanisms of Semiconductor Devices	996
23.1.1 Diode Switching	996
23.1.2 MOSFET Switching	1000
23.1.3 IGBT Switching	1003
23.2 The Zero-Current-Switching Quasi-Resonant Switch Cell	1003
23.2.1 Waveforms of the Half-Wave ZCS Quasi-Resonant Switch Cell	1005
23.2.2 The Average Terminal Waveforms	1009
23.2.3 The Full-Wave ZCS Quasi-Resonant Switch Cell	1014
23.3 Resonant Switch Topologies	1016
23.3.1 The Zero-Voltage-Switching Quasi-Resonant Switch	1017
23.3.2 The Zero-Voltage-Switching Multiresonant Switch	1019
23.3.3 Quasi-Square-Wave Resonant Switches	1020
23.4 Soft Switching in PWM Converters	1025
23.4.1 The Zero-Voltage Transition Full-Bridge Converter	1025
23.4.2 The Auxiliary Switch Approach	1029
23.4.3 Auxiliary Resonant Commutated Pole	1031
23.5 Summary of Key Points	1033
Problems	1034

Appendices

RMS Values of Commonly Observed Converter Waveforms	1037
A.1 Some Common Waveforms	1037
A.2 General Piecewise Waveform	1040
Magnetics Design Tables	1043
B.1 Pot Core Data	1044
B.2 EE Core Data	1045
B.3 EC Core Data	1046
B.4 ETD Core Data	1047
B.5 PQ Core Data	1048
B.6 American Wire Gauge Data	1049
References	1051
Index	1071



CPSIA information can be obtained
at www.ICGtesting.com
Printed in the USA
LVHW060811090321
680965LV00001B/1



Robert W. Erickson · Dragan Maksimović

Fundamentals of Power Electronics

Third Edition

Fundamentals of Power Electronics, Third Edition, is an up-to-date and authoritative text and reference book on power electronics. This new edition retains the original objective and philosophy of focusing on the fundamental principles, models, and technical requirements needed for designing practical power electronic systems while adding a wealth of new material. Improved features of this new edition include: new material on switching loss mechanisms and their modeling; wide bandgap semiconductor devices; a more rigorous treatment of averaging; explanation of the Nyquist stability criterion; incorporation of the Tan and Middlebrook model for current programmed control; a new chapter on digital control of switching converters; major new chapters on advanced techniques of design-oriented analysis including feedback and extra element theorems; average current control; new material on input filter design; new treatment of averaged switch modeling, simulation, and indirect power; and sampling effects in discontinuous conduction mode and current programmed mode.

Fundamentals of Power Electronics, Third Edition, is intended for use in introductory power electronics courses and related fields for both senior undergraduates and first-year graduate students interested in converter circuits and electronics, control systems, and magnetic and power systems. It will also be an invaluable reference for professionals working in power electronics, power conversion, and analog and digital electronics.

- Includes an increased number of end of chapter problems;
- Updated and reorganized, including three completely new chapters;
- Includes key principles and a rigorous treatment of topics.

ISBN 978-3-030-43879-1



9 783030 438791

► [springer.com](https://www.springer.com)

PHI CON CH
12/01

15/27

TRƯỜNG ĐẠI HỌC CÔNG NGHỆ
TRUNG TÂM THÔNG TIN



Mã sách: 070703676