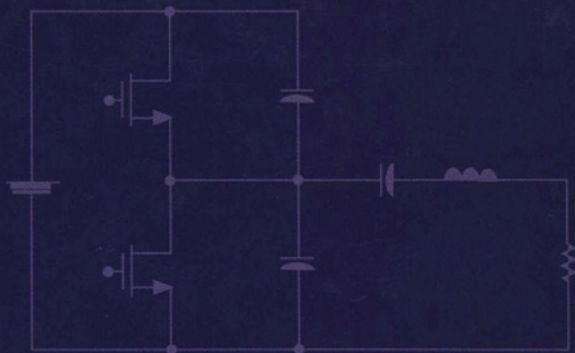
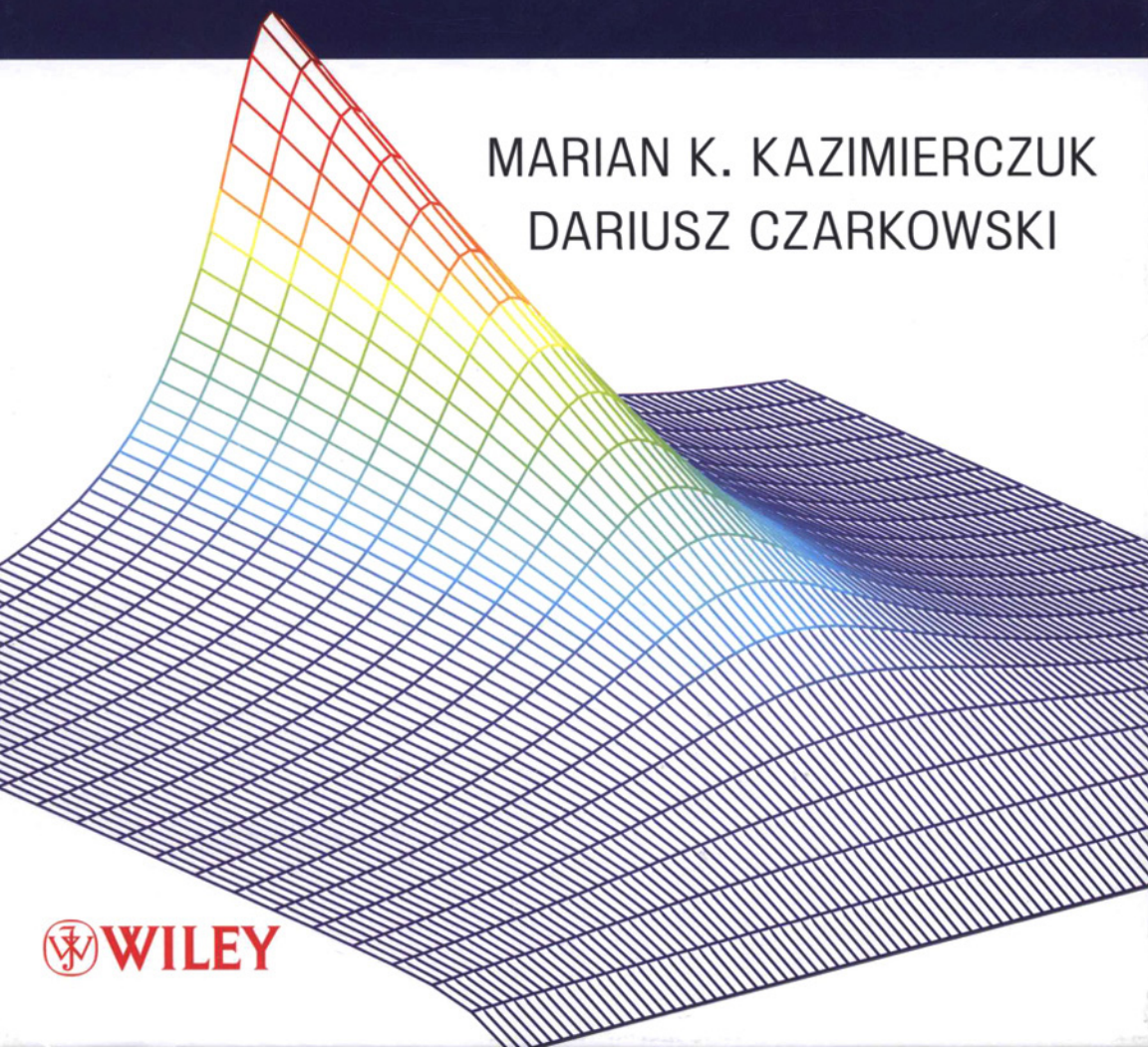


SECOND EDITION



RESONANT POWER CONVERTERS

MARIAN K. KAZIMIERCZUK
DARIUSZ CZARKOWSKI



 **WILEY**

RESONANT POWER CONVERTERS

RESONANT POWER CONVERTERS

Second Edition

Marian K. Kazimierczuk
Wright State University

Dariusz Czarkowski
Polytechnic Institute of New York University



A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Kazimierczuk, Marian.

Resonant power converters / Marian K. Kazimierczuk, Dariusz Czarkowski. — 2nd ed.
p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-90538-8 (cloth)

1. Electric current converters. 2. Electric resonators. 3. Power electronics. I. Czarkowski, Dariusz. II. Title.

TK7872.C8K39 2010

621.3815'322—dc22

2010031082

Printed in Singapore

10 9 8 7 6 5 4 3 2 1

To Alicja, Anna, Katarzyna, and Andrzej
To Hanna, Barbara, and Bartosz

vii

2.3.6	Input Resistance	16
2.3.7	Voltage Transfer Function	16
2.3.8	Ripple Voltage	18
2.4	Class D Transformer Center-Tapped Rectifier	20
2.4.1	Currents and Voltages	20
2.4.2	Power Factor	22
2.4.3	Power-Output Capability	23
2.4.4	Efficiency	24
2.4.5	Input Resistance	25
2.4.6	Voltage Transfer Function	25
2.4.7	Ripple Voltage	26
2.5	Class D Bridge Rectifier	28
2.5.1	Power-Output Capability	29
2.5.2	Efficiency	31
2.5.3	Input Resistance	31
2.5.4	Voltage Transfer Function	31
2.6	Effects of Equivalent Series Resistance and Equivalent Series Inductance	34
2.7	Synchronous Rectifiers	38
2.7.1	Gate-Drive Power	39
2.7.2	Efficiency	40
2.7.3	Input Resistance	40
2.7.4	Voltage Transfer Function	40
2.8	Summary	42
2.9	References	43
2.10	Review Questions	44
2.11	Problems	45
3	Class D Voltage-Driven Rectifiers	47
3.1	Introduction	47
3.2	Assumptions	47
3.3	Class D Half-Wave Rectifier	48
3.3.1	Currents and Voltages	48
3.3.2	Power Factor	50
3.3.3	Current and Voltage Stresses	51
3.3.4	Efficiency	51
3.3.5	Input Resistance	53

3.3.6	Voltage Transfer Function	53
3.3.7	Ripple Voltage	55
3.4	Class D Transformer Center-Tapped Rectifier	56
3.4.1	Currents and Voltages	56
3.4.2	Power Factor	57
3.4.3	Efficiency	59
3.4.4	Input Resistance	60
3.4.5	Voltage Transfer Function	60
3.4.6	Ripple Voltage	61
3.5	Class D Bridge Rectifier	62
3.6	Synchronous Rectifiers	66
3.6.1	Efficiency	66
3.6.2	Input Resistance	67
3.6.3	Voltage Transfer Function	67
3.7	Summary	69
3.8	References	69
3.9	Review Questions	71
3.10	Problems	71
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

4.6	Review Questions	108
4.7	Problems	108
5	Class E Low di/dt Rectifiers	109
5.1	Introduction	109
5.2	Low 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 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

7.6	Design Example	225
7.7	Full-Bridge Parallel-Resonant Inverter	227
7.7.1	Voltage Transfer Function	227
7.7.2	Currents, Voltages, and Powers	228
7.7.3	Efficiency	230
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
8.3.1	Assumptions	237
8.3.2	Resonant Circuit	238
8.3.3	Voltage Transfer Function	242
8.3.4	Energy Parameters	244
8.3.5	Short-Circuit and Open-Circuit Operation	253
8.4	Design Example	254
8.5	Full-Bridge Series-Parallel-Resonant Inverter	257
8.5.1	Voltage Transfer Function	257
8.5.2	Currents and Voltages	258
8.5.3	Powers and Efficiency	259
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
9.3.1	Assumptions	264
9.3.2	Boundary Between Capacitive and Inductive Load	264
9.3.3	Voltage Transfer Function	269

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

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 $\pi 1a$	354
12.6.3	Resonant Circuit $\pi 2a$	357
12.6.4	Resonant Circuit $\pi 1b$	358
12.6.5	Resonant Circuit $\pi 4a$	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

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

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

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

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