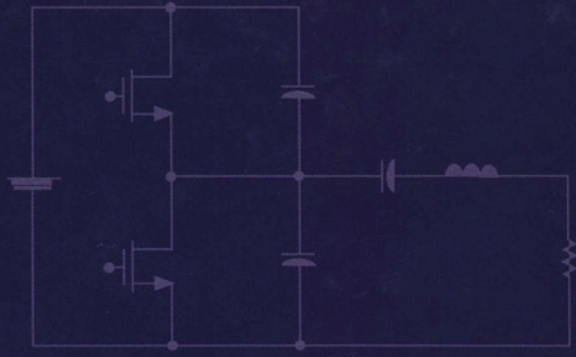


SECOND EDITION



# RESONANT POWER CONVERTERS

MARIAN K. KAZIMIERCZUK  
DARIUSZ CZARKOWSKI

A 3D surface plot with a grid pattern, colored with a rainbow gradient from red at the peak to blue at the base. It is positioned in the lower half of the cover, behind the authors' names.

 **WILEY**



# RESONANT POWER CONVERTERS



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Second Edition

**Marian K. Kazimierczuk**  
Wright State University

**Dariusz Czarkowski**  
Polytechnic Institute of New York University



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





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# PREFACE

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Energy is considered number one of 10 challenges facing humanity today. Energy processing is a large portion of energy technology. Power electronics is a branch of electrical and electronic engineering concerned with the analysis, simulation, design, manufacture, and application of switching-mode DC-DC power converters. Resonant power conversion is in the center of the renewable energy and energy harvesting technologies. This book is focused on the analysis and design of DC-AC resonant inverters, high-frequency rectifiers, and DC-DC resonant converters that are basic building blocks of various high-frequency, high-efficiency low-noise energy processors. The past two decades have initiated a revolution in and unprecedented growth of power electronics. Continuing advances in this area have resulted in DC and AC energy sources that are smaller, more efficient, lighter, less expensive, and more reliable than ever before. Power processors are widely used in the computer, telecommunication, instrumentation, automotive, aerospace, defense, and consumer industries. DC-DC converters are being used in power supplies to power practically all electronic circuits that contain active devices. The growing escalation in complexity of modern electronic systems is imposing challenging demands on the capabilities of circuit designers.

Many design problems encountered in a great diversity of products can be solved using the unique capabilities of resonant technology. Information on resonant power processors is scattered throughout many different technical journals, conference proceedings, and application notes. This volume brings the principles of resonant technology to students, scientists, and practicing design engineers. The state-of-the-art technology of high-frequency resonant power processors is covered in a systematic manner for the first time. The reader will be introduced to the topologies, characteristics, terminology, and mathematics of resonant converters. The

*fundamental-frequency component approach* is used in the analyses of DC-DC resonant converters. The book provides students and engineers with a sound understanding of existing high-frequency inverters, rectifiers, and DC-DC resonant converters and presents a general and easy-to-use tool of analysis and design of resonant power circuits. It is written in a clear, concise, and unambiguous style.

The text provides rigorous in-depth analysis to help the reader understand how and why the power converters are built as they are. The fundamental-frequency component method is used throughout the entire book. This approach leads to relatively simple closed-form analytic expressions for converter characteristics, which provides good insight into circuit operation and greatly simplifies the design process. Graphic representations of various characteristics are emphasized throughout the text because they provide a visual picture of circuit operation and often yield insights not readily obtained from purely algebraic treatments.

This book is intended as a textbook for senior-level and graduate students in electrical engineering and as a reference for practicing design engineers, researchers, and consultants in industry. The objective of the book is to develop in the reader the ability to analyze and design high-frequency power electronic circuits. A knowledge of network analysis, electronic circuits and devices, complex algebra, Fourier series, and Laplace transforms is required to handle the mathematics in this book. Numerous analysis and design examples are included throughout the textbook. An extensive list of references is provided in each chapter. Problems are placed at the end of each chapter. Answers to selected problems are given at the end of the book. Complete solutions for all problems are included in the *Solutions Manual*, which is available from the publisher for those instructors who adopt the book for their courses.

The book is divided into three parts: Part I, "Rectifiers," Part II, "Inverters," and Part III, "Converters."

High-frequency rectifiers are covered in Chapters 2 through 5. Chapter 2 deals with Class D current-driven rectifiers, and Chapter 3 is devoted to the study of Class D voltage-driven rectifiers. Each of these chapters contains analyses of three types of rectifiers, namely, the half-wave, transformer center-tapped, and bridge rectifiers. Chapter 4 presents two Class E low  $dv/dt$  rectifiers, whereas Chapter 5 deals with two Class E low  $di/dt$  rectifiers.

High-frequency resonant inverters are discussed in Chapters 6 through 14. The Class D series-resonant converter is thoroughly covered in Chapter 6. Many topics discussed in this chapter apply also to other resonant inverters presented in the following chapters. The Class D parallel-resonant inverter is the topic of Chapter 7. Chapters 8 and 9 discuss dual Class D series-parallel and Class D CLL resonant inverters, respectively. The Class D current-source inverter is covered in Chapter 10. Chapter 10 also discusses zero-voltage-switching techniques in resonant inverters. The Class D current-source inverter is covered in Chapter 11. An example of a constant-frequency phase-controlled Class D resonant inverter, namely, the single-capacitor phase-controlled resonant inverter is given in Chapter 12. The Class E resonant inverters are analyzed in Chapters 13 and 14. Chapter 13 deals with a zero-voltage-switching Class E inverter, and Chapter 14 presents a Class DE power inverter, which is a zero-current-switching Class E inverter.



Converters are studied in Part III, which ties together the material of Parts I and II. Resonant DC-DC converters that are a result of cascading resonant inverters with high-frequency rectifiers are presented in Chapters 15 through 22. Chapters 15 through 19 discuss converters with inverters presented in Chapters 6 through 10. Hence, Chapter 15 covers a Class D series-resonant converter, Chapter 16 presents a Class D parallel-resonant converter, Chapter 17 deals with a Class D series-parallel-resonant inverter, Chapter 18 gives an analysis of a Class D CLL resonant converter, and Chapter 19 discusses a Class D current-source converter. An example of matching a Class D inverter with a Class E rectifier that leads to a Class D inverter/Class E rectifier resonant converter is presented in Chapter 20. Chapter 21 gives an analysis of a single-capacitor phase-controlled resonant converter that belongs to a broad family of phase-controlled converters. Chapter 22 presents zero-voltage switching (ZVS) and zero-current switching (ZCS) quasi-resonant DC-DC power converters (QRCs), multiresonant DC-DC converters (MRCs), and zero-voltage-transition converters (ZVTs) and zero-current transition DC-DC converters (ZCTs). Chapter 23 contains modeling and control of resonant power converters.

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The authors invite the readers to contact them directly or through the publisher with comments and suggestions about this book.

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MARIAN K. KAZIMIERCZUK  
DARIUSZ CZARKOWSKI



## ABOUT THE AUTHORS

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**Marian K. Kazimierzuk** is Robert J. Kegerreis Distinguished Professor of Electrical Engineering at Wright State University, Dayton, Ohio, USA. He has received M.S., Ph.D., and D. Sci. degrees from the Department of Electronics, Technical University of Warsaw, Warsaw, Poland. He is the author of six books, 145 archival refereed journal papers, 175 conference papers, and seven patents. He is a Fellow of the IEEE. He received the Outstanding Teaching Award from the American Society for Engineering Education (ASEE) in 2008, National Professorship of Technical Sciences of Poland in 2009, and Southwestern Ohio Council for Higher Education (SOCHE) Award in 2010. His honors also include the Board of Trustees' Award, Brage Golding Distinguished Professor of Research Award, Outstanding Faculty Member Award, Excellence in Professional Service Award, and several college Excellence in Teaching Awards. His research interests are in the areas of power electronics, including resonant DC-DC power converters, PWM DC-DC power converters, modeling and controls, RF power amplifiers and oscillators, semiconductor power devices, high-frequency magnetic devices, renewable energy sources, and evanescent microwave microscopy. He has served as an Associate Editor of the *IEEE Transactions on Circuits and Systems*, *IEEE Transactions on Industrial Electronics*, *Journal of Circuits, Systems and Computers*, and *International Journal of Circuit Theory and Applications*.

**Dariusz Czarkowski** is an Associate Professor at the Department of Electrical and Computer Engineering, Polytechnic Institute of New York University, Brooklyn, NY, USA. He received an M.S. degree in electrical engineering from AGH University

of Science and Technology, Cracow, Poland, an M.S. degree in electrical engineering from Wright State University, Dayton, OH, and a Ph.D. degree in electrical engineering from the University of Florida, Gainesville, FL. His research interests are in the areas of power electronics and power systems. He has served as an Associate Editor of the *IEEE Transactions on Circuits and Systems* and *International Journal of Power and Energy Systems*.

# LIST OF SYMBOLS

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$C_{pR}$	Power-output capability of rectifier
$C$	Resonant capacitance
$C_c$	Coupling capacitance
$C_{ds}$	Drain-source capacitance of MOSFET
$C_{ds(25V)}$	Drain-source capacitance of MOSFET at $V_{DS} = 25$ V
$C_f$	Filter capacitance
$C_{fmin}$	Minimum value of $C_f$
$C_{gd}$	Gate-drain capacitance of MOSFET
$C_{gs}$	Gate-source capacitance of MOSFET
$C_{iss}$	MOSFET input capacitance at $V_{DS} = 0$ , $C_{iss} = C_{gs} + C_{gd}$
$C_{oss}$	MOSFET output capacitance at $V_{GD} = 0$ , $C_{oss} = C_{gs} + C_{ds}$
$C_o$	Transistor output capacitance
$C_{rss}$	MOSFET transfer capacitance, $C_{rss} = C_{gd}$
$C_s$	Equivalent series-resonant capacitance
$D_k$	$k$ th diode
$f$	Switching frequency
$f_o$	Resonant frequency
$f_p$	Frequency of pole of transfer function Corner frequency of output filter
$f_r$	Resonant frequency of $L$ - $C_s$ - $R_s$ circuit
$f_s$	Switching frequency
$f_z$	Frequency of zero of transfer function
$f_H$	Upper 3-dB frequency
$i$	Current through resonant circuit
$i_{cr}$	AC component of $i_{CR}$

$i_i$	AC current source
$i_o$	AC load current
$i_{Cf}$	Current through filter capacitance
$i_{CR}$	Current through the $C_f$ - $R_L$ circuit
$i_{Dk}$	Current through $k$ th diode
$i_R$	Input current of rectifier
$i_S$	Switch current
$i_{Sk}$	Current through $k$ th switch
$I_l$	Capacitor DC leakage current
$I_m$	Amplitude of $i$
$I_n$	$n$ th harmonic of the current to $R_L$ - $C_f$ - $r_C$ circuit
$I_{pk}$	Magnitude of cross-conduction current
$I_{rms}$	rms value of $i$
$I_{Cf(rms)}$	rms value of $i_{Cf}$
$I_{DM}$	Peak current of diode
$I_{Drms}$	Rms value of diode current
$I_D$	Average current through diode
$I_O$	DC output current
$I_{OFF}$	Current at which the transistor turns off
$I_{Omax}$	Maximum value of $I_O$
$I_{SM}$	Peak current of switch
$k$	Ratio $R_L/r_C$
$K_I$	Current transfer function of rectifier
$L$	Resonant inductance
$L_e$	Inductance of electrodes
$L_f$	Filter inductance
$L_{fmin}$	Minimum value of $L_f$
$L_t$	Inductance of terminations
$L_{ESL}$	Equivalent series inductance
$M$	DC-DC voltage transfer function of converter
$M_{VI}$	Voltage transfer function of inverter
$M_{VI}$	Amplitude of the voltage transfer function of inverter
$M_{Vs}$	Voltage transfer function of switches
$M_{Vr}$	Voltage transfer function of resonant circuit
$ M_{Vr} $	Magnitude of voltage transfer function of resonant circuit
$M_{VR}$	Voltage transfer function of rectifier
$n$	Transformer turns ratio
$P_i$	Input power of rectifier
$P_{Ic}$	AC conduction loss in filter inductor and capacitor
$P_r$	Conduction loss in $r$
$P_{rC}$	Conduction loss in filter capacitor
$P_{If}$	Average value of power loss associated with current fall time $t_f$
$P_{Ir}$	Average value of power loss associated with voltage rise time $t_r$
$P_{toff}$	Turn-off switching losses
$P_{ton}$	Turn-on switching losses