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RESONANT POWER CONVERTERS

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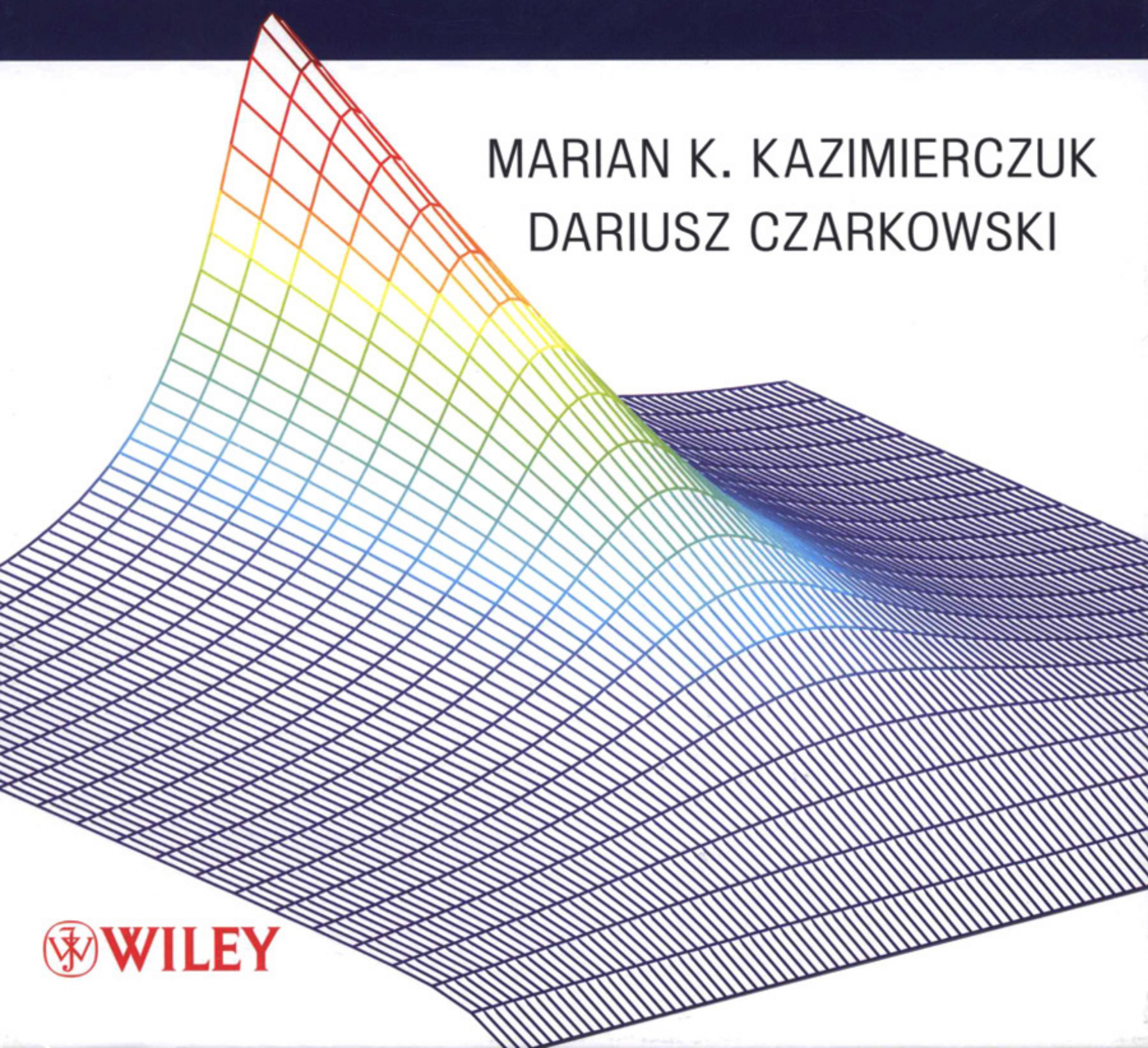

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To Alicja, Anna, Katarzyna, and Andrzej
To Hanna, Barbara, and Bartosz

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PREFACE

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.

We are pleased to express our gratitude to many individuals for their help during the preparation of this book. The first author had the privilege to teach numerous superb students at the Technical University of Warsaw, Warsaw, Poland, and at Wright State University, Dayton, Ohio. He would like to express his deepest appreciation to them for their research contributions, ideas, suggestions, and critical evaluations of the original manuscript. He also wishes to express his gratitude to Rafal Wojda for the MATLAB figures.

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

May 2010

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LIST OF SYMBOLS

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	kth 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 kth diode
i_R	Input current of rectifier
i_S	Switch current
i_{Sk}	Current through kth switch
I_l	Capacitor DC leakage current
I_m	Amplitude of i
I_n	nth 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
$\mathbf{M_{VI}}$	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_{lc}	AC conduction loss in filter inductor and capacitor
P_r	Conduction loss in r
P_{rC}	Conduction loss in filter capacitor
P_{tf}	Average value of power loss associated with current fall time t_f
P_{tr}	Average value of power loss associated with voltage rise time t_r
P_{toff}	Turn-off switching losses
P_{ton}	Turn-on switching losses