PHILIP T. KREIN

ELEMENTS OF POWER ELECTRONICS

INTERNATIONAL SECOND EDITION

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Elements of Power Electronics

In memory of

Theodore J. Krein

1929–2013

and

Evelyn Leech Krein

1930–2014

Preface

Power electronics drives the 21st century energy revolution by providing essential energy enablers for computer systems, portable digital products, solid-state lighting, transportation electrification, motor control, renewable and alternative resources, battery management, home appliances, energy-efficient buildings, and a host of other applications. Motors with integrated power electronics are commonplace today. Wind and solar energy use power electronics to interconnect with grid resources. Electric and hybrid cars and trucks reduce emissions and enhance fuel economy. Data centers and cloud computing resources draw an increasing share of global electricity. Power electronics is being integrated with digital and analog electronics in high-performance integrated circuits. The field has emerged as an important topic of study for students in electrical and computer engineering.

The international second edition of *Elements of Power Electronics* presents power electronics in its many facets. The objective is to lay a foundational base from which engineers can examine the field and practice its unusual and challenging design problems. It provides a framework that leads to families of conversion types and shows how various circuits branch out from this foundation. It includes supporting material about real devices and components, addressing issues that include magnetics design and applications of passive components. These issues are fundamental for practicing designers. Power semiconductors and other power devices have reached the point at which almost any application challenges can be addressed. Imaginative circuit designers have found a huge variety of solutions to many types of power electronics problems. A system-level understanding is valuable for assessing new applications or addressing vital applications in new ways. There is much more to do to prepare solutions that are more efficient, more reliable, more cost effective, and more functional than known approaches.

Why study power electronics? First, because it is fun. Power electronic circuits and systems are the basic energy blocks behind things that light up, move, take us from place to place, manage information, use batteries, communicate, cook a meal, or store data. These are changing the world in profound ways. Second, because it is a broad field that makes use of all of a student's knowledge of electrical engineering while seeking a new depth of understanding. Working knowledge of circuits, semiconductor devices, digital and analog design, electromagnetics, power systems, electromechanics, and control will benefit a power electronics engineer. Third, because it brings life, vitality, and breadth to abstract concepts. To the power electronics engineer, Kirchhoff's laws are the beacons that guide design and the snares that catch the unwary or careless. Since power processing is a universal need, power electronics designers often work across wide power ranges (microwatts to megawatts, for instance) and in many application domains.

New in the International Second Edition

The international second edition has been revised extensively on the basis of student and reader feedback. The organization is sequential to match the teaching sequence that is being used. Power conversion examples are developed in Chapter 1, based on more comprehensive coverage of energy methods. Converter concepts and other foundational information have been wrapped in with circuit analysis and design to link the applications. There are more examples on power filters and their design. Implementation issues such as high-side switching now appear with converter design. Basic material such as Fourier series and three-phase circuits has been moved into the Appendixes. Aspects of circuit operation such as discontinuous modes are included with converter analysis and design.

A new objective of this edition is to provide fundamental text material on renewable and alternative energy. Many power electronics engineers entered the field because it gives them the tools to make profound changes to energy systems, energy infrastructure, and global standards of living. Expanded design examples, with application discussion and emphasis on emerging energy advances, have been added to almost every chapter. Alternative energy, solid-state lighting, and electric transportation are just three typical application domains expanded here in examples and problem sets.

There is enhanced emphasis here on growing circuit applications such as active rectifiers, which are rapidly supplanting passive and classical rectifiers even in small power supplies. The treatment of pulse width modulation has been expanded to address space-vector modulation. The chapter on sources and loads includes new sections about source characteristics of batteries, fuel cells, and solar cells. The power semiconductor device material emphasizes power MOSFETs and IGBTS, which have become the mainstream devices for energy conversion. Emerging devices based on wide bandgap semiconductors, especially SiC and GaN, are introduced. The chapters on control have been restructured with more examples. Advanced topics that include ac-ac converters, resonant circuits, and geometric controls are presented near the end. The net result is a more concise version that emphasizes power conversion circuits and enhances material on applications.

The reference lists and problem sets at the end of each chapter have been expanded. Some problems in each chapter have been labeled explicitly as advanced material with an icon. They are intended for readers seeking in-depth challenges. Many of these and other problems emphasize design and encourage readers to develop judgment about power electronics in context. There are many options for design problem approaches, and many of the advanced problems do not have unique solutions.

Organization and supplements

The book is organized into six parts. In the first part, two chapters on principles lay out the applications and tools of switching power conversion. In the second part, three chapters on converters present general energy conversion circuits and their operation. The third part provides five chapters that present real components and their functions in energy processes, ranging from ways to model and evaluate real sources and loads, capacitors, inductors, power semiconductors, and interface circuits for power devices. The fourth part provides two chapters on control in power electronics. The fifth part presents advanced topics in three chapters, including ac–ac converters and resonant circuits.

An undergraduate course in power electronics might cover Chapters 1–8 in depth, with more limited coverage of Chapters 9–10. An accompanying lab course covers additional applications. The graduate course covers Chapters 9–15. Prior courses in circuits, electronics, and electromagnetics are assumed. Prior courses in electromechanics, analog and digital filter design, and power systems are not vital but make sense in the context of a broad curriculum on modern power and energy issues.

Several readers have asked about laboratory experiments and exercises. A supplemental laboratory manual, with complete details and a comprehensive set of experiments, is freely available electronically on the textbook website at www.oxfordtextbooks.co.uk/orc/krein2e. The equipment used in our laboratory has been designed and built through the open source Blue Box project at the University of Illinois. All circuit designs, drawings, fabrication details, and documents are available for public use under open-source licenses. Instructors should request access to presentation slides and additional course materials by contacting Oxford University Press.

Power electronic circuits can be a challenge to simulate, and many readers ask about tools and methods. In this book, many simulations are developed through Mathcad® or through direct equations implemented in Mathematica®. In addition to these, some of the most respected industry tools include PSIM® (powersimtech.com) and the freeware tool PowereSIM (www.poweresim.com). While many designers use PSpice®, this tool requires special techniques, especially if closed-loop converter controls are to be explored. Professional-grade tools include Transim® (www.transim.com) and proprietary power electronics toolboxes developed for MATLAB® and Simulink® (www.mathworks.com). Sample simulations can be found on the textbook website. Given the rapid evolution of power electronics simulators, the text does not emphasize specific tools.

Acknowledgments

I am grateful to the many hundreds of students who have provided feedback on the first edition and its use. The classroom and laboratory experiences of these undergraduate and graduate students have guided the revisions in the second edition. Many sections were inspired by challenging questions from students. Their enthusiasm for energy advances is the main motivation for this book.

The comments of the external reviewers have been valuable in completing the second edition. I deeply appreciate both the encouragements and criticisms. The changes to this edition owe much to these reviewers.

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Zia Yamayee, University of Portland
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Credits and caveats

Many power conversion circuits and control techniques are the subject of active patent protection. The author cannot guarantee that specific circuits or methods described in the text are available for general use. This is especially true of resonant conversion material in Chapter 8.

Power electronics by its nature is an excellent subject for laboratory study. However, it brings many more hazards than more familiar areas of electronics. Readers who plan experimental work in the field should take proper safety precautions in the laboratory.

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NOMENCLATURE

Symbol	*Meaning*
α	Phase delay angle
β	Turn-off angle; transistor current gain
δ	Difference angle, for relative phase control
ϵ	Electric permittivity; thermal emissivity
η	Efficiency, P_{out}/P_{in}
θ	Angle
λ	Flux linkage, Wb-turns
μ	Magnetic permeability
ξ	Time constant ratio, t/T; damping factor
ρ	Resistivity
σ	Electrical conductivity; Stefan–Boltzman constant
τ	Time constant, L/R or RC
ϕ	Flux; phase angle
ω	Radian frequency; radian shaft rotational speed
$\mathcal{P}$	Permeance
$\mathcal{R}$	Reluctance
A	Area
B	Magnetic flux density
C	Capacitance
D	Duty ratio
E	Electric field
F	Force
G	Open-loop transfer function; conductance
H	Magnetic field intensity; feedback transfer function
I	Current
J	Current density
K	Closed-loop transfer function
L	Inductance
M	Modulating function

N	Number of turns
P	Power
Q	Reactive power; quality factor; charge
R	Resistance
S	Apparent power
T	Period; temperature
V	Voltage
W	Work; energy
X	Reactance
Y	Admittance
Z	Impedance
a	Turns ratio; commutation parameter
b	Fourier sine coefficient
c	Constant (in general); Fourier component amplitude
d	Time-varying duty ratio
e	Control error
f	Frequency
g	Gap length; transconductance
h	Heat transfer coefficient
i	Time-varying current
j	$\sqrt{-1}$
k	Modulation index; gain; thermal conductivity
l	Length
m	Integer index
n	Integer index
p	Integer index; instantaneous power
q	Switching function; heat flow
s	Laplace operator
t	Time
u	System input; Heaviside's step function; commutation interval
v	Time-varying voltage
x	State variable
y	Output variable

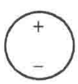
Special Circuit Symbols


Ideal dc voltage source


Ideal ac voltage source


Ideal dc current source


Ideal ac current source



Voltage source (ac or dc)


Generic transistor (BJT, FET, IGBT)

Contents

PART I: PRINCIPLES