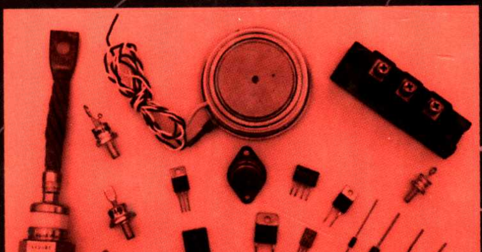
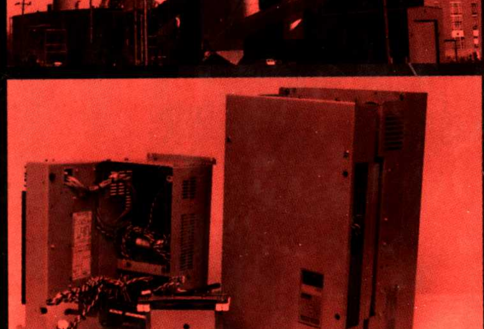
Elements of Power Electronics





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New York Oxford
OXFORD UNIVERSITY PRESS
1998

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Oxford New York
Athens Auckland Bangkok Bogota Bombay Buenos Aires
Calcutta Cape Town Dar es Salaam Delhi Florence Hong Kong
Istanbul Karachi Kuala Lumpur Madras Madrid Melbourne
Mexico City Nairobi Paris Singapore Taipei Tokyo Toronto Warsaw
and associated companies in
Berlin Ibadan

Published by Oxford University Press, Inc.,
198 Madison Avenue, New York, New York, 10016
http://www.oup-usa.org

Library of Congress Cataloging-in-Publication Data
Krein, Philip T., 1956–
Elements of power electronics / Philip T. Krein.
p. cm. — (The Oxford series in
electrical and computer engineering)
Includes bibliographical references and index.
ISBN 0-19-511701-8 (cloth)
1. Power electronics. I. Title. II. Series.
TK7881.15.K74 1997
621.31'7—dc21 96-37809
CIP

Printing (last digit): 9 8 7 6 5 4 3 2
Printed in the United States of America
on acid-free paper

PREFACE

INTRODUCTION

Power electronics is one of the broadest growth areas in electrical technology. Today, electronic energy processing circuits are needed for every computer system, every digital product, industrial systems of all types, automobiles, home appliances, lamps and lighting equipment, motor controllers, and just about every possible application of electricity. At one time, the growth was pushed by energy conservation goals. Today, there are many more benefits in terms of reliable, lightweight power processors. A host of new applications is made possible by improvements in semiconductors and by better understanding of power electronics. Motors with integrated electronic controls will soon be the norm. Portable telephones and communication devices demand tightly optimized power management. Advanced microprocessors need special techniques to supply their power. Utilities worry about the quality of their product, and about how to use electronics for more effective power delivery.

This text presents modern power electronics in its many facets. But it is not a loose collection of information. Rather, the intent is to lay down a firm conceptual base from which engineers can examine the field and practice its unusual and challenging design problems. What makes the treatment different? First, a sound scientific framework is established, then students are encouraged to observe how the many converter types and methods branch out naturally from this framework. Second, the treatment is structured for aspiring student engineers. It is written to help students synthesize their electrical engineering study, as they finish an education and begin a career or advanced study. Third, it covers a great deal of support material, such as models for passive components and basic design strategies for magnetics, that is rarely taught but is ubiquitous for the practicing designer.

With a few important exceptions, past treatments of power electronics begin with devices, then develop specific application circuits case by case. In such a broad field, students with little experience are hard pressed to find the deep commonality. A few hours of Web browsing confirms how much misinformation exists about power electronics and design of conversion circuits. Modern devices have reached the point at which they no longer limit the applications. Imaginative designers have found a huge variety of solutions to many types of power electronics problems. It is essential to develop a system-level understanding of the needs and techniques, since a device focus can be unnecessarily constraining. Even so, books continue to be published following the practice of past treatments. Notable exceptions include the 1981 book by Peter Wood, *Switching Power Converters* (Van Nostrand), where a switching function approach was introduced as the first unifying framework for power electronics. More recently, the text by Kassakian, Schlecht, and Verghese, *Principles of Power Electronics* (Addison-Wesley, 1991), builds on Wood's framework with many extensions. Unfortunately, these two books tend to be best suited for students pursuing advanced degrees. This new book owes its roots to the Wood text, and shares the philosophy of the Kassakian text. However, from the outset it was planned for undergraduate students or other engineers with no prior power electronics background.

Why study power electronics? First, because it is fun. Power electronic circuits and systems are the basic energy blocks needed for things that move, light up, cook a meal, fire a combustion cylinder, or display information on a video monitor. Second, because it makes use of all a student's knowledge of electrical engineering, and aims at a new level of understanding. To most students, circuit laws are lifeless mathematical equations. To the power electronics engineer, Kirchoff's laws are the beacon that guides a design—and the snare that catches the unwary or careless. A power electronics engineer needs a working understanding of circuits, semiconductor devices, digital and analog design techniques, electromagnetics as it affects layout and device action, power systems and machines, and the inner action of major applications. Third, because of the challenge. Since power processing is needed just about everywhere, there are few areas with more variety of design tasks. A power electronics expert might work on a 10 MW backup system one day, and on a 1 W system for battery processing the next. Fourth, because of the opportunity. The next personal computer you buy will have a power supply as big as the rest of its electronics combined. It will place extreme performance demands on the supply, and will require total reliability. The power supply will be a significant fraction of the cost to build the computer. Yet the computer manufacturer employs dozens of hardware-software engineers for every power electronics engineer. The need is there, and will grow.

ORGANIZATION AND USE

The book is organized into five parts. Four are here in your hands. Part V, the laboratory supplement, is available through a World Wide Web site. In Part I, the framework for power electronics is established. The three chapters in Part I offer a historical perspective, and establish key framework concepts such as switching functions, equivalent methods for filter design, diode circuit analysis, and regulation. Part II covers all the major converter classes—dc–dc, ac–dc, dc–ac, ac–ac, and resonant converters—in considerable depth. Students are often surprised to learn that they can become effective designers of useful converters by the time they are through Chapter 4. Chapter 8 presents perhaps the first undergraduate text material on the emerging subject of resonant converters. Part III covers the issues of components, from models for sources and loads to power semiconductors to the circuits that drive them. Unique features include the fundamental approach to magnetics design, coverage of wire sizing and parasitic resistance effects, and extensive examples. Part IV introduces control methods, again at the undergraduate level. Chapters 15 and 16 discuss general control issues and develop the popular frequency domain design approach. Chapter 17 provides a new perspective on an especially simple approach to large-signal control.

The book is big because of the breadth of the field. The general layout supports a first course at the senior level, based on Part I and Part II. A second course would cover Part III and Part IV. At the University of Illinois, there is just one course at present. We attempt to cover Chapters 1–6, 11, and 12 in detail, with briefer treatments of 7–10 and 13–14. The chapters are relatively independent, so a variety of course arrangements can be supported. As prerequisites, students should recognize that all their basic course work in electrical engineering will be brought to bear for the study of power electronics. Prior courses in circuits, in electronics, in systems, and in electromagnetics are essential. Prior courses in electromechanics, analog or digital circuit and filter design, and power systems can be helpful, but are not vital.

A few things are not here. Space and time do not permit detailed coverage of individual applications. Motor control and telecommunications power are two examples. It is not possible to provide adequate coverage for dc or ac motor control, or for telecommunications power system design. Beyond the introduction in Chapter 6, the motor control application is left to books from others. The telecommunications application is left to a number of dc–dc converter examples.

The book makes extensive use of computer tools, and students are encouraged to follow this lead. However, no floppy disk is included because few readers find time to learn the programs on such disks. Instead, several example listings are given in the Appendix. Also, students may visit the Web site http://power.ece.uiuc.edu/krein_text to find copies of programs for downloading and to obtain updates to programs or to course materials. A group of industry-based students developed extensive Mathcad® applications. Some of these can be found on the site. Additional problems will be posted as well. Instructors can request Web access to problem solutions through the publisher.

A few words on chapter problems: In this book, a great many of the problems have a design orientation. This means the problems are open-ended, and not always completely specified. Students are encouraged to think about the *context* of a problem, and fill in information when necessary. There are no tricks here. In general, each problem attempts to describe a real system.

UNITS, STANDARDS, AND SIGNIFICANT DIGITS

In general, the International System (SI) of Units is used throughout the text, consistent with IEEE standards. There are some exceptions in magnetics and capacitive components, in which the centimeter is common as the unit of length. If units are not listed explicitly, SI units should be assumed. Appendix B provides a review of some of the unit issues. When possible, graphics symbols are taken from *IEEE Standard 315-1975* (reaffirmed, 1993). The standard gives procedures for creating combination symbols. Unusual symbols, such as that for an ideal ac current source, attempt to follow the procedures.

There are dozens of numerical examples and hundreds of numerical problems in this text. It is important to be aware of significant digit issues. A real circuit application commonly has only about two significant digits. Tolerances on capacitors, inductors, and timing elements are wide. However, in power electronics we are often interested in small differences for efficiency measurements or other detailed information. It is important that small differences not be lost to round-off error in repeated calculations. In examples here, digits are carried through, and round-off is performed only as the last step in the computation.

ACKNOWLEDGMENTS

I am indebted to the many students who have given their insight and their active help in bringing this text about. Richard Bass, now at Georgia Institute of Technology, shared many suggestions on the lab material and as we began to use these notes in place of a published text. Pallab Midya, now at Motorola Corporation, along with Dr. Bass, provided some of the insights now present in Chapter 17 and in the lab sections of Part V. Christopher Nekolny, now at Commonwealth Edison, assisted in first-round production of Part I. A special debt is owed to Rüdiger Munzert, who spent many hours proofreading during his exchange visit from Technische Hochschule Darmstadt. He helped me simplify the English throughout the text, and made personal contributions to Chapter 17.

Final round preparation could not have been completed without the efforts of four current students. Matthew Greuel created most of the lab figures. Daniel Logue found a way to build camera-ready computer output for simulation figures. Richard Muyshondt created several simulations and assisted with proofreading. Luis Amaya became the resident SPICE expert for circuit simulation. I am very grateful for all of this assistance.

My colleagues in power electronics have made many constructive suggestions. The ideas from David Torrey of Rensselaer Polytechnic Institute have been particularly useful, and I appreciate the encouragement. The comments of Thomas Sloane of Alpha Technologies were especially significant and challenging. Others provided encouraging comments too numerous to be mentioned here.

I am grateful for the support of my wife, Sheila Fitzgerald Krein, and family in this project. They have tolerated the long hours and extra workload with grace. It has been a difficult time because of some family tragedies, and I deeply appreciate their forbearance.

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.

NOMENCLATURE

Symbol	*Meaning*
α	Phase delay angle
β	Turn-off angle
δ	Difference angle, for relative phase control
ϵ	Electric permittivity
η	Efficiency, P_{out}/P_{in}
λ	Flux linkage, Wb-turns
μ	Magnetic permeability
ξ	Time constant ratio, t/T
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
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
R	Resistance
S	Apparent power
T	Period; temperature
V	Voltage
W	Work; energy
X	Reactance
Y	Admittance
Z	Impedance
a	Turns ratio
b	Fourier sine coefficient
c	Constant (in general)
d	Time-varying duty ratio
e	Control error
f	Frequency
g	Gap length
h	Heat transfer coefficient
i	Time-varying current
j	$\sqrt{-1}$
k	Modulation index; gain
l	Length
m	Integer index
n	Integer index
p	Integer index; instantaneous power
q	Switching function
s	Laplace operator
t	Time
u	System input; Heaviside's step function
v	Time-varying voltage
x	State variable
y	Output variable

CONTENTS

PART I

PRINCIPLES