Principles of Power Electronics

Second Edition

Substantially expanded and updated, the new edition of this classic textbook provides unrivaled coverage of the fundamentals of power electronics.

It includes:

- Comprehensive and up-to-date coverage of foundational concepts in circuits, magnetics, devices, dynamic models, and control, establishing a strong conceptual framework for further study.
- Extensive discussion of contemporary practical considerations, enhanced by real-world examples, preparing readers for any design scenario from low-power dc/dc converters to multi-megawatt ac machine drives.
- New topics including SiC and GaN wide-bandgap materials, superjunction MOSFET and IGBT devices, advanced magnetics design, multi-level and switched-capacitor converters, RF converter circuits, and EMI.
- Over 300 new and revised end-of-chapter problems, designed to enhance and expand understanding of the material, with solutions for instructors.

Unique in its breadth and depth, and providing a range of flexible teaching pathways for instructors at multiple levels, this is the definitive guide to power electronics for graduate and senior undergraduate students in electrical engineering, and practicing electrical engineers.

John G. Kassakian is Professor of Electrical Engineering Emeritus at the Massachusetts Institute of Technology. He is the founding President of the IEEE Power Electronics Society, a Fellow of the IEEE, a member of the US National Academy of Engineering, and has taught, conducted research, and consulted in power electronics for over 45 years.

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Martin F. Schlecht is the founder of SynQor, a supplier of high-performance power conversion solutions, and prior to that was Professor of Electrical Engineering at the Massachusetts Institute of Technology for 15 years. He has over 40 years of research, teaching, and industrial practice in power electronics.

"*Principles of Power Electronics* was a landmark in power electronics pedagogy when it was first published more than three decades ago. It is thrilling to see how these distinguished authors have not only thoroughly brought the book's core contents up to date, but also expanded its coverage to include several new topics that are increasingly important for students to learn as they prepare to enter this exciting field. Bravo!"

Thomas Jahns, *University Wisconsin – Madison*

"The second edition of the *Principles of Power Electronics* makes this classic book even more valuable. The book teaches power electronics from the ground up, providing the formal framework to learn its fundamentals and many advanced topics. This highly accessible book is an excellent text for a foundational course in power electronics. A must-have for both beginners and experienced practitioners."

Khurram Afridi, *Cornell University*

"The new edition of *Principles of Power Electronics* is a must for anyone in the field of power electronics, from the student learner to a working professional. The coverage is comprehensive, with detailed explanations backed up by well-chosen worked examples and illustrative problems. The treatment of magnetics, analysis, and design is particularly strong and a welcome addition."

Gerard Hurley, *University of Galway*

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To our students,
who have been our best teachers,

and to Daniel Perreault Nakajima,
in memoriam.

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Preface

The field of power electronics has advanced substantially since the initial publication of *Principles of Power Electronics* in 1991. New semiconductor devices, magnetic materials, fabrication technologies, and new modeling and control techniques have all combined to create an increasingly diverse universe of applications in which power electronics is embedded. Many component advances and the demands of new applications have pushed power converter switching frequencies into the hundreds of megahertz, more than an order of magnitude higher than what was practical at the time of publication of the first edition. And, simultaneously, the number of power electronics courses being taught worldwide has experienced a manifold increase. At a time when the efficient and socially responsible generation and use of energy are increasingly critical concerns globally, the importance of power electronics cannot be overstated.

As with the first edition, this second edition of *Principles of Power Electronics* is not intended as a reference book. It is a textbook specifically designed to *teach* the discipline of power electronics. Although the coverage is broad, we develop topics in sufficient depth to expose the *fundamental* principles, concepts, techniques, methods, and circuits necessary to understand and design power electronic systems for applications as diverse as a 100 mW switching converter operating at 100 MHz, a 25 MW motor drive, or a 1 GW high-voltage dc transmission terminal. All power electronics shares a common base, and we have tried to make this fact clear.

Principles of Power Electronics is divided into four parts, and each part has undergone significant rethinking, revision, and updating for this edition, as outlined below. Each begins with an overview chapter that establishes context for the remaining chapters of the part. These overviews are substantial enough to stand independently, and are intended to do so for certain teaching purposes.

Part I, "Form and Function," is the book's backbone. There we present the relationship between the form, or topology, of a power circuit and the functions it performs. The common features of circuits that perform the basic electrical energy conversion functions – ac/dc, dc/dc, dc/ac, and ac/ac – are introduced in this part. The deeper purpose of Part I, however, is to present ways of thinking about power electronic circuits, visualizing their behavior, and understanding their relationships with one another, so as to enable extension to new situations, and serve as the basis for synthesis as well as analysis. There is new material in this part on dc/dc converter topologies, multi-level converters and the use of flying capacitors, switched-capacitor converters, polyphase sources and converters, the concept of space-vector modulation for three-phase inverters, resonant converters (including RF converter designs), and soft switching.

Part II, "Dynamic Models and Control," considers the unique problems of modeling and controlling power electronic systems. We present analytical approaches to modeling and understanding their dynamic behavior, and show how to use these in designing and evaluating practical

feedback control schemes. The emphasis is on fundamental formulations that apply across a range of power electronic systems, as illustrated by extensive examples in these chapters. The structuring of the material in this part is substantially revised relative to the first edition, for improved accessibility. The development of averaged models has also been extended considerably beyond dc/dc converters, with generalizations to track the dynamics of the fundamental (and harmonics) of converter waveforms. On the other hand, we have condensed the treatment of material that is now standard fare in undergraduate electrical engineering classes (and well supported by other textbooks), for example the analysis and feedback control of continuous-time, linear, time-invariant (LTI) systems described in the frequency domain or via LTI state-space models. Because of its role in stability evaluation of power electronic systems and its importance in the design of fully digital control systems, we retain our introduction to the topic of sampled-data modeling and control.

Part III, "Components," examines the behavior and characterization of the elements from which power electronic circuits are constructed. A review of semiconductor device physics precedes a discussion of specific device behaviors. The first edition's detailed development of the physics of specific devices has been replaced by a more phenomenological treatment. Also developed in this part is a discussion of the benefits and challenges of using the new wide-bandgap materials, SiC and GaN. The presentation of magnetic components has been expanded in this edition from a single chapter to four. This additional material addresses the challenge of designing magnetic components for the high switching frequencies now made possible by new MOSFET structures and GaN devices. We spend considerable time describing the behavior of magnetic materials, and the design and construction of inductors and transformers used at these high frequencies.

Part IV, "Practical Considerations," treats a variety of important additional topics that must be considered in the design of any practical system. Among these issues are gate and base drives, electromagnetic interference and filtering, snubbers, clamps and soft switching, and thermal modeling and heat sinking. New to this part is a discussion of circuit fabrication technologies necessary for very-high-frequency operation.

Unlike many power electronics texts which are designed for a single course, the scope of *Principles of Power Electronics* encompasses a *curriculum* of several sequential courses. A course in power electronics might use this book in one of several ways. Chapters 1 through 8, 9 (through Section 9.6), 10 (through Section 10.5), and the overview chapters in Parts II through IV would serve well as the basis for an advanced undergraduate or first graduate subject. Chapters 23 (Gate and Base Drives) and 18 (Introduction to Magnetics) might also be included. A more advanced graduate course might skim Part I and address Part II in detail. Other advanced courses may be tailored to need by selecting various chapters from Parts II through IV. Each chapter in Parts I, III, and IV is relatively self-contained. Selections from Part II can be made in at least two ways. Chapter 12 (Dynamic Models and Control: An Overview) and Chapter 13 (Averaged-Circuit and State-Space Models) may be used together in a course that emphasizes dynamic modeling of power electronic systems. An advanced graduate course that is particularly concerned with control could include Chapter 14 (Linear Models and Feedback Control), and if addressing machine control, could add Section 9.7 (Space-Vector Representation and Modulation for Three-Phase Systems).

We use examples extensively in this book to illustrate concepts or techniques introduced in the text, and also to introduce ways of thinking about problems, methods of analysis, and the use of approximations. The examples also form the basis for many of the end-of-chapter problems, and the creative instructor can use them to generate additional exercises, problems, or examples. We designed the end-of-chapter problems to stimulate thinking about the material presented in the chapter. That is, they are not intended as routine exercises to drill students in the use of particular equations in the text. Often, we introduce new circuits, concepts, or ways of approaching problems by using previous discussions in the text as a basis for considering the new material. We also present practical variations of circuits discussed in the text.

The notes and bibliography at the end of each chapter point you to selected papers in the research literature, and to books that underlie, complement, or extend the chapter material. These bibliographies, however, are not exhaustive.

We hope that instructors find this book to be a valuable teaching resource, and that students find it provides a challenging but enlightening learning experience.

Acknowledgments

It is no exaggeration to say that this second edition of *Principles of Power Electronics* would not exist if it weren't for the commitment, energy, care, and good-humored responsiveness of Sandeep Kaler at Toronto Metropolitan (formerly Ryerson) University. Despite the demands of the final stages of a doctoral program, he single-handedly worked to generate almost all the figures in this edition – recreating them from the first edition as needed, and preparing many new ones, then adjusting them wherever and whenever necessary. He also provided helpful feedback on various sections of the text. We are immensely grateful.

We are similarly indebted to Mike Ranjram on the faculty at Arizona State University who helped develop some portions of the text, contributing especially to the newer material in Part II, and revisiting various elements in this part from the first edition – checking the analysis, running new simulations, generating associated figures. He also vetted most of the end-of-chapter problems in the book while preparing a solutions manual for instructors.

We have had the benefit of careful reading and feedback from many colleagues (among them, former students, and their former students!) with whom we shared various draft chapters as we developed this second edition. They include Khurram Afridi, Arijit Banerjee, Richard Blanchard, Jessica Boles, Vahe Caliskan, Minjie Chen, Jesus del Alamo, Malik Elbuluk, Alex Hanson, Gerard Hurley, Jeffrey Lang, John H. Lienhard II, David Otten, Mohammad Qasim, Colm O'Rourke, Seth Sanders, Kenji Sato, Aleksandar (Alex) Stanković, Charles Sullivan, Joseph Thottuvelil, Amirnaser Yazdani, Xin Zan, and Yuhao Zhang. (We regret any inadvertent omissions there might be in this listing.) This brief mention cannot do justice to their generous and expert efforts – and the book was notably improved by their involvement.

Generations of students and teaching assistants in our introductory and advanced power electronics classes have worked with the material here, using the first edition of the book, and then drafts of this edition. We have counted on their being critical, fearless, and constructive in their feedback, and have never been disappointed.

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