Fundamentals of Power Electronics

SECOND EDITION

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Dedicated to

Linda, William, and Richard

Lidija, Filip, Nikola, and Stevan

Contents

Preface

The objective of the First Edition was to serve as a textbook for introductory power electronics courses where the fundamentals of power electronics are defined, rigorously presented, and treated in sufficient depth so that students acquire the knowledge and skills needed to design practical power electronic systems. The First Edition has indeed been adopted for use in power electronics courses at a number of schools. An additional goal was to contribute as a reference book for engineers who practice power electronics design, and for students who want to develop their knowledge of the area beyond the level of introductory courses. In the Second Edition, the basic objectives and philosophy of the First Edition have not been changed. The modifications include addition of a number of new topics aimed at better serving the expanded audience that includes students of introductory and more advanced courses, as well as practicing engineers looking for a reference book and a source for further professional development. Most of the chapters have been significantly revised and updated. Major additions include a new Chapter 10 on input filter design, a new Appendix B covering simulation of converters, and a new Appendix C on Middlebrook's Extra Element Theorem. In addition to the introduction of new topics, we have made major revisions of the material to improve the flow and clarity of explanations and to provide additional specific results, in chapters covering averaged switch modeling, dynamics of converters operating in discontinuous conduction mode, current mode control, magnetics design, pulse-width modulated rectifiers, and resonant and soft-switching converters.

A completely new Chapter 10 covering input filter design has been added to the second addition. The problem of how the input filter affects the dynamics of the converter, often in a manner that degrades stability and performance of the converter system, is explained using Middlebrook's Extra Element Theorem. This design-oriented approach is explained in detail in the new Appendix C. Simple conditions are derived to allow filter damping so that converter transfer functions are not changed. Complete results for optimum filter damping are presented. The chapter concludes with a discussion about the design of multiple-section filters, illustrated by a design example.

Computer simulation based on the averaged switch modeling approach is presented in Appendix B, including PSpice models for continuous and discontinuous conduction mode, and current-mode control. Extensive simulation examples include: finding the dc conversion ratio and efficiency of a SEPIC, plotting the transient response of a buck-boost converter, comparing the control-to-output transfer functions of a SEPIC operating in CCM and DCM, determining the loop gain, line-to-output transfer function, and load transient response of a closed-loop buck voltage regulator, finding the input current waveform and THD of a DCM boost rectifier, and comparing the transfer functions and output impedances of buck converters operating with current programmed control and with duty cycle control. The major purpose of Appendix B is to supplement the text discussions, and to enable the reader to effectively use averaged models and simulation tools in the design process. The role of simulation as a design verification tool is emphasized. In our experience of teaching introductory and more advanced power electronics courses, we have found that the use of simulation tools works best with students who have mastered basic concepts and design-oriented analytical techniques, so that they are able to make correct interpretations of simulation results and model limitations. This is why we do not emphasize simulation in introductory chapters. Nevertheless, Appendix B is organized so that simulation examples can be introduced together with coverage of the theoretical concepts of Chapters 3, 7, 9, 10, 11, 12, and 18.

Middlebrook's Extra Element Theorem is presented in Appendix C, together with four tutorial examples. This valuable design-oriented analytical tool allows one to examine effects of adding an extra element to a linear system, without solving the modified system all over again. The theorem has many practical applications in the design of electronic circuits, from solving circuits by inspection, to quickly finding effects of unmodeled parasitic elements. In particular, in the Second Edition, Middlebrook's Extra Element Theorem is applied to the input filter design of Chapter 10, and to resonant inverter design in Chapter 19.

In Chapter 7, we have revised the section on circuit averaging and averaged switch modeling. The process of circuit averaging and deriving averaged switch models has been explained to allow readers not only to use the basic models, but also to construct averaged models for other applications of interest. Examples of extensions of the averaged switch modeling approach include modeling of switch conduction and switching losses. Related to the revision of Chapter 7, in Appendix B we have included new material on simulation of converters based on the averaged switch modeling approach.

Chapter 8 contains a new substantial introduction that explains the engineering design process and the need for design-oriented analysis. The discussions of design-oriented methods for construction of frequency response have been revised and expanded. A new example has been added, involving approximate analysis of a damped input filter.

Chapter 11 on dynamics of DCM (discontinuous conduction mode) converters, and Chapter 12 on current-mode control, have been thoroughly revised and updated. Chapter 11 includes a simplified derivation of DCM averaged switch models, as well as an updated discussion of high-frequency DCM dynamics. Chapter 12 includes a new, more straightforward explanation and discussion of current-mode dynamics, as well as new complete results for transfer functions and model parameters of all basic converters.

The chapters on magnetics design have been significantly revised and reorganized. Basic magnetics theory necessary for informed design of magnetic components in switching power converters is presented in Chapter 13. The description of the proximity effect has been completely revised, to explain this important but complex subject in a more intuitive manner. The design of magnetic components based on the copper loss constraint is described in Chapter 14. A new step-by-step design procedure is given for multiple-winding inductors, and practical design examples are included for the design of filter inductors, coupled inductors and flyback transformers. The design of magnetic components (transformers and ac inductors) based on copper and core loss considerations is described in Chapter 15.

To improve their logical flow, the chapters covering pulse-width modulated rectifiers have been combined into a single Chapter 18, and have been completely reorganized. New sections on current control based on the critical conduction mode, as well as on operation of the CCM boost and DCM flyback as PWM rectifiers, have been added.

Part V consists of Chapter 19 on resonant converters and Chapter 20 on soft-switching converters. The discussion of resonant inverter design, a topic of importance in the field of high-frequency electronic ballasts, has been expanded and explained in a more intuitive manner. A new resonant inverter design example has also been added to Chapter 19. Chapter 20 contains an expanded tutorial explanation of switching loss mechanisms, new charts illustrating the characteristics of quasi-square-wave and multi-resonant converters, and new up-to-date sections about soft-switching converters, including the zero-voltage transition full-bridge converter, the auxiliary switch approach, and the auxiliary resonant commutated pole approach for dc–dc converters and dc–ac inverters.

The material of the Second Edition is organized so that chapters or sections of the book can be selected to offer an introductory one-semester course, but yet enough material is provided for a sequence of more advanced courses, or for individual professional development. At the University of Colorado, we cover the material from the Second Edition in a sequence of three semester-long power electronics courses. The first course, intended for seniors and first-year graduate students, covers Chapters 1 to 6, Sections 7.1, 7.2, 7.5, and 7.6 from Chapter 7, Chapters 8 and 9, and Chapters 13 to 15. A project-oriented power electronics design laboratory is offered in parallel with this course. This course serves as a prerequisite for two follow-up courses. The second course starts with Section 7.4, proceeds to Appendices B and C, Chapters 10, 11 and 12, and concludes with the material of Chapters 16 to 18. In the third course we cover resonant and soft-switching techniques of Chapters 19 and 20.

The website for the Second Edition contains comprehensive supporting materials for the text, including solved problems and slides for instructors. Computer simulation files can be downloaded from this site, including a PSpice library of averaged switch models, and simulation examples.

This text has evolved from courses developed over seventeen years of teaching power electronics at the University of Colorado. These courses, in turn, were heavily influenced by our previous experiences as graduate students at the California Institute of Technology, under the direction of Profs. Slobodan Ćuk and R. D. Middlebrook, to whom we are grateful. We appreciate the helpful suggestions of Prof. Arthur Witulski of the University of Arizona. We would also like to thank the many readers of the First Edition, students, and instructors who offered their comments and suggestions, or who pointed out errata. We have attempted to incorporate these suggestions wherever possible.

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