Preface

In many university curricula, the power electronics field has evolved beyond the status of comprising one or two special-topics courses. Often there are several courses dealing with the power electronics field, covering the topics of **converters**, **motor drives**, and **power devices**, with possibly additional advanced courses in these areas as well. There may also be more traditional power-area courses in **energy conversion**, **machines**, and **power systems**. In the breadth vs. depth tradeoff, it no longer makes sense for one textbook to attempt to cover all of these courses; indeed, each course should ideally employ a dedicated textbook.

This text is intended for use in introductory power electronics courses on converters, taught at the senior or first-year graduate level. There is sufficient material for a one year course or, at a faster pace with some material omitted, for two quarters or one semester.

The first class on converters has been called a way of enticing control and electronics students into the power area via the "**back door**". The power electronics field is quite broad, and includes fundamentals in the areas of:

- Converter circuits and electronics
- Control systems
- Magnetics
- Power applications
- Design-oriented analysis

This wide variety of areas is one of the things which makes the field so interesting and appealing to newcomers. This breadth also makes teaching the field a challenging undertaking, because one cannot assume that all students enrolled in the class have solid prerequisite knowledge in so many areas. Indeed, incoming students may have individual backgrounds in the power, control, or electronics areas, but rarely in all three. Yet it is usually desired to offer the class to upper-division undergraduate and entering graduate students.

Hence, in teaching a class on converters (and in writing a textbook), there are two choices:

1. Avoid the problem of prerequisites, by either (a) assuming that the students have all of the prerequisites
   and discussing the material at a high level (suitable for an advanced graduate class), or (b) leaving out
   detailed discussions of the various contributing fields.
2. Attack the problem directly, by teaching or reviewing material from prerequisite areas as it is needed. This material can then be directly applied to power electronics examples. This approach is suitable for a course in the fourth or fifth year, in which fundamentals are stressed.

Approach (2) is employed here. Thus, the book is not intended for survey courses, but rather, it treats fundamental concepts and design problems in sufficient depth that students can actually build converters. An attempt is made to deliver specific results. Completion of core circuits and electronics courses is the only prerequisite assumed; prior knowledge in the areas of magnetics, power, and control systems is helpful but not required.

In the power electronics literature, much has been made of the incorporation of other disciplines such as circuits, electronic devices, control systems, magnetics, and power applications, into the power electronics field. Yet the field has evolved, and now is more than a mere collection of circuits and applications linked to the fundamentals of other disciplines. There is a set of fundamentals that are unique to the field of power electronics. It is important to identify these fundamentals, and to explicitly organize our curricula, academic conferences, and other affairs around these fundamentals. This book is organized around the fundamental principles, while the applications and circuits are introduced along the way as examples.

A concerted effort is made to teach converter modeling. Fundamental topics covered include:

- Fundamentals of PWM converter analysis, including the principles of inductor volt-second balance and capacitor charge balance, and the small-ripple approximation (Chapter 2).
- Converter modeling, including the use of the dc transformer model, to predict efficiency and losses (Chapter 3). Realization of switching elements using semiconductor devices. One-, two-, and four-quadrant switches. A brief survey of power semiconductor devices (Chapter 4).

- An up-to-date treatment of switching losses and their origins. Diode stored charge, device capacitances, and ringing waveforms (Chapter 4).
- Origin and steady-state analysis of the discontinuous conduction mode (Chapter 5).
- Converter topologies (Chapter 6).
- The use of averaging to model converter small-signal ac behavior. Averaged switch modeling (Chapter 7).
- Converter small-signal ac transfer functions, including the origins of resonances and right half-plane zeroes.
- Control-to-output and line-to-output transfer functions, and output impedance (Chapter 8).
- A basic discussion of converter control systems, including objectives, the system block diagram, and the effect of feedback on converter behavior (Chapter 9).
- Ac modeling of the discontinuous conduction mode. Quantitative behavior of DCM small-signal transfer functions (Chapter 10).
- Current-programmed control. Oscillation for $D>0.5$. Equivalent circuit modeling (Chapter 11).
- Basic magnetics, including inductor and transformer modeling, and loss mechanisms in high-frequency power magnetics (Chapter 12).
- An understanding of what determines the size of power inductors and transformers. Power inductor and transformer design issues (Chapters 13 and 14).
- Harmonics in power systems (Chapter 15).
- A modem viewpoint of rectifiers, including harmonics, power factor, and mitigation techniques in conventional rectifiers, and operation of sophisticated low-harmonic rectifiers (Chapters 16-18).
- Analysis and modeling of low-harmonic rectifiers (Chapters 17-18).
- Resonant inverters and dc-dc converters: approximate analysis techniques, characteristics of basic converters, and load-dependent properties (Chapter 19).
- Zero voltage switching, zero current switching, and the zero-voltage-transition converter (Chapter 19).
- Resonant switch converters, including basic operation, efficiency and losses, and ac modeling (Chapter 20).

On teaching averaged converter modeling: I think that this is one of the important fundamentals of the field, and hence we should put serious effort into teaching it. Although we in the academic community may debate how to rigorously justify averaging, nonetheless it is easy to teach the students to average: Just average all of the waveforms over one switching period. In particular, for the continuous conduction mode, average the inductor voltages and capacitor currents over one switching period, ignoring the ripple. That’s all that is required, and I have found that students quickly and easily learn to average waveforms. The results are completely general, they aren’t limited to SPDT switches, and they can easily be used to refine the model by inclusion of losses, dynamics, and control variations. To model dynamics, it is also necessary to linearize the resulting equations. But derivation of small-signal models is nothing new to the students - they have already seen this in their core electronics classes, as well as in numerous math courses and perhaps also in energy conversion. It isn’t necessary to teach full-blown state-space averaging, but I have included an optional (with asterisk) section on this for the graduate students. I personally prefer to initially skip Sections 7.4 and 7.5. After covering Chapters 8 and 9, I return to cover Sections 7.4 and 7.5 before teaching Chapters 10 and 11.

Averaging aside, it is also important to teach modeling in a pedagogically sound way. The object is to describe the important properties of the converter, in a simple and clear way. The dc transformer represents the basic function of a dc-dc converter, and so the modeling process should begin with a dc-dc transformer having a turns ratio equal to the conversion ratio of the converter. For example, the model of the buck-boost converter ought to contain a buck transformer cascaded by a boost transformer, or perhaps the two transformers combined into a single D: D’ transformer. This first-order model can later be refined if desired, by addition of loss elements, dynamic elements, etc.

The design-oriented analysis methods of R. D. Middlebrook have been well accepted by a significant portion of the power electronics community. While the objective of this text is the introduction of power electronics rather than design-oriented analysis, the converter analyses and examples are nonetheless done in a design-oriented way. Approximations are often encouraged, and several of the techniques of design-oriented analysis are explicitly taught in parts of Chapters 8 and 9. We need to teach our students how to apply our academic theory to real-world, and hence complicated, problems. Design-oriented analysis is the missing link.

Chapter 8 contains a “review” of Bode diagrams, including resonant responses and right half-plane zeroes. Also included is material on design-oriented analysis, in the context of converter transfer functions. The Bode diagram material is covered in more depth than in prerequisite classes. I have found that the material of Chapter 8 is especially popular with continuing education students who are practicing engineers. I recommend at least quickly covering this chapter in lecture. Those instructors who choose to skip some or all of Chapter 8 can assign it as reading, and hold students responsible for the material. In a similar manner, Chapter 9 contains a "review" of classical control systems, in the context of switching regulators. This chapter explicitly makes the connection between the small-signal converter models derived in other chapters, and their intended application. Many power area students are unfamiliar with this material, and even control-area students comment that they learned something from the design-oriented approach.

Parts III, IV, and V can be covered in any order. Part III includes a review of basic magnetics, a discussion of proximity loss, and an introduction to the issues governing design of magnetic devices. The inclusion of step-by-step design procedures may be somewhat controversial; however, these procedures explicitly illustrate the issues inherent in magnetics design. Student tendencies towards cookbook mentality are mitigated by the inclusion of homework problems which cannot be solved using the given step-by-step procedures. Part IV, entitled "Modern rectifiers," covers the issues of power system harmonics, generation of harmonics by conventional rectifiers, and low-harmonic rectifiers. Chapters 17 and 18 cover low-harmonic rectifiers in depth, including converter analysis and modeling, and rectifier control systems. Resonant converters are treated in Part V. There have been a tremendous number of papers written on resonant converters, most of which are very detailed and complicated. Indeed, the complexity of resonant converter behavior makes it challenging to teach this subject in depth. Two somewhat introductory chapters are included here. State-plane analysis is omitted, and is left for an advanced graduate class. In Chapter 19, resonant inverters and dc-dc converters are introduced and are analyzed via the sinusoidal approximation. Soft switching is described, in the context of both resonant converters and the zero-voltage transition converter. Some resonant network theorems are also presented, which yield insight into the design of resonant inverters with reduced circulating currents, with zero-voltage switching over a wide range of load currents, and with desired output characteristics. Resonant switch converters are introduced and modeled in Chapter 20.

Most chapters include both short analysis problems, and longer analysis and/or design problems. References are given at the end of each chapter, these are not intended to be exhaustive bibliographies, but rather are a starting place for additional reading.

This text has evolved from course notes developed over thirteen years of teaching power electronics at the University of Colorado, Boulder. These notes, in turn, were heavily influenced by my previous experience as a graduate student at the California Institute of Technology, under the direction of Profs. Slobodan Cuk and R. D. Middlebrook, to whom I am grateful. In addition, I appreciate the numerous helpful technical discussions and suggestions of my colleague at the University of Colorado, Prof. Dragan Maksimovic. I would also like to thank the following individuals for their suggestions: Prof. Arthur Witulski (University of Arizona, Tucson), Prof. Sigmund Singer (Tel-Aviv University, Israel), Dr. Michael Madigan, and Carlos Oliveira.

Robert W. Erickson
Boulder, Colorado