Classic Power Electronics Text—Updated, But Further Refinement Is Possible

Fundamentals of Power Electronics, *Third Edition*, Robert W. Erickson, Dragan Maksimović, Springer, 2020, 1084 pages, PDF review copy, paper book: ISBN 978-3-030-43879-1.

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The authors of the third edition of this major work on power electronics are professors at the University of Colorado at Boulder and were students of Slobodan Ćuk and R. D. Middlebrook at Cal Tech. Anyone serious about power electronics will have a copy of this book, in some edition, on their power-electronics bookshelf or computer. But even for those who have an earlier version, I recommend obtaining a copy of this third edition for the new and necessary material it provides.

In the preface, the authors indicate no major change in the direction of the book other than to update it. I took a deep plunge into the second edition years ago, published in 2001 by Kluwer. This review will focus on the third edition's updates and some persisting weaknesses in the book, which mainly concern the theory on how to model current-mode control and methods of magnetics design. But first, a quick recap of what's covered in this text.

The book is organized into six parts and 23 chapters according to the major categorizations of converter topics by the authors. *Converters,* in this case, refer to power-transfer circuits, which are the central subsystem of power converters. Power-transfer concepts and circuit component details, especially of power switches, are mixed in part I, and presented for both CCM and DCM operation of circuits with fixed parameters—in steady-state or *equilibrium*.

Part II is about dynamics and control, about developing linear models for nonlinear (switch) functions in the converter through switch-cycle averaging. Once linearized, circuit models of converter (power-transfer circuit) transfer functions are presented, applying continuous control theory and control methods for stabilizing feedback loops.

Part III covers magnetics principles, with inductor design based on the K_g method. Rudiments of transformer design follow. Design optimization is not developed beyond K_g. (More on this shortly.)

In part IV, a mix of "advanced" concepts is presented. One of the difficulties in writing a book about converters is in trying to explain some group of concepts without assuming that the reader has some grasp of other related concepts. For instance, without some knowledge of power circuits, it is difficult to explain the relative merits of various power-transfer characteristics. Or it is hard to explain power circuits with transformers without having covered magnetics.

The authors manage this conundrum by organizing the book as a two-stage presentation, beginning with a mix of basic concepts and then bootstrapping from them into topics that assume some knowledge of power converters from parts I through III. Advanced topics include more control theory, function linearization for modeling, and from their Caltech mentor, Middlebrook's Extra-Element Theorem, applied to power-transfer circuits with some offshoots of it such as the *n*-Element Theorem.

This update to the book contains a refinement of a number of circuit theorems based on port manipulations, beginning perhaps with Blackman's theorem. Middlebrook refined existing methods, including that of Cochrun and Grabel for finding poles in circuits. (The EET and variations on it such as the ZEET are derived in *Circuit Dynamics* and in *Transistor Amplifiers.*[1])

Input filter design, which is covered in part IV, deserves a chapter because of the circuit instability that can arise from negative incremental resistance at a constant-power port. A chapter is also given to peak current control, a topic that involves discrete-time feedback control and has a history of development over several decades and four generations of models. The authors settle for the third-generation model of F. Dong Tan and Middlebrook. (More on this subject shortly.) Some discrete-time control theory is offered—an essential topic if peak (or valley) current control modeling is to be fully understood, and kudos to the authors for recognizing the need for this in a converter textbook.

Part V is mainly about rectifiers, including power-factor correction. The timely topic of power quality emerges from it in the discussion of power-line harmonics in polyphase distribution. Part VI returns to a type of converter based on resonance in the power-transfer circuit. Resonant power circuits are unavoidable because of parasitic reactances, and the old engineering adage that "if you can't fix it, feature it" is applied by using parasitic elements to advantage, especially in zero-power switching, to reduce switching loss at high frequencies.

This book, in summary, is organized beginning with steady-state behavior of converters, then covers topics that can be categorized as power-transfer circuit *topology* (that is, the *form* of circuits, without parts values), magnetics, and then dynamics and control. "Advanced" topics include the increasing interest in resonant converters and soft-switching, and an update on semiconductor advances in switches. The book spans the range from components to subsystems to power systems. It also includes power-factor controlled rectifiers and some three-phase concepts.

While *Fundamentals* provides valuable updates as I have highlighted above in my overview, and these include explanations of newer theory, there are areas where the authors could have gone further. This occurs most notably in modeling of peak-current mode control. The discussion of this topic is updated in the third edition, but it stops disappointingly short of the most advanced and "refined" waveform-based model. It stops at the third-generation "unified" model of Tan and Middlebrook, and does not extend to the latest refinement into a true unified model. Previous editions of the book presented only the *first-generation* model of switched power circuit control—the state-space or *low-frequency averaged* (lf-avg) *model*, also by Middlebrook, from the 1970s, which the authors would have learned from their mentor.

This model appears in previous editions and does not account for sampling effects caused by PWM switching. It is accurate only at frequencies a decade or more below the switching frequency and is often inadequate because it fails to include subharmonic oscillation. The *second-generation* model of Ray Ridley does include this effect and is a major improvement, but has theoretical deficiencies involving sampling in the feedback loop. This book presents some discrete control theory needed for understanding the problem.

Around 1980, Ray Ridley and Richard Tymerski, who were both Ph.D. students at VPI, made modeling breakthroughs; Ridley recognized that the peak current control loop functioned as a current sampler, with flux stored in the inductor, the dual of storing charge in a hold capacitor. By introducing sampling theory, and by using the cycle-averaged PWM-switch model that Tymerski developed with Vatché Vorpérian as advisor, a theoretical explanation resulted for the subharmonic oscillation that can occur in these control loops. In the frequency domain, it is a resonant peak in gain at half the sampling frequency, f_s. It is a kind of instability alternating every other switching cycle with a different duty-ratio.

Speaking of which, Ridley also contributed to the refinement of power-electronics language—a topic of neglect—by calling it duty-*ratio* instead of duty cycle because it is not a cycle but rather a ratio. This book continues to propagate much of the outmoded language: "copper" instead of *conductor* (not all wires are made of Cu) makes "copper" a figure of speech (a *synecdoche*) and is generally avoided in technical explanation in preference for words with a narrower range of more precise meanings.

The familiar but ambiguous nineteenth-century expressions, "ac" (bipolar or varying?) and "dc" (unipolar or constant?) are also applied to voltages nowadays, resulting in linguistic absurdities like "direct current voltage"; is it current or voltage? And magnetics also has its share of misnomers. The authors bridge from "magnetomotive force" (which it is not; page 409) to "scalar potential" (which it is), to bring readers familiar with the misnomer to better language.

Another very helpful concept, though it is not presented by the authors in this book (or most others), is to make explicit the difference between circuit and field magnetic reference frames by foregoing use of magnetomotive force or "MMF" in favor of "field-referred current", or *field current* for short. This parameter has the units of amperes and thus is a current, referred to the field from the circuit.

Returning to peak-current control, Ridley and Tymerski around 1980 advanced peak-current control modeling to the second-generation *sampled-loop* model of Ridley's. Ridley has been content to continue the use of his model, teaching it in industry courses. For many electronics engineers, it has the right depth into control aspects of converters and explains subharmonic oscillation.

However, for those seeking better models, this second-generation model has weaknesses. For one, the sampler is placed in the feedback path of the loop, preventing the formation of a transfer function for the loop. "Sampling algebra" can be found in discrete-time control books, and it can be shown (as I did in a past article in How2Power Today[2]) that the sampler must be placed immediately after the feedback input summer, as it appears in the third-generation model of Tan and Middlebrook, in their "unified model" that appeared in the mid-1990s. This is the model that Erickson and Maksimović chose for updating their book, a model over two decades old.

The lf-avg model had one advantage over the sampled-loop model in that its currents were averaged over switching cycles while the sampled-loop model produces only currents at the boundaries between cycles as points in time. *Average* currents and voltages are theoretical approximations of *constant* currents and voltages and are what is usually specified at the ports of converters. A model that expresses converter behavior in average quantities is thus closer to what is of interest in converter design.

Tan and Middlebrook's *unified model* returned to average currents and correctly relocated the sampler to the beginning of the loop forward path. They also made some refinements in simplifying how changes in port voltages affect loop dynamics, by simplifying quantities in the PWM-switch, the nonlinear element in the loop.

A minor note is struck in the background music of this review as we consider that this third-generation *unified model* did not achieve true unification. The problem is discussed in detail in part 5 of my *H2P* series[3] on this topic and the lack of unification is summarized as follows. The "unified" model is not fundamentally unified but is a piecemeal adaptation of various features of lf-avg and sampled-loop modeling. The phase of sampled currents at the end of each cycle in the sampled-loop model is not that of the incremental average inductor current, $\bar{i}_l$ phase in the cycle.

The "unified" model introduces cycle current averaging to replace the single sample point per cycle. However, in the "unified" model, the constant factor in the PWM transfer function, F_{m0}, is derived from the cycle-averaged inductor current while the dynamics are taken from the sampled-loop model. Two independent models, of PWM and loop, are merged but not really unified. As a consequence, the PWM transfer function, F_m has quasistatic factor, F_{m0} that contains a pole (a function of frequency) and is in disagreement with every other developed PWM model.

In the fourth-generation *refined model*, the blocks in the block diagram of the model are instead derived from a single set of triangle-wave current equations, thereby producing a truly unified model and avoiding extraneous assumptions about how to model the PWM block. The quasistatic PWM transfer function, F_{m0} is extracted from the discrete-time duty-ratio equations. In the unified model, F_{m0} is extracted out of $\bar{i}_l$ from lf-avg equations and not from sampled-loop dynamics derivations. The two parts of the "unified" model come from independent sets of assumptions.

The derivation of the refined model expresses $\bar{i}_l$ in the discrete time-domain early in the sampling analysis so that subsequent development results in dynamics based on it, thereby modeling $\bar{i}_l$ dynamically and allowing F_{m0} to fall out of the derivation. The authors do not do this and retain the lack of refinement of the Tan-Middlebrook unified model. While this model is an advancement over the sampled-loop model, it has its own theoretical inconsistencies. Specifically, the unified model fails to include the effect on phase for incremental (small-signal) average current and retains the phase produced by the sampled-loop model sampled (not averaged) current.

So much for the discrete-time modeling weaknesses in the book. The text has strengths in continuous-time or "classical" control theory as applied to power circuits, with extensive examples having frequency-response magnitude and phase plots that show how to analyze continuous control loops. Others have been publishing books on refined methods, following Middlebrook's EET lead, of simplifying circuit analysis. Vorpérian and Basso (reviewed in *How2Power Today*) and myself (in *Circuit Dynamics*) have contributed to this endeavor.

This third edition also provides extended explanations of often-encountered converter loops—another reason to have a copy of this book. It is the most complete and thorough single volume on power converters (but not power electronics generally; motor drives are not included).

Now we go on to magnetics. I declare a bias in that I have made what I see as numerous refinements or advancements in magnetics design optimization, in book form[4] and in articles in *How2Power Today*. With this disclaimer, part III of this book begins with chapter 10, coverage of magnetic components as found in typical electric-machine book chapters with a mid-20th-century vintage.

Similar coverage is found, for instance, in *Electric Machines* by G.R. Slemon and A. Straughen of the U. of Toronto (Addison-Wesley, 1980). An exception in electric-machines books is that of Paul Krause of Purdue U., an "émigré" from GE in Schenectady, NY, home of Steinmetz, from whence electric-machine theory began propagating, though with a significant refinement each decade, by R. H. Park (in the 1920s), H. C. Stanley ('30s), then Gabriel Kron, and D.S. Brereton ('40s), ending with the final form of electric-machine theory contributed by Krause ('50s), free of the steady-state limitation of phasor theory.

In a rhyming (if not a repeat) of history, peak current loop control has also gone through a significant refinement each decade, beginning with Middlebrook's lf-avg model in the '70s, then Ridley's sampled-loop model in the '80s, Tan and Middlebrook's "unified" model in the '90s, culminating in the refined model in the late 2000s.

The K_g method is used for magnetics design in the book. Marian K. Kazimierczuk also uses it in *High-Frequency Magnetic Components*.[5] However, it is time to move on to more refined and comprehensive methods developed in *PMDO*. Magnetic component design is nontrivial but can be conceptually refined and simplified over existing methods of the 20th century.

Beyond understanding the issues raised above concerning control theory, magnetics design and other concepts, readers of both second and third editions of this book should be aware of some uncorrected errors. On page 427 is Figure 10.23, a repeat without correction of Fig. 13.23 in the second edition. (I had sent E&M errata on this before the third edition, but it remains uncorrected.) The wire diameter given on the graph is the *insulated* wire diameter when it should be the *conductive* wire diameter. Consequently the f_δ—the frequencies at which the penetration or skin depth, δ equals that of the conductive wire radius—are low.

On page 441, equation 10.94 corresponds to 13.93 in the second ed. The cosine summation in the equation is an even function, though the waveform is shown in Fig. 10.38 (13.38, second ed.) as an odd function. The Fourier series should have sin instead of cos and $I_j = 0$, j even. On page 481, Figure 11.16 has been corrected from the second edition, which has the vertical value as 0.078 instead of 0.040.

The table for PFC rectifier circuits on page 909, under the boost circuit of the first line, has erroneous expressions carried over from the second edition. The CCM Boost Transistor Average expression should contain a 4 instead of an 8, and for the diode rms expression, an 8 instead of a 16. Otherwise, the boost form factor of κ = rms/avg for equal input and output voltages is $\kappa = 0.711 < 1$, whereas the rms always exceeds the average and as always, $\kappa \geq 1$.

A good treatment of resonant converters also appears in this edition, continuing from the second edition. A few trifling errors were brought over from the second edition; on page 963, last line, cross out "with decrease". On page 966, third line, end of line, "zero-voltage" should be "zero-current". The final error in my second edition errata list (sent to E&M long ago), in the index under "Meal length", is corrected in the 3rd Ed. to "Mean length".

Another update that's worth noting in this edition, chapter 19 gives the basic concepts of discrete-time control, introduced and developed in a converter context, including the design of digital loop compensation for µCs. Program examples are in Matlab, popular in academia, and not Mathcad, more popular in industry, though both are quite readable forms of mathematics programming. Discrete-time integrators (rectangular and trapezoidal) and the discrete sequence z-domain are explained. The bilinear transform that spans the z and s^* (sampled s) domains—what in control books is called the w-domain—appears in the context of frequency warping. Limit-cycle quantization, caused by computation with a finite number of bits, is illustrated in converter waveforms.

This book of over 1000 pages is rigorous and comprehensive, and well worth keeping close at hand for anyone involved in the engineering of power electronics. Despite the weaknesses highlighted above, its many strengths overcompensate, though I am hoping that by the fourth edition, the authors will have read some articles at *H2P* on topics covered in their fine book that could nevertheless use additional refinement.

References

1. *Circuit Dynamics* and in *Transistor Amplifiers* by Dennis Feucht.
2. "Current-Loop Control In Switching Converters Part 4: Clarifications Of Existing Models" by Dennis Feucht, How2Power Today, December 2011.
3. "Current-Loop Control In Switching Converters, Part 5: Refined Model" by Dennis Feucht, How2Power Today, January 2012.

4. *Power Magnetics Design Optimization (PMDO)*, Innovatia.

5. *High-Frequency Magnetic Components, 2nd Ed*. by Marian K. Kazimierczuk, Wiley, 2014, reviewed in How2Power Today.

About The Author

Dennis Feucht has been involved in power electronics for over 35 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

To read Dennis' reviews of other texts on power supply design, magnetics design and related topics, see How2Power's Power Electronics Book Reviews.