Power Electronics Text Delivers Insights On Control, Covers Neglected Converter And Circuit Types

Principles of Power Electronics, Second Edition, John G. Kassakian, David J. Perreault, George C. Verghese and Martin F. Schlecht, Cambridge U. Press, 2024, 800 pages, hardback, ISBN 978-1-316-51951-6.

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This book is a premier MIT contribution to power electronics and covers the subject-matter in four parts titled Form and Function, Dynamic Models and Control, Components and Devices, and Practical Considerations. It follows in the MIT tradition of emphasizing fundamental concepts in some depth and in seeking a larger, more general and comprehensive view of the subject. For instance, it covers all four types of converters whereas most books skip bipolar to bipolar (ac-ac) waveform conversion.

In part 1, rectification and phase control of SCRs in polyphase rectifiers—a topic germane to electrical engineering—is followed by PWM control of resistance (dc-dc) converters. An entire chapter covers switched-capacitor circuits, including multilevel bridge circuits and voltage multipliers beyond the classic capacitor-diode ladders. I have not seen in other books the analysis of switched-C circuits, both slow-switched and fast-switched as presented here.

The central element of power-transfer circuits is the PWM switch, for which there are three configurations. The PWM-switch is a SPDT switch with common terminal in series with an inductor. The authors introduce this element in part 1, but add a capacitor across the active and passive terminals for the basic three-terminal device, calling it a *canonical switching cell*. The authors have a proclivity for generalizing their expanded meanings by endowing them with neologisms. The addition of a capacitance across the PWM-switch is an example, and such novelties give readers new insights into familiar concepts.

In addition to the basic three configurations, their isolated forms with the addition of transductors (transformers or coupled inductors—my neologism) are included, with a sprinkling of magnetics and circuit behavior to fill in the explanations. In writing a power-electronics book, it is quickly realized that the logical progression of explanation can only be iterative, starting with an introduction of concepts that give the framework followed by more detailed development in later sections. In the chapter on inverters ("dc-ac converters"), bridge-circuit behavior, reactive loads, harmonic reduction, and waveform properties are mixed in as required.

As noted above, the book does not overlook ac-ac converters. Moreover, the book is comprehensive in including a substantive coverage of cycloconverters. Consequently, this book covers "power" for both electrical and electronics engineers. Additionally, inverter control and multilevel converters—circuits quite important for high-power conversion in electrical engineering and for their output waveshape—are discussed in some detail.

Throughout this first part, emphasis is given to the bidirectionality of power flow through converters, and how replacement of diodes with active devices allows bidirectional flow, transforming inverters with flow in one direction into power-factor-corrected battery chargers in the other.

The polyphase conversion chapter is also relevant to electrical engineering. Multiple phases are a logical lead-in to vector representation of waveforms and state-variable or *state-space* formulation of power-circuit analysis. The three-phase to two-phase Clarke transform appears as do matrices and "space-vector modulation," a category of schemes for combining phase sequence switching with PWM to approximate a desired (sinusoidal) waveshape.

Multilevel bridge circuits for inverters end the "Polyphase Sources and Converters" chapter sections, followed by "PROBLEMS" for students that (in MIT fashion) include the development of new concepts or variations on those in the chapter and not merely plug-and-grind substitutions into derived formulas.

Part 1 also includes a chapter on resonant converters. While it cannot be as complete as the previously-reviewed, *Resonant Power Converters* by Kazimierczuk and Czarkowski,[1] the basic concepts begin with resonant-circuit theory and variable-frequency control for parallel and series resonance. Resonance also appears in power circuits as "soft-switching" whereby switches only change state with zero voltage across them (ZVS) or current through them (ZCS).

A chapter on high-frequency conversion addresses inherent resonances formed by parasitic reactances, with design based on the engineering adage that "If you can't fix it, feature it." High-frequency circuit and control schemes are presented. The final chapter of part 1 is on cycloconverters and a generalization as matrix converters.

Part 2 is about converter dynamics. This book differs in its approach to dynamics and control with an emphasis on state-space formulation of both control schemes and systems. While this is not new—Tymerski and Li used it in their "early unified" model of peak-current control, and it is common in electric-machine theory—this text brings in more advanced methods applicable not only to linear time-invariant (LTI) circuits but also to switched circuits which are both nonlinear and time-variant.

The passive components of power circuits are approximated as linear (including magnetic components). The authors explain "local average" and "local ω_s-component," the fundamental component in a Fourier series for the switching frequency, and substitute for the complex frequency s in analysis $s + j\cdot\omega_s$. Feedforward and feedback control concepts appear. The authors prefer to present control compensation in the categories of proportional or proportional-integral compensators, categories that emerged from motion control in the past, though they also present the more general method of pole-zero placement in compensator design.

The problem of how to linearize switches and switched circuits leads to switch-period averaging and the preferred method of linearizing circuits by replacing the nonlinear elements with linear equivalent models. Continuous control is discussed and frequency-response (Bode) plots appear. This is followed by a more advanced topic, that of robustness: the ability of a system to maintain its performance over a parametric range of operation. In continuous control, stability robustness can be measured as phase margin, the amount of loop-gain phase remaining before it becomes oscillatory.

Chapter 13 derives a switch-cycle average model of the "canonical switching cell" (CSC), which as mentioned above, is given as a PWM-switch with capacitor between active and passive switch terminals. The significance of the additional capacitor was previously explained in the book in connection with an important topic often overlooked in most books, that of power-port impedances.

In the three different two-port configurations of the CSC the capacitor appears as an input C, an output C, or a bridging C, adding an impedance constraint on the circuit ports. The PWM-switch model, by itself does not bring this out, though attendant capacitors are readily included in such circuits. The authors prefer to include the relevant C in the switch model.

System and control formulation now becomes explicitly *state-space* (or *state-variable* in some other books), referring to the state x and output y equations that are a more general alternative to s-domain equations from Laplace transformation. State-space description of power circuits starts with a *system* (math language for "multiple related") of first-order differential equations. A circuit with n reactances will be described by nth-order differential equations, but these can be made equivalent to a system of n first-order equations by defining the nth-order derivatives as n first-order derivatives. Thus each nth-order system can be put in state-space form.

The n variables of the circuit that define its state each have a first-order equation of the form

$$\frac{d}{dt}x(t) = \dot{x}(t) = f\,(x(t), u(t), t)$$

where $u(t)$ are the input variables and f is derived from circuit analysis.

The output, $y(t) = g(x(t), u(t), t)$ where g is another circuit-derived function; $g(u(t))$ is the transmittance and for an LTI circuit, the transfer function. This might seem cumbersome compared to solving a circuit in the s-domain with its resulting algebraic equations, but it is more general and allows matrix methods to be applied.

The authors are aware that readers cannot be expected to be proficient at either matrix calculus or state-space control theory, and they do an excellent job of building up the knowledge needed to use state-space theory as the text moves along. Indeed, their construction of matrix math for engineers is some of the most understandable I have ever encountered. They then develop some sampling ("sampled-data") theory that can be incorporated into state-space theory, but sampling also applies to switched circuits analyzed in the s-domain as piecewise-continuous per switching cycle and LTI in each of the circuit switch states.

In section 13.5, "Generalized State-Space Models," they come to peak-current ("current-mode") control. It is state-space formulated and immediately brings in slope compensation in example 13.8. This illustrates what slope compensation is but defers from achieving the "holy grail" of peak-current control, the inductor-current to input (from the outer voltage control loop) transfer function for a linearized cycle-averaged peak-current-controlled power-transfer circuit.

It was premature to expect that transfer function here, for the next chapter (14, "Linear Models and Feedback Control") derives the requisite switch-averaged circuit model, places it into the running example (boost-buck) circuit and derives the v_o/d transfer function, where d is the incremental *duty-ratio*. This is usually called *voltage-mode* control.

The authors do not try to be comprehensive in giving the transfer function of every PWM-switch configuration of power-transfer circuit as does another "gold-standard" power-electronics book, that of Erickson and Maksimović.[2] The critical knowledge conveyed in a textbook is in how to do it; the other configurations are exercises left for the reader or in the problems at the end of each chapter.

A notational aside: Back in the late 1980s, Ray Ridley recognized that *duty-ratio* is a better, more accurate, expression than the older *duty-cycle* because it is a ratio of on-time to switching period and is not a "cycle". To their notational credit, the authors also use "duty-ratio". (And for whatever reason, Ridley has gone back to using "duty-cycle"!)

Furthermore with regard to notation, an irony of the book is that while it formulates power theory in more recent state-variable or *state-space* forms, it retains obsolete and ambiguous expressions such as "ac" and "dc" that are easily replaced by more specific waveform language such as *unipolar, bipolar, static*, *varying* or *ripple*. Furthermore, in magnetics, "copper" is a figure of speech—a *synecdoche*—that is literally "winding" or "conductor". In technical communication, we try to avoid imprecise speech. "Copper" might just as well be aluminum.

The authors also faced the same notational conundrum I encountered in writing *Power Converter Design Optimization*,[3] of which symbols to use for multiple transformed functions. Different domains of t, s, s^*, z, or w have different transformed x functions. I made the same decision as the authors, of using (what I call) "isomorphic notation", which does not change the symbol of a function when it is transformed to a different domain, such as $x(t) \rightarrow x(z)$, but depends (as an isomorphism—a "meta-function") on the domain variable to identify it.

Finally, in subsection 14.4.1, the Laplace transform appears and is applied to state-space circuit equations. The archetypal "Buck-Boost Converter" example is invoked, the average incremental switch model is applied, the state-space matrices appear (with matrix elements in s) and the result is an s-domain transfer function, with pole-pair and RHP zero, and corresponding Bode plots. Then the time-domain response is considered.

The remainder of chapter 14 provides the background discrete-time systems theory for power-circuit analysis. Along the way, examples 14.6 through 14.8 again return to peak-current, or *current-mode* control. The problem is set up as a piecewise LTI model described by generalized state-space equations. By "generalized," it's meant that a constraint equation is set up that relates the variables of interest to those in the state-space equations for state x and output y. This is motivated by the indirect role that duty-ratio has in current-mode control, and the need to have an equation that relates it to the state-space variables.

The piecewise-LTI model is a set of LTI circuits, one per switched-circuit state. The authors prefer this formulation of the problem because the "variables of interest may be sampled values of components of the state vector, averages computed over the cycle, or harmonic components over the cycle." The inductor current is a triangle-wave with harmonics above the switching frequency, outside the Nyquist interval of frequencies, and is not taken into account in waveform-based current-mode control models.

The generality resulting from linearizing a nonlinear generalized state-space model is further expressed (p. 396) that linearization "at a constant steady state results in an LTI sampled-data model. Such an LTI discrete-time model is, explicitly or implicitly, the basis for most careful small-signal stability studies in power electronics."

It is important to note that *cycle-average* current as a state variable is a *dynamic* variable. The state-space approach to current-mode control of the authors implicitly assumes this. In decades of previous generations of peak-current loop modeling, the average was independently constructed as a quasistatic current—and nobody seemed to have caught this fact. Consequently, the valley-current phase resulted in the transfer function whereas the phase of the average occurs earlier in the switching cycle. This is implicit in the state-space model being developed here and is also in the refined (and perhaps final) waveform-based model.[4, 5]

The peak-current problem continues to be addressed from the sampled-circuit incremental model in example 14.6. The next state depends on the present state, the peak-current command (v_{in}) and incremental duty-ratio d_k. The resulting solution corresponds in vector form to scalar solution of the *waveform equations.*[6]

Going forward, the main goal of the authors is to find stability conditions for the peak-current-control circuit. They begin the discrete-time LTI analysis, noting how easy it is to go from the discrete time-domain sequence $x[k]$ to the z-domain. The convergence of series from (the ratio test of) calculus can be applied to test for stability; the circuit is unstable for steady-state duty-ratio $D > ½$.

Example 4.8 then applies to the common-inductor (buck-boost) transfer circuit. The authors derive its circuit dynamics without a compensating ramp and switching frequency well above the loop dynamics. This is roughly comparable to the second-generation sampled-loop model of Ridley[7] though the stability analysis assumes some control knowledge of the *z*-domain. This leads to transfer functions, in particular of the CP (buck) circuit, with example 14.9 for duty-ratio, not peak-current, control.

Basic feedback control design occupies the next sections of chapter 14. In section 14.9.2, "Current-Mode Control," the book has what appears to me to be a *circuit-based*, not *waveform-based*, approach to the current-mode problem reminiscent of Robert Sheehan's modeling effort at National Semiconductor (now TI) which starts with circuit generalization instead of the idealized current waveform and its equations. The ongoing buck-boost example problem is solved but there is no general configuration-independent solution as would result in waveform-based modeling.

Second, the approximation of average cycle current to that of the input (commanded) current (example 14.12, p. 416), $\bar{i}_L \approx i_P$, avoids the problem of expressing average i_L as a dynamic variable $i_L(t)$. The previous models of both Ridley and Tan-Middlebrook (the sampled-loop and "unified" models) gave an independent construction for what the cycle average should be (and they are equivalent, though derived in different ways) and it is quasistatic, not dynamic. (That is, it is constructed for an average at 0+ Hz.)

The missing equation applied in the refined model is that of the average for the triangle-wave inductor current. It relates simply the cycle average to both the peak (i_P) and valley ($i[k+1]$) values of the cycle and is a function of time. When combined with the waveform equations, a refined transfer function that accounts for average current phase results.[4, 5] Substituting the average current expression, $i_l(k) = 2\cdot\bar{i}_l(k) - i_i(k)$, where k is at the end of the cycle ($k + 1$ in the book), i_l ($\tilde{i}_L$) is the incremental inductor current and i_i (i_P) is the (commanded) input to the current loop, into the waveform current equation[6] and reducing,

$$\bar{i}_l(k) = -\frac{D}{D'}\cdot\left(\bar{i}_l(k-1)+\tfrac{1}{2}\cdot[i_i(k)-i_i(k-1)]\right)+\frac{1}{D'}\cdot i_i(k)$$

where k is at the end of the cycle and is initially $k - 1$. Compared to the valley-current expression, it has the same form but with the additional i_i difference term added to $\bar{i}_l(k-1)$.

For $i_i(k) = i_i(k-1)$, i_I is changing at a constant rate, i_i is constant, and $\bar{i}_l(k) = i_l(k)$. This leads to transfer function $\bar{i}_L / i_i(s)$, the closed-loop dynamic response of the *cycle-average* current. I did not find this important transfer function derived in the book.

Third, the book entangles current-loop compensation with the dynamics of the loop apart from compensation considerations. The slope-compensated waveform is input to the PWM circuit as i_M, shown in the block diagram of the figure.

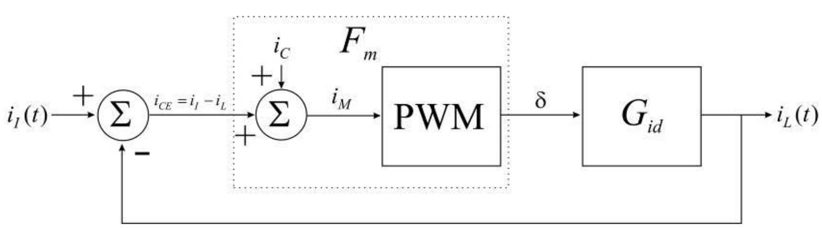

Figure. Current feedback loop with slope compensation waveform i_C added to error quantity i_{CE} as i_M.

Slope compensation schemes differ in how i_C is added to i_I and the summation requires an additional summing block. The summation as shown in the figure occurs within the forward path, adding the error quantity i_{CE} and the compensation function i_C;

$$i_M(t) = i_{CE}(t) + i_C(t) = [i_I - i_L] + i_C$$

Two other possible locations for the summation of i_C are in the input path and the feedback path. For the input path, input i_I effectively becomes $i_I + i_C$:

$$i_M = [i_I + i_C] - i_L$$

A summer in the feedback path subtracts i_C from i_L. Then compensated error quantity i_M is the compensated feedback current subtracted from the input to form the PWM input quantity;

$$i_M = i_I - [i_L - i_C]$$

Addition is associative and commutative, and with no additional processing between summations, the three means of combining the three quantities comprising i_M are equivalent. Consequently, we can consider the effect of i_C to be that of an addition to commanded input i_I.

It should therefore be possible to substitute $i_I + i_C$ for i_I into the uncompensated closed-loop $i_L(i_I)$ and derive the compensated inductor-current closed-loop equation. Thus, loop dynamics derivations can logically precede compensation considerations. This also simplifies explanation of each.

Part 3 begins with switches, covering the major properties of semiconductor passive and active switches. Capacitors and magnetic components follow. Chapters 16 and 17 explain the device physics in the detail of a course on solid-state electronics. SiC and GaN transistors are briefly covered, yet adequate for most circuit design.

Chapter 18 introduces some basic properties of single- and multiple-winding magnetic components, largely as circuit elements. The next chapter continues with transformer two- and three-port electrical models, then magnetic field-referred models. Transfer circuits with multiple outputs from secondary windings that require regulation can interact because of their leakage inductances and series inductances (for CP circuits) and this might require that secondary winding dynamics be analyzed with these models. Equivalent circuits for transformers with interacting windings are developed.

Chapter 20 arrives at magnetic design. Having written a book[8] and multiple series of *How2Power Today* articles on power-magnetics design optimization, I was eager to see what was covered. The authors derive the K_g method for optimal design, yet this method is not very comprehensive (as they describe in subsection 20.1.2).

That method excludes some important magnetics performance constraints such as maximized core transfer-energy density,[9] sustaining minimum efficiency over a range of current,[10] bundle design (number of strands of a given size) to optimize eddy-current winding loss,[11, 12] or for inductors, maximization of inductance in the saturation region of core operation (if a minimum inductance is desired).[13]

In a more refined optimization, winding inductance is a free parameter that results from optimizing performance parameters. Magnetic (core) and electric (winding) design are in logical sequence rather than concurrent, as in the K_g method.[8, ch. 6]

In the first part of the design—the magnetic design—either a core network or shape-based[14] thermal model is applied so that thermal effects are also taken into account, and core sizing must include input voltage range.[15-18] These considerations are not presented or optimized in the book.

Inductor energy storage limits are considered but no inductor saturation model[13] is presented. Design optimization reaches the state of development of core area-product (Section 20.3) and the K_g method, or a variant on it. (Except for the references, other books are no better in advancing magnetics design.)

Subsection 20.4.3 optimizes inductor turns to minimize loss that parallels the derivation of Van den Bossche and Valchev.[19] The significant magnetic material performance factor $\hat{B} \cdot f_s$[20] is explained, a parameter that Ferroxcube gives in their databooks but hardly anyone else seems to have discovered its significance.

Another optimization is the maximization of power transfer across windings, from primary to secondary. This is covered (pages 631-634), though the implied circuit model for the transformer is only valid for perfect power transfer. Minimum loss (page 632) does not necessarily result in maximum interwinding power transfer (transfer efficiency),[21] and minimizing total (core plus winding) loss is a different design goal than optimizing loss for maximum power transfer. They do not differ widely in a high-efficiency magnetics design, but they are also not the same.

Chapter 21, "Magnetics Loss Analysis and Design," covers both winding and core losses in more detail. The 1D field solution of Dowell is derived from basic principles resulting in expressions for skin and proximity effects. The effect of winding layers on proximity effect is presented. Dowell plots are shown with the approximate equation for the wire size at the minimum constant-frequency resistance ratio F_r. Most converters operate at a fixed switching frequency, and this is the relevant F_r. (The other is constant wire size versus variable frequency F_R.)

The field solution resulting in the Dowell equation is based on parallel conducting plates. To relate this to equivalent round or square winding wires, some geometric transformation is required. In subsection 21.2.4 the authors express (page 665) that the resulting transformation is approximate and that a better result is obtained by a direct solution that results in a modified Bessel function.

However, Kazimierczuk[22] (and reference [8]) have a more accurate formula. The authors recognize that the Dowell equation loses accuracy at high wire size and porosity, but optimal design usually avoids these regions of operation.

The authors cover winding design configurations of interleaved layers and the effect of nonsinusoidal waveshape on loss but not the analysis or design of "Litz wire": winding bundles of twisted strands of wire and the effect of strand size and number of strands in a bundle,[21, 22] or on *bundle* F_r, which is $f_r = F_r / N_s$ where N_s is the number of strands in a bundle. (And then there are multi-layer bundles.)

Neither does foil eddy-current loss appear. These omissions are not weaknesses of the book, but are brought out here to alert the reader that there is much more to magnetics, enough for books such as [22] and [19], and one (reference 8) that specifically addresses magnetic design optimization.

The Dowell equation invariably appears in the book as only $F_r\,(\xi, M)$ where ξ is conductor size in units of skin depth and M is number of winding layers. However, M need not be the only explicit constraint for the equation. From winding geometry, expressions can be derived and substituted for M that hold winding area or number of bundle strands constant.

The resulting Dowell plots show the effect on $F_{rA} = F_r(\xi, M)$ from these constraints. Winding area is allotted based on winding area optimization in the core window, and is a given geometric parameter for windings. The resulting F_{rA} plots with fixed winding area are most insightful for winding optimization of eddy-current loss.

The final part 4 of the book is titled "Practical Considerations" or what in reference [3] is a volume on *Power Circuits*. It covers gate- and base-drive circuits, including high-frequency circuits for driving SiC gates by using a transformer with gate and source return windings for separating gate drive current from source current. The same scheme is used for oscilloscope probes by wrapping a turn or two of the probe cable around a toroidal ferrite core. The transformer behavior presents a high-impedance path to parallel current return paths outside the core.

An antisaturation clamp for BJTs (or power Darlingtons) keeps the BJT from going into deep saturation, which increases b-c junction charge and hence switching time needed to remove the charge. Snubbers for damping resonances and soft switching are presented in chapter 24. (More detailed analyses are given in [3] for flyback and push-pull circuit snubbers.) EMI reduction is also mentioned in connection with snubbers.

Chapter 25 covers the easily neglected topic of thermal design. The basic equations, including "Thermal Ohm's Law" and thermal network modeling appears with some mention of convection, transient thermal models and device safe operating area.

The final chapter 26 is about another topic for which whole other books exist: "Electromagnetic Interference and Filtering". Filter design, circuit damping, input filtering for CP (buck) transfer circuits, and the difference between common- and differential-mode waveforms are explained. The final topic is about circuit-board layout and parasitic (unintended) circuit elements. The index has eight three-column pages.

Despite my emphasis in this review of book omissions or limitations, it should be kept in mind that power electronics as a field of knowledge is simply too wide for any one book to cover it comprehensively. Different books on the subject bring out different concepts. The better books include unique material, and this one achieves this, especially in its use of state-space analysis and the inclusion of sampling theory and discrete-time control, and how it applies to power systems.

In a previous *How2Power Today* review of the third edition of *Fundamentals of Power Electronics* by Erickson and Maksimović (E&M),[2] I referred to it as a gold-standard book in power electronics. This book deserves the same acclaim. For the ardent power-electronics engineer, this book should be alongside that of E&M, and perhaps also that of Hurley and Wölfle, references [19], [22], and some others.

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