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Industry Pioneer Introduces Engineers To Broad Field Of Power Supply Design

Fundamentals of Power Supply Design, Robert A. Mammano, First edition, Texas Instruments, 2017, 333 numbered pages, ISBN: 978-0-9985994-0-3.

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Bob Mammano has been a leading figure in the development of power conversion, having designed the first PWM controller IC. Mammano more recently worked at (Texas Instruments) TI, through TI's acquisition of Unitrode, of which Mammano was a founding member. He is a retired TI Fellow.

When I dove into this book, I could tell from the section topics in the table of contents that it would be an interesting read. This is an industry- and design-oriented book. So what is a power supply? The second sentence of chapter one sets the tone (p. 1):

> *…[From] the average electronic-system designer, you may well get the answer: "A power supply is an abomination that takes up too much space in my enclosure, uses up some of my available power, heats up my sensitive circuitry, and blows a hole in my budget!"*

The challenge of power-supply design is thereby made direct and obvious. Mammano's depth of experience begins to come through in chapter 1. An ordinary power-electronics engineer will know most of the essential facts in this chapter, but they are presented with additional auxiliary facts and comments that add interest—an educating form of engineering entertainment. For instance, some of the different utility-grid voltages and frequencies around the world are listed in introducing power sources as power supply (PS) inputs. Another list gives battery voltages for various sources including telecom, the military, industry and automobiles.

The introductory chapter ends with a summary of the rest of the book:

> *The remainder of this book will begin with the process of voltage regulation and introduce the components we have to work with. We will then move into the details of specific power circuit topologies and the control algorithms used to give them functionality, devoting specialized chapters to describing control loop dynamics, magnetic technology and fault management. Further chapters will provide insight into related subjects such as preventing electromagnetic interference, meeting safety standards, and designing for the ever increasing demand for higher energy efficiency. Finally, this book will end with a practical look at the techniques for converting all this theory into successfully working hardware.*

Chapter 2 starts with the simplest useful voltage regulator, a resistor and avalanche diode, then moves on to amplifier feedback regulation and the progression to low-dropout regulators. The overall description of switching supplies is clear and refined, showing that the author's experience has led to conceptual refinement and an emphasis on the root features of topics.

Chapter 3 is on power supply components: resistors, capacitors, diodes and transistors, with a good explanation of MOSFET turn-on and turn-off behavior with an inductive, diode-clamped drain load. Mammano likes to use lists and tables, and the presentation has somewhat of a slide-show ambience. Yet the information density is not sparse.

Then the storage elements, inductors, carry this quote: "… a SMPS designer still needs a basic understanding of magnetics to determine the important parameters required by his application." Chapter 7 is about magnetics. In weighing the tradeoff between choosing a high or low inductance for a converter, "the accepted guideline or rule of thumb is to pick an inductance value that yields a ripple current of 10 to 30% of the maximum output-load current at maximum input voltage." However, optimization can be applied and the thumb-rule avoided. Such optimization is a book in itself, but not this book.

The emphasis is on width, not depth, of coverage. For instance (page 34),

> *The term A_L is an arbitrary parameter defined by manufacturers as a convenient "catch-all" value to collect all the magnetic and dimensional core parameters into one term.*

The manufacturer A_L is the *field-referred inductance*, $\mathscr{L}$—the per-turn-squared *L*—and *is* a major, meaningful parameter in magnetics—hardly arbitrary. Fig. 3.15 summarizes the common core materials and besides ferrite and powdered-iron (Fe-pwd) for switching converters, includes NiFeMo ("Molyperm") but not FeSiAl, which is cheaper than NiFeMo and can improve over Fe-pwd when higher power density is required. For an introduction to inductors, however, the amount of detail in this chapter is "spot on", as the British would say. It is enough information about magnetics for some circuits-focused designers.

In describing magnetic components with multiple windings (which I ask you to join with me and call by the *structural* name, *transductors*), Mammano, following common practice, calls them *transformers*, which names one of the *behaviors* of a transductor. Yet he *does* distinguish coupled-inductor behavior from that of transformer behavior without naming it as such. Here is an instance in which the lack of a standard word for multi-winding magnetic components can cause confusion between structure and behavior.

As for naming refinements, here is another, which is commonplace in the industry (p. 37): "Any energy stored in both magnetizing and leakage inductances has to be reset between power cycles to prevent saturation." The statement is true. However, a better word for "reset" tells what actually happens instead: *defluxed*. This is the dual word of capacitive *discharge*. It is flux that must be decreased or inverted. "Reset" comes from logic-circuit language and does not apply well here. The core is not a digital device (except in core memories.)

Moving on in chapter 3 are the IC controllers, a topic in which Mammano is well-versed. The first PWM controller, the Silicon General SG1524 is highlighted, and for good reason. Silicon General was founded by Mammano in 1969, and he designed the SG1524 as the first PWM controller. Mammano lists and describes the problems in integrating analog and power circuits on the same chip.

Chapter 4 covers the various converter circuit types ("topologies"). In engineering fashion, Mammano lists the often-conflicting design criteria. He starts with the three PWM-switch configurations (without calling them that). Then he covers some combinations of PWM-switch configurations such as this popular one in the figure below (which Tim Hegarty of TI has covered in a couple of How2Power Today articles), lacking an established name (p. 48.)

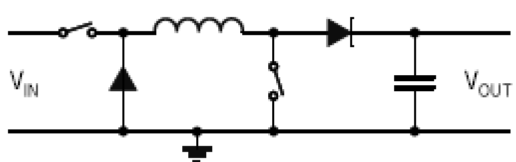

Figure 4.2 – The buck-or-boost circuit combines two topologies which share a common inductor.

Also, he presents in passing the Ćuk converter, which is a PWM-switch common-inductor (CL) configuration with an extra winding (or uncoupled inductor) for current steering. Mammano describes it as a "combination of a boost converter with a flyback converter in a single design designated SEPIC, for single-ended, primary-inductance converter" (or what I call a SEcondary Polarity-Inverted Ćuk). He identifies the key tradeoff; "both the switch and the rectifier must block the highest circuit voltage (V_{IN} + V_{OUT}), and also conduct peak current equal to the sum of the input and output currents."

Flyback (CL) converters, Ćuk-derived or not, are not optimal for high-power applications—at least when it comes to switch utilization. The flyback circuit he describes in comparison to the CP with transformer, or the *forward* converter, is operated in DCM. The disadvantages attributed to it decrease when operated deep in CCM. The key benefit of Ćuk's discovery (which did not appear in the book) was *current steering*, which can be applied to any of the PWM-switch configurations, and is a significant concept to know for design.

The next step is to add a transformer to the buck (CP) and "flyback" (CL) converters. As for the boost converter, he writes: "with a transformer, the boost [CA] and flyback [CL] topologies become identical." Not really; what distinguishes the CA from the CL is their voltage transfer functions; the CA is $1/D'$; the CL is D/D'. Adding a transformer does not change that. An example of a boost converter with a transformer is the boost push-pull circuit (of which the Weinberg converter is a special case), and is optimal for applications with low-R_g (high current, low voltage) inputs such as battery converters for inverters.

About the push-pull forward converter: "by driving the transformer in both directions, no additional reset is necessary. This eliminates the need for any additional reset circuitry," but this is true only for an ideal transformer without leakage inductance. When either switch turns off in its half-cycle, the transformer magnetizing current transfers to the other winding and flows through the body-drain diode of the other

MOSFET. However, the leakage current needs a path through what is usually implemented as a series RC snubber across the windings (between MOSFET drains.) Mammano mentions what happens without the snubber circuit in passing, and also brings out another important design consideration: flux imbalance in the primary windings. Neither are developed here in detail. Snubbers are covered later.

Other converter cameos include a chopper (push-pull with fixed D = 0.5) driven by a buck converter, and series-switch, half- and full-bridge forward converters. Again, he identifies the critical design considerations that can be subtle and time-consuming to neophyte designers. Subsequent topics are CCM and DCM, and the RHP zero of the CA (boost) and CL (which he calls "flyback") configurations for which he gives the intuitively appealing Lloyd Dixon circuit interpretation—a good insight to have when looking at the *s*-domain transfer functions, and synchronous rectification, the replacement of diodes with an active switch.

Going further with topologies, the full-bridge circuit is driven with multiple switch sequences and the consequences noted. As for secondary circuits, the current doubler is developed with a cute star-to-delta conversion in the sequence of circuit transformations.

Chapter references are to the popular Unitrode (now TI) seminar notes. In the preface, Mammano tells how he drew significantly from them to put the topics they cover into a more organized and accessible form. For that, this book should have appeal to those who remember Lloyd Dixon's seminar talks, the free lunch (!), and those valuable soft-cover books given out at the seminars. (They can be downloaded from the TI website.) Mammano pays special tribute to Dixon, from whom many of us neophytes gained insights into power electronics. Dixon said at one seminar that this was Unitrode's alternative to advertising, and we attendees certainly preferred it to reading an ad.

On to deeper water, chapter 5 is about control, starting with hysteretic control. The color illustration from the book is shown below.

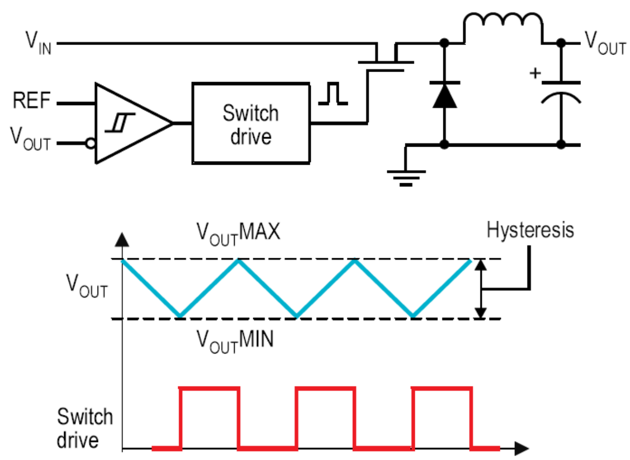

Figure 5.1 – The implementation and operation of a hysteretic controller.

This is followed by a list of advantages and disadvantages for this control scheme. This is the common form of presentation in the book: lists of benefits and limitations a designer must know for the given circuit. Then some improvements to hysteretic control follow, as constant on-time (and off-time) schemes, followed by the more familiar voltage-mode control, and then peak current-mode control. In its disadvantages list, Mammano writes: "Two feedback loops are difficult to analyze." That can be a profound statement. The inner (current control) loop is the hard one.

As I continue to read, I eagerly await Mammano's treatment of current-mode control. How far will he descend into this abyss? Next is average current control, a significant scheme often overlooked and advantageous over peak current control in PFCs, for instance. The two current control schemes are compared and relative merits assessed.

More recently, controllers have used multiphase control so that multiple outputs can be paralleled for high-current, low-voltage (low R_O) applications such as contemporary microprocessors. Input and output ripple current is reduced by multiple offset phases. The ripple frequency scales with the number of paralleled converters and can have a smaller inductor to filter out the higher-frequency ripple at the output.

Resonant converters can absorb whole books (as evidenced by the *How2Power Today* review of Marian Kazimierczuk's book, *Resonant Power Converters*). Mammano offers a token example of the successfully-applied LLC resonant half-bridge circuit.

Chapter 6 continues control, specifically feedback, and presents basic feedback control theory. Control modeling begins with a buck converter with voltage control and proceeds to find the transfer functions—but they are expressed in canonical instead of normalized form, making it harder to relate the math to the circuit. (A red flag went up in the back of my mind that perhaps control theory is not Mammano's forte, at least in mathematical form. The book is light on math.)

He proceeds to give a basic explanation of Bode plots. Everything is presented at about the level of depth that many circuit designers operate. (To his credit, Mammano uses control-theory notation instead of the ambiguous choice of symbols in many active-circuits textbooks. Is $\beta = H(s)$ or a BJT parameter? Both appear in BJT feedback circuits!)

The stability measures of gain and phase margins are listed equally, though phase margin is more useful. Three op-amp frequency-compensation circuits are then presented, showing their poles and zeros with some advice on where they should be placed relative to circuit element values. These explanations are very clear and exactly what most designers are looking for.

While proceeding to an example problem, consideration of switching frequency first appears, which is the sampling frequency of the feedback loop—a loop that until now has been analyzed as though it were continuous (that is, purely analog). Circuit events occur within each cycle at turn-off of the active switch, and this is a sampling behavior.

He cautions: "From basic control theory, we know that we should not expect to provide linear control up to a frequency where there will be fewer than at least five samples per switching period." The additional phase delay over that of a continuous circuit is $(-180°)\cdot(f\,/f_s)$. For five samples per cycle, $f = f_s/5$, the delay is −36°, a significant amount in many cases. Five samples per switching period would be a loop frequency of $5\cdot f_s$ where f_s = switching frequency, and would put it far above the Nyquist frequency of $f_s/2$.

I think what is meant here is that the highest loop frequency should be no more than $f_s/5$. That would put the loop gain-bandwidth product, $f_T < f_s/5$ so that the loop gain, $|G\cdot H| < 1$ at $f_s/5$. In the next sentence, he says essentially that. The example is worked through, Mathcad plots presented, then a prototype built and compared. They compare well, though low output capacitor series resistance shows an unstable loop. But for more series-R, the loop is very stable.

And now, the abyss; current-loop control is encountered. Which generation of waveform-based model (of the four) will he use? (For full descent into the abyss, see the *How2Power Today* series on peak or valley current-loop control.) The block diagram shows something like the second-generation sampled-loop model of Ray Ridley. Ridley remains content with his model, but others have moved on from it.

Mammano recognizes (p. 123) that in "Analyzing this two-loop system, where the gain of a voltage-control loop is modified by a current-feedback loop could be quite difficult." Yet taken step by step, it is quite possible for many engineers. Using intuitive circuit explanations and some hand-waving, the abyss is avoided, and what is typically adequate is provided.

The chapter moves on to a section on measuring loop response. It comes across to me as another explanation of what Middlebrook, then Ridley, have presented, using network analyzers to make the measurements, with or without isolation from the circuitry. In the references for the chapter, Ridley is cited along with Robert Sheehan, who came to TI from the National Semiconductor acquisition. Sheehan has some interesting modeling development based on circuits instead of waveforms. (TI has posted some of his papers on this. It is circuit-based rather than waveform-based converter modeling.)

Chapter 7 changes course back to magnetics. It opens with: "Magnetic theory is often difficult to grasp for many electrical engineers who find it relatively easy to describe the flow of electrical current in a conductor …" then charts the course to successful designs "while not delving too deep into magnetic theory." He then gives some historical background bullet items, beginning with Aristotle in 600 BC. Names of Gilbert, Oersted, Ampere, Faraday, Maxwell, and Einstein are included in the list.

He then offers simplifications of two of Maxwell's equations: Faraday's and Ampere's Laws. Not only does he avoid vector calculus, he happily avoids bad fields language—the "EMF" and "MMF" words—but mixes referral factors with units ("A-turns"), which can cause confusion if not distinguished. Then along comes permeability, the *B*(*H*) loop, and the recognition that full core utilization (maximum energy density) is achieved when operated near saturation. (It must also be operated near the maximum thermally-allowed ΔB for maximum energy density.)

Inductor design includes basic inductance derivation from Maxwell's equations and magnetic circuits with air gaps. Then a questionable bullet item about the core power-loss curves is given: "From a thermal standpoint, it is desirable to keep the core loss below 100 mW/cm^3 at the maximum expected operating temperature." (This might have originated from an *early* Magnetics Inc. catalog rule-of-thumb.) This is not generally true; it depends greatly on the core size. Allowable limits for a temperature rise 40°C above ambient can vary from 41 mW/cm^3 for E450-26 cores to over 1 kW/cm^3 for small cores. A thermal model is needed from which to calculate the allowable core loss.

RMS calculation for triangle-wave current waveforms appears before diving into eddy-current effects. Skin and proximity effects are described, and better, are illustrated. For core sizing, the common but crude *area product* method is given. The procedure for designing transformers is not unlike others found in the literature but does not emphasize performance optimization. (The topic is complicated; I spent two years, full-time, refining, clarifying, and simplifying *power magnetics design optimization* and wrote a book with that title; see www.innovatia.com.) Mammano recognizes this complexity, ending the chapter with "While the number of variables and decision points are many, the process is straightforward and an adequate understanding is always a key element in completing a project without the need to recycle through design."

The magnetics-chapter references do not include some of the best textbooks on the subject. The first I recommend is *High-Frequency Magnetic Components* by Marian Kazimierczuk, and the other is *Transformers and Inductors for Power Electronics* by Gerard Hurley and Werner Wölfle. Both have been reviewed in *How2Power Today*. The first is more complete and rigorous in covering eddy-current effects. The second is closer in style to this book but contains more detail (being an entire book on magnetics) and is somewhat closer to what designers might be seeking on magnetics.

Chapter 8 covers "ancillary" power-circuit details, such as input and output capacitor design formulas, line-powered peak-charging rectifier circuits, offline voltage doublers, power-factor correction (PFC), line distortion, regulations, and some description of the boost converter and average current control for PFC.

A simpler PFC scheme using a multiplier follows. In this scheme, the commanded input to the current controller follows the input voltage, and a multiplier is used to scale the amplitude so that the output voltage is regulated. Using two converter circuits in a kind of multiphase or "interleaved" manner can reduce input current ripple. The power loss of the input rectifier diodes can be reduced by replacing half of them with two MOSFETs, which also works into a dual-boost scheme. Finally, a buck PFC scheme briefly appears.

Power supply starting problems are often significant and are covered in this chapter. These include undervoltage protection and soft-start, snubbers, and switched-capacitor converters.

Chapter 9 deals with EMI, and we're back to fields. The acceptable magnitude of EMI is what causes problems (p. 188): "Thus it is easy to fall into a trap by assuming that some possible noise sources are too insignificant to consider." Differential- and common-mode noise and filtering are followed by radiated EMI and spread-spectrum frequency dithering.

Chapter 10 is about fault protection beginning with design for human safety. Most of the chapter concerns over- and undervoltage, overcurrent, and overtemperature protection and various means of implementing them. Current-transformer design is followed by load-sharing schemes when supplies are paralleled.

Chapter 11 moves into the realm of optimization, and in particular maximization of efficiency. Governments are imposing minimum efficiency requirements on consumer power supplies, with percentages usually running in the high 70s to low 90s range, depending on output power. Causes of inefficiency are enumerated, such as conduction loss, power-switch switching loss, and magnetic loss.

After this, it is time to step back and consider the strategy of power-supply design from a system standpoint. Different converter circuits are recommended as optimum at various power ranges. However, the overall strategy, as is so often the case, is piecemeal and not systematic. Current steering, which has many benefits to reduce EMI and increase efficiency, does not appear. Additional techniques are given such as sensing the induced voltage for regulation from the secondary circuit during the off-time, as isolated voltage feedback.

We are not finished. Chapter 12 is titled “Digital Power Control”. This is microcontroller (µC) based converter control. Mammano alerts us to what I perceive as a sign of technology gone awry (p. 278):

> *A fully integrated chip design where the semiconductor manufacturer has incorporated digital circuitry to implement more complex functions while minimizing cost. With this approach, the user need not be aware of whether the internal operation of the circuitry is analog or digital—he merely follows application information provided by the supplier.*

There is a trend in the IC business to make ICs “black boxes”, at odds with the open-technology attitude of the past, when the customer was informed about what the product was, and not merely in how to use it.

Which kinds of power supplies are amenable to µC control? The first Mammano presents is a solar-powered lighting system with solar charger for a lead-acid (not nickel-iron!) battery with maximum input power capability. Battery charging has various states, and it is all well-suited to µC control. Indeed, consumer battery chargers on the market usually have µCs in them for this reason, and to drive the user interface. A second example is a PFC followed by the effects of µC quantization and delay from computation in a real-time system. The versatility of a µC is emphasized. More is said about the PMBus.

Chapter 13 is by a different author, Robert Kollman, on power supply construction, and begins by expounding on parasitics. There is some overlap with previous material, but it is largely complementary. The resistance of a typical circuit-board via is 0.8 mΩ. And a via has a thermal resistance of about 100°C/W (page 322). Layout examples are shown for minimizing parasitics. This chapter covers what is often neglected, and shows maturation of thinking in power-supply engineering.

And that’s about it. Page 333 has biographical information on Robert Mammano, and it is a significant part of the history of power supply technology. *Power supply* is a broad topic and the many topics involved within it cannot be developed in depth in a single book. Yet there is value in presenting not only the width of the field, but also enumerating and highlighting the many design considerations of importance. In pursuing that goal, this book does a superb job.

Anyone designing power supplies will benefit from having, and reading, a copy. It took me a couple of days to do a close scan of it, reading most of the text. For the price of the book, I could have paid as much or more for a convention seminar and gotten much less. If you are involved in switching converter design, buy a copy and start reading.

About The Author

Dennis Feucht has been involved in power electronics for 25 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](#).

