Book Aims To Demystify Power Supply Control

An Intuitive Guide to Compensating Switching Power Supplies, Christophe Basso, 159 numbered pages, glossy soft cover, 8.5 × 11 inch, Faraday Press, Ken Coffman, Editor at Stairway Press, ISBN 978-1-960405-37-1, 2024.

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Author Christophe Basso has designed converter control ICs for ON Semiconductor (now called onsemi) in Toulouse, France and has written related books reviewed in How2Power Today.[1,2,3] The preface of this manual neatly summarizes the problem it addresses: "… when teaching seminars, designing the control loop often comes back as the most difficult issue encountered by engineers. The theory is usually well understood but the implementation of what is described in textbooks is lacking in practical details, often unique to the specific control scheme. Many converters are stabilized by trial-and-error then shipped without the assurance that the product will remain stable during its operating lifetime."

The organization of the book contents might contribute to why Basso calls it a manual; each page covers a topic with a page title as though it were written from a slide presentation. This manual is intended to be practical in filling in details that are missing in the control theory that applies to switching converters. This includes an emphasis on circuit simulation, using SIMPLIS. The theoretical centerpiece is the control (duty-ratio) to output incremental transfer function, derived more simply by applying high-level circuit theorems summarized in a *How2Power Today* review[1] of Basso's previous book.

The book begins by summarizing basic feedback control concepts with an emphasis on feedback loop stability. Frequency-response (Bode) plots are applied in the analysis with phase and gain margins as stability criteria. In the time-domain, transient step response is also introduced as a means of assessing stability.

The convention in control textbooks is to label the forward path G and feedback path H, but in Basso's scheme, G and H both appear in the forward path. Instead of *damping* ζ, the equivalent parameter found in narrow-band communications literature $Q = 1/2\cdot\zeta$ appears instead. Closed-loop Q_c is plotted against phase margin for a pole-pair.

The design scheme focuses on choosing a crossover frequency (where the loop gain magnitude is one). For the three PWM-switch configurations, guidelines are given as heuristic equations for the crossover-frequency range; all are, of course, below the Nyquist switching frequency. The rationale for the ranges is not developed analytically.

Next, a quasistatic PWM model is presented which has a transfer function of $1/V_p$ where V_p is the sawtooth waveform excursion. The phase response is flat, of course, for a quasistatic PWM, though the effects of comparator propagation delay modify the quasistatic model as shown by frequency-response graphs.

Although not derived in this book, the PWM dynamic model has an approximate single-pole transfer function of

$$F_m(s) \approx \left(\frac{4}{\Delta I_{L0}\cdot D'}\right)\cdot\frac{1}{\frac{2}{\pi\cdot D'}\cdot\left(\frac{s}{\omega_s/2}\right)+1},\ [s/(\omega_s/2)]^2 << 1,\ \Delta I_{L0} = \frac{V_{OFF}\cdot T_s}{L}$$

The history of PWM modeling in power-control feedback loops shows the difficulty of analytically deriving the best equation. Basso does not divert attention to this but retains a practical outlook, resorting to simulation instead.

To demonstrate the practicality of what the book presents, the effects on output voltage waveforms of different choices of crossover frequency are shown (page 21) by the graph of Fig. 1. The tradeoff between a high-speed control loop (f_c) and amplitude of the perturbed output voltage is evident.

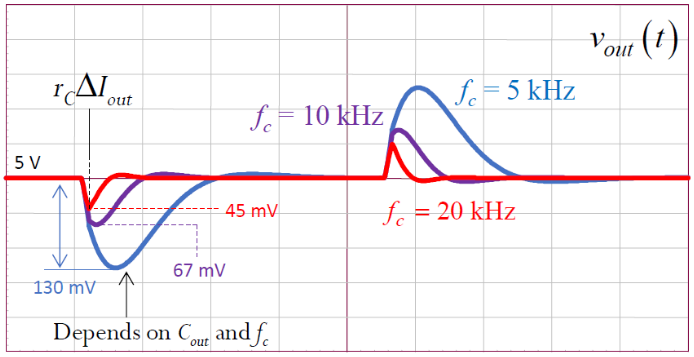

Fig. 1. The plots demonstrate the tradeoff between f_c and output voltage ripple amplitude (Figure from page 21 of Basso's book).

The control transfer function for proceeding further in the design is required to design the loop compensation of the error amplifier. Basso explains the logic of an error amplifier circuit by beginning with a quasistatic inverting op-amp, then replacing the feedback resistor with a capacitor, which places a pole at the origin and increases quasistatic loop gain for greater accuracy.

The phase margin around f_c is increased, after a page on the effect of poles and zeros on frequency response, by three circuits, each of increasing complexity, that contribute greater amounts of phase lead. The transfer functions are given for each. Then the response details of each are explored and circuits simulated.

Basso's step-by-step procedure for loop compensation has a clear rationale, giving the reader the impression that loop compensation is not so difficult after all. And that is the whole point of the manual!

Some of the *practical* considerations include the finite bandwidth of the op-amp in the compensator circuit. Basso derives the transfer function for typical op-amps having a dominant open-loop pole and a single-pole response.

Some of the techniques for working with Bode plots that are not in most textbooks are given to simplify the design task. These simplifications are both theoretically justifiable and important because they make loop design tractable for those who otherwise would despair of loop analysis and make guesses for parts values instead, resulting in the kind of unreliable power supplies this book is intended to avoid.

I have one minor comment about how to express gain magnitude. Control theory originally grew out of communications circuit theory where large signal ranges occur that are better expressed on a logarithmic scale, and the scaling of bels, or decibels, became the practice.

Basso continues with this convention, though I have found it simpler and clearer to express log-scaled quantities in decades or octaves; for example, 50 dB = 2.5 decades. The unit reference quantity for log-zero still must be made explicit, but scaling in decades avoids the unnecessary multiplying or dividing by 20 (or 10 for power).

PID compensators add three parallel responses for a combined effect of a pole and two zeros. Transfer functions having more zeros than poles for analog circuits are unrealizable, and the D block of the PID diagram, when implemented in analog circuits, will have an additional pole. It can be separated from the zero so that the high-frequency gain magnitude will be finite. This results in a circuit of infinite bandwidth, and additional high-frequency poles in actual circuits will eventually cause the gain to decrease toward zero. Yet the effect on loop gain is to decrease phase delay and increase stability.

Basso then adds this "missing pole" as a factor onto the PID transfer function and *voila!* The type 3 compensator—the most complicated one given previously—has the same form, with two poles, two zeros and the (frequency-independent) quasistatic gain as a factor out front in the transfer function. Attempting to design control loops with PID parameters is annoying, and Basso circumvents it by focusing on poles and zeros independent of the block diagram topology of the compensator—a more *intuitive* procedure. The transfer function for it is given on a new page.

One of the indications that Basso has mastered the simplification of control analysis is that he puts transfer functions in *normalized* instead of *canonical* form, where frequency always appears as a ratio with pole or zero in the denominator. The frequency-dependent rational function then becomes unitless. (Poles and zeros at the origin have infinite gain at 0+ Hz but can also be put in this form so that the quasistatic gain is projected to the zero-crossing frequency in the origin pole or zero ratio.)

On page 44, the topic shifts to optocouplers (OCs). They have a current gain which manufacturers specify as a "current transfer ratio". Basso explains how to characterize its single-pole frequency response on the bench. By having the OC collector drive a common-base (CB) NPN BJT to form a cascode stage, the pole frequency is increased. Or the OC emitter connects to the emitter of a CB PNP BJT to form a complementary diff-pair. (Basso calls it a "cascode" though a cascode is a CE BJT driving a CB BJT. This is a common-collector (CC) or "emitter-follower" driving a CB BJT.) Either circuit is an improvement in OC dynamics.

Output-side circuitry involving the popular TL431 (a well-designed part) is developed from a design viewpoint. Fast and slow paths in the TL431 circuit are each designed for an accurate and stable loop. The fast path is through the resistor that drives the OC diode; the slow path is the active path through the TL431.

Attention then turns briefly from the TL431 to transconductance amplifiers commonly found in power-controller ICs, then to digital compensators, starting with a desired continuous complex-frequency *s*-domain function converted to the *w*-domain by applying the trapezoidal integration $s \to z$ transformation. In *z*, the discrete time-domain implementation of the function is straightforward. It is not necessary to understand circuit dynamics in the *z*-domain as some control textbooks teach to go through *z* to discrete time as found in real-time software. Digitizing the PID follows on several pages (64 to 67).

On page 68, the compensation methods developed previously are now included in an overall scheme for "Stabilizing Switching Converters". Step one is necessary: having the control-to-output transfer function, whether derived analytically, by simulation, or by measurement with a frequency-response analyzer (FRA) instrument.

I agree with Basso on this but it is a demanding first step analytically, considering that several decades of effort have been put into deriving the peak (or valley) current control loop, and no generally-agreed-upon result exists in the literature. (However, this does not mean that one does *no*t exist; see the *How2Power* series[4] for both an explanation of why and a theoretically correct refined model.)

Basso's second step is to specify the critical control parameters, foremost among them being the feedback loop crossover frequency f_c. The third step is to simulate. Hence, the procedure is a combination of analytic, semi-empirical, and optionally experimental (measurement-based) methods. Fig. 2, from page 68, is a graph for comparing SPICE simulation with FRA measurement.

As the Nyquist frequency ($f_s/2$)—where f_s is the switching frequency—is approached, simulation deviates appreciably from measured behavior. (This is also true of some peak-current loop models.) Thus, keep $f_c << f_s$, a condition that makes valid the 1970s Middlebrook first-generation model (as presented in Erikson & Macsimović, *Fundamentals of Power Electronics, Second Edition*).[5]

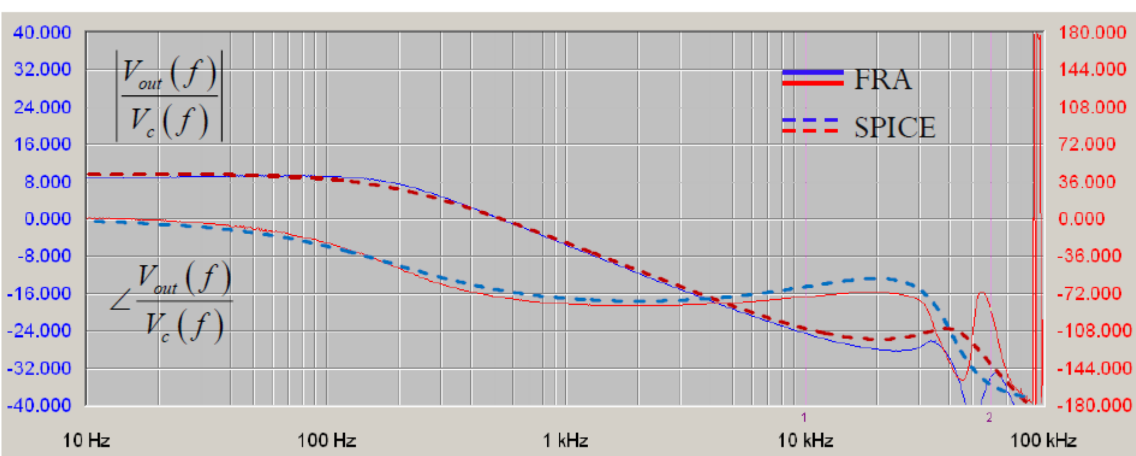

Fig. 2. Bode plots of measured (FRA) and simulated (SPICE) loop response (Figure from page 68).

Around page 70 is emphasized the importance of verifying, then testing with a prototype, for acceptable behavior over the power port input voltage and output current ranges and not at only the extreme values.

Statistical analysis using Monte Carlo simulation is one way of testing a design under numerous possible conditions.

The background music of the book changes as EMI is considered, beginning with how the filter impedance presented to the input power port—a constant-power port with negative incremental resistance—can be unstable if the filter-converter circuit loop is not positive in incremental resistance. Basso has a clever way of presenting the instability criterion by making a feedback loop of the input circuit.

Design examples follow; (p. 73) the buck circuit in voltage mode is given a few pages. Basso then broaches a *practical* topic of what the tolerance needs to be on frequency-compensation components. On page 82, synchronous rectification comes and goes as (p. 82) the buck circuit in current mode is designed. Slope compensation is added with simple equations for calculating how much slope; no rationale for them is given. On page 85, the CCM transfer function is

$$H(s) = \frac{V_{out}(s)}{V_{err}(s)} = H_0 \frac{1+\frac{s}{\omega_z}}{1+\frac{s}{\omega_p}} \frac{1}{1+\frac{s}{\omega_n Q}+\left(\frac{s}{\omega_n}\right)^2} \qquad H_0 \approx \frac{R_{load}}{R_i} \frac{1}{1+\frac{R_{load}T_{sw}}{L_1}\left[m_c(1-D)-0.5\right]}$$

It is not clear how this result was obtained. The CM circuit has two loops, the inner current loop, which has (given the second-order Padé approximation for the zero-order hold from Tymerski and used by Ridley) a zero-pair, a pole-pair and an additional pole. The zero and pole in *H(s)* are in the outer voltage loop. The single pole-pair does not adequately model the contribution of the current loop. H_0 resembles the quasistatic factor of the PWM transfer function, or F_{m0}.

This expression does not repeat the error of the Tan-Middlebrook "unified" model by placing some of the dynamics in the quasistatic factor. (For more on that, see the *How2Power* series on peak current control.[4]) It also does not appear to have been derived from Ray Ridley's second-generation sampled-loop model.

Constant on-time CCM control of a buck power-transfer circuit is also covered (p. 88) and has no subharmonic instability. A constant on-time leaves valley current as the control variable and is suitable for buck transfer circuits. Various buck-derived circuit variations are designed and analyzed.

Then on page 104 the manual moves on to boost power circuits and by page 110, to power-factor correction (PFC) for boost circuits. PFCs require some form of multiplier at a circuit level and this is avoided by simulating with a multiplier block; what is in it is your choice. Some of the nifty translinear circuits of Barrie Gilbert could be applied here. On PFC waveform distortion, Basso does not do too much with it. (See my book, *Waveshape Converters*[6] for details on multiplier circuits and PFC waveshape distortion.)

The third and last PWM-switch common-inductor (CL) (buck-boost and flyback) transfer circuit configuration appears on page 116. More of the same kind of design and analysis proceeds for variations on it including regulation with multiple outputs. Slope compensation for the UC384x controller (p. 136) is followed by various power circuits controlled by a UC384x. Its two series diodes following the error amplifier, and before the /3 divider, allow the PWM input voltage to be as low as 0 V, which allows cycle skipping under light load.

A CL circuit variation with coupled-inductor current steering is the SEPIC (the Single-Ended Primary-Inductance Converter which might be more aptly described as the SEcondary Polarity-Inverted Ćuk) circuit. LLC resonant circuits also appear (p. 145) and include hysteresis control that indirectly determines frequency while directly controlling the extrema of the output voltage waveform. For these more-complicated circuits, with either resonance or current steering, simulation is applied to analyze their loop response. No transfer functions are derived.

The LLC with current control by (p. 151) "the NCP1399 from onsemi turns the high-side switch on while monitoring the resonant current. When the current reaches the setpoint, the controller turns the switch off. It precisely records this on-time and activates the low-side switch on for the exact same duration. A 50% duty ratio is obtained and the switching frequency is, again, indirectly set by the peak current setpoint." As an IC designer at ON Semiconductor, Basso has some close personal experience with this circuitry. (It reminds me of a kind of triangle-wave generator in Tektronix TM500 FG instruments of long ago.)

The manual winds down with some example circuits and their prototype boards presented by Basso at APEC late last decade. The book ends with book recommendations, papers, articles and Internet sites.

As for differences in design preference, instead of choosing a crossover frequency for the loop response, I prefer to decide the damping instead and then let f_c fall out of that because damping is directly related to transient response. Sometimes both resonant frequencies and damping are free to be chosen.

Basso's procedure is similar in that he decides early what the phase margin should be to achieve the desired damping (Q_c). Because this is a *practical* manual, it is not unreasonable to expect a more concrete, circuit-oriented approach to converter control, though it is possible to generalize much of this by working out the theory for all three PWM-switch configurations and their variations starting with the waveforms, the central one being the inductor current.

As is characteristic of Basso's books, this one has a relaxed but reasonably rigorous style of presentation that communicates well and has the right depth of theory for most engineers. It should be a welcomed complement to his other books on related topics in power supply design.

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4. "Special Series On Current-Mode Control" by Dennis Feucht, originally, published in the September 2011 through March 2012 issues of How2Power Today.

5. *"Fundamentals of Power Electronics," Second Edition* by Robert W. Erickson and Dragan Maksimović.

6. *Waveshape Converters* by Dennis L. Feucht, available in PDF at innovatia.com.

About The Author

Dennis Feucht has been involved in power electronics for 40 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.