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Book Review

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Text Offers Updated SPICE Tutorial For Simulating Today's Power Supply Designs

Switched-Mode Power Supply Simulation with SPICE, Steven M. Sandler, Faraday Press, 2018, 307 pages, glossy paperback, ISBN-13: 978-1-941071-63-2.

Reviewed by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

This book is an update of a previous version, published by a new electronics book start-up, Faraday Press, run by Ken Coffman in Apache Junction, AZ. The book is essentially a SPICE tutorial and guide for power electronics applications. Much of it is similar to what is found in the existing PSPICE literature, though it covers power-circuits aspects of simulation in particular.

The obvious convergence problem for SPICE is discontinuous functions of time. This is discussed and seems to be a manageable problem, though as early as the 1980s, Richard Tymerski (PWM-switch model from VPI) and his graduate student, Duwang Li, at Portland State U. were working on a simulator that solved these kinds of problems more elegantly than a post-fix patch of SPICE. Yet the SPICE solution is said to work well enough.

I will devote most of this review to chapter 2 on simulation of magnetic components. First to be gotten out of the way are some minor annoyances or opportunities for improvement of the book. The magnetics world has largely standardized on the MKS or SI system and not CGS: Tesla, not Gauss, A/m, not Oersteds. This simplifies calculations by eliminating the CGS to MKS conversions. Second, obsolete and literally incorrect language continues to be used, though it is embedded in magnetics history. In particular, EMF (induced voltage) and MMF (field-referred current) are not forces and should be called what they are.

Third, duality conversion, with its contortions, is presented, though it is not really necessary if one works with the magnetic form of Ohm's and Kirchhoff's Laws. Fourth, some of the basic magnetics equations look like those in 60-Hz transformer textbooks from the 1960s. They are "high entropy equations" (to use a phrase from David Middlebrook) and can be presented in more meaningful ways that have intuitive appeal.

On the positive side, the circuit-oriented theory as applied to simulation modeling looks correct to me, and Tables 2.1 and 2.2 are good additions to the book. The first gives the duality correspondences and the second, the electric-magnetic correspondences. The difference in how magnetic paths are configured (series or parallel) in a magnetic component affects modeling, and the author clearly brings this out. In the past this was not as important because "integrated magnetics" and current-adjusted variable inductors (which use the two legs of an EE core differently) were not as commonplace.

Now let's look in more detail at magnetic component modeling, an abyss that can lead to more levels of complication than most simulating engineers will want to contemplate. Having spent the last several years descending this abyss (see my book *Power Magnetics Design Optimization (PMDO)* to see how deep this rabbit-hole can go), what follows are some comments about additional complications or simplifications for the modeling beyond what is presented. There are two nonlinear effects of importance: core saturation and winding eddy-current losses. Both can be modeled, though nonlinearly.

The saturation model used in the book (Fig. 2.22, page 60) has a single bipolar (±) breakpoint for an otherwise linear $B(H)$ and no hysteresis. This is oversimplified; most power magnetic components are operated in the saturation region and it is closer to logarithmic than linear. *Saturation* refers to the sublinearity of $B(H)$, $\lambda(i)$ or $L(i)$ curves, and is quantified by the *saturation factor*, the ratio of μ or $\mathcal{L}$ at a given current to the zero-current value:

$$k_{sat}(i)=\frac{\mu(i)}{\mu(0)}=\frac{\mu(i)}{\mu_i}=\frac{\mathcal{L}(i)}{\mathcal{L}(0)}=\frac{\mathcal{L}(i)}{\mathcal{L}_0}$$

$\mathcal{L}_0$ is tabulated (as A_L) in core catalogs as a function of materials and core sizes. This k_{sat} parameter is important but only appears in the book in the shadowy background and is not given a symbol. The fractional saturation curves, $[\mu(H)/\mu(0)]$, shown in Fig. 1, are derived from the plots for iron-powder cores of Micrometals, Inc. catalog 4G, page 18. Constructing a line on the semi-log saturation plot tangent to the curve at k_{sat} = 0.5, the inflection point which is at or near the typical operating-point for power inductors, leads to a simplified asymptotic model for saturation.

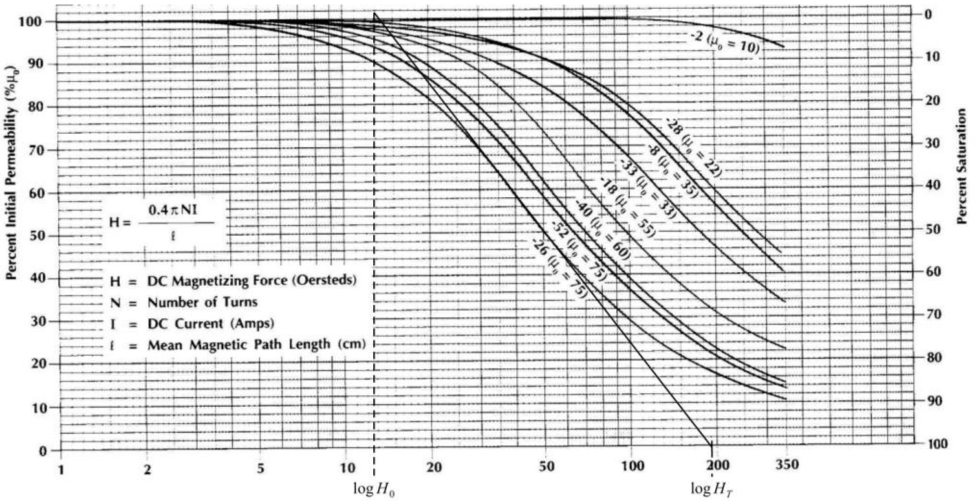

Fig. 1. Linearized approximation at k_{sat} = 0.5 of saturation region, drawn on Micrometals catalog curve for 26 material.

The graph of the simplified model in the saturation region is shown in Fig. 2.

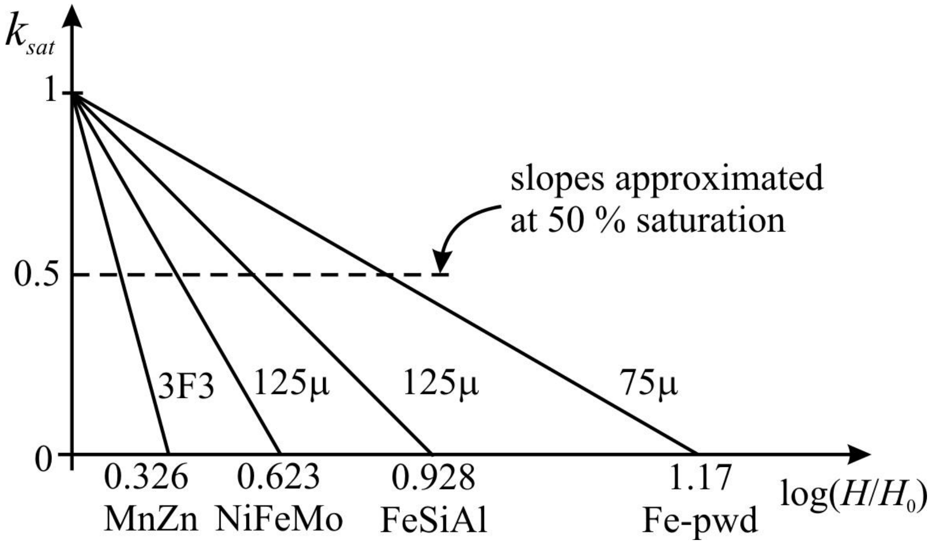

Fig. 2. Semi-log asymptotic approximation of saturation region of $k_{sat}(H)$, normalized to H_0 for various materials.

I recommend consideration of this model for both simplifying and improving saturation modeling. (A future article in this publication will cover this model in detail.)

Inductance, or from a size-independent field standpoint, permeability, μ, not only decreases with increasing current (or H) but also with increasing frequency. The "bandwidth" of the core material is characterized by two different frequency parameters. The frequency at which $\mu(f)$ begins to decease is f_μ. However, core power loss also rises with frequency exponentially, but so does power transfer rise linearly. Where the maximum power transfer occurs is f_{MAX} above which the core is increasingly suboptimal for power transfer. Figure 2.26 (page 68) of the book presents f_μ.

We descend to the next level of the abyss at page 90, where eddy-current effects appear. These affect winding resistance and its power loss. One optimization the book covers is maximization of winding-to-winding power transfer, a topic usually given short shrift in the literature. (But not in *PMDO*.) On pages 90 - 93, the modeling of winding loss with frequency includes some of the usual plots of Dowell's equation and a single-pole, single-zero (phase lead) model for approximating the effect. However, in a SPICE that allows an equation to be given to model the behavior of a circuit element, a resistor modeling wire resistance (per winding) with the algebraic approximations to Dowell's equation would be accurate to a few percent or better across a wide range of frequencies and especially, wire sizes:

$$F_r(\xi_r, M) \approx \frac{1}{\xi_r^2} + \left(\frac{5 \cdot M^2 - 1}{45}\right) \cdot g_r^4 \cdot \xi_r^2, \xi_r < 1$$

$$F_r \approx \frac{2 \cdot M^2 + 1}{3} \cdot \frac{g_r}{\xi_r} = (2 \cdot M^2 + 1) \cdot \frac{g_r}{3} \cdot \frac{1}{\xi_r}, \ \xi_r > 1.94 \approx 2$$

ξ_r range	$\xi_r < \xi_{rv} < 1$	$\xi_{rv} \le \xi_r < 1$	$\xi_r > 1.5$
$F_r \approx$ constant ·	$1/r_c^2$, $1/A_c$	r_c^2, M^2	$1/r_c$, M^2

where ξ_r = round-wire conductive radius/skin depth = $r_c/\delta(f)$; M = number of layers; $g_r \approx 1.547$, a geometric conversion constant for round wire to the flat plates of Dowell's eqn; F_r = fixed-frequency eddy-current resistance multiplier of R_δ, the static resistance of a wire with $r_c = \delta$.

The winding resistance depends on the wire size (r_c or, normalized by skin depth, ξ_r), by the number of layers, and by whether layers of windings with opposing fields are interleaved or configured as multifilar. The rabbit-hole for magnetics modeling has only begun to be entered.

Chapter 3 covers EMI filter design. For the converter input port, a negative resistance results at the port terminals because the converter is controlled to input constant power. Thus, if the voltage decreases, more current is drawn to maintain power and an increase of current with a decrease of voltage at the same terminals is a negative resistance. This resistance can result in an undamped resonance and oscillation. Although this is more about design than SPICE modeling, the modeling appears in the construction of the filter compensation circuits. Inrush current limiting is also covered—a good chapter on a topic not widely understood.

Chapter 4 is about PWM-switch common-passive "buck" converters, beginning with a circuit-simple hysteretic control converter. The author worked out some of the modeling analytically (that is with algebraic equations) to compare to the simulations—a very good idea when using a simulator! Chapter 5 moves on to PWM-switch common-inductor "flyback" converters. Simulated circuits valid for both CCM and DCM operation are presented with SPICE netlists and some resulting waveforms for particular circuit parameters. Chapter 6 reverts to linear regulators and the low-dropout regulator.

Simulators appeal to bench-driven engineers in that circuits and their element values can be tinkered with. Resulting waveforms for circuits too complicated to analyze appear with relative ease. The circuit could be built on the bench and probed, but the simulator has the power to impose idealized situations that reveal more about the circuit than a bench prototype. For instance, Fig. 6.6 (page 192) shows a "simple modification which has been added … (L1, C1)" which "allows us to measure the open-loop gain and phase [of the loop] while the circuit loop is still closed." This measurement is harder to make on a prototype circuit.

Chapter 7 switches to "DC-to-AC Conversions" and begins with how to generate sine-waves in SPICE. A push-pull converter circuit appears with nonlinear load modeling. Then a three-phase sine generator appears. SPICE netlists, circuits, and waveforms accompany all the developments. Chapter 8 is the inverse function of inverters, the power-factor corrector (PFC), including three-phase PFC.

Chapter 9 is about improving simulator performance, about better models and a more nuanced use of the simulator. The last chapter is "Solving Convergence and Other Simulator Problems" It is succeeded by "References"—106 of them—and no index.

For engineers who are inclined to simulate power circuits, this book should be within arm's reach on the bookshelf along with Christophe Basso's book, *Switch-Mode Power Supplies: SPICE Simulations and Practical Designs* (McGraw-Hill, 2008). Basso is mentioned as contributing to this book along with Rudy Severns of Springtime Enterprises, a long-time contributor to progress in power electronics.

About The Author

Dennis Feucht has been involved in power electronics for over 30 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.