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Text Charts New Analytical Course For Optimizing Power Supply Magnetics

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Power Magnetics Design Optimization, Dennis L. Feucht, (www.innovatia.com), first printing: 2016, 456 pages, glossy paperback, $60 U.S., ISBN: 9781682736272.

What, an author reviewing his own book? Like engineering decisions, reviews have their tradeoffs. Authors reviewing their own books are likely to lack the objectivity of a dispassionate observer, yet can offer insights only known to the author. This review attempts the latter. The motivation for the book is a case in point.

Around the beginning of the last year, I was asking questions about the design optimization of magnetic components and I was not finding answers to them in the textbooks or articles available on magnetics. This led to 16 months of intensive theoretical magnetics research culminating in this book, as well as previously published and forthcoming articles for How2Power, and one paper for the IEEE Transactions thus far.

The hard part of engineering is sometimes knowing the right questions to ask. Finding answers might be hard work but success depends greatly on asking the right questions to set the direction of the quest. In my mind, there were five questions I wanted to address. The first question, which was addressed a few years earlier, was how to maximize transfer-power density for coupled inductors. That question was answered and appears in the opening part of "Optimization," chapter 5 of the book, and also in a series of articles in *How2Power Today* (see the reference.)

The second question I asked was whether there might be a better, simpler way to model the thermal aspect of the magnetic component. A new method based on the normalization of various core shapes to that of the simple and worst case—that of a sphere—results in the *thermal shape factor*. Core power-loss density estimation is thereby simplified and reduced to manageable proportions in chapter 3, "Magnetic Design."

My third question was why *unibundle* construction is not used more widely. This is *N*-filar construction, but with both windings (or sets of windings) of opposite current polarity, wound together in a single bundle. Sometimes the integer division of turns built up with identical strands of wire is not right, or the number of strands to be connected is overwhelming. Yet for many applications, the scheme is feasible and has many advantages over sequential winding construction. A probabilistic analysis of the effective number of layers in a bundle is derived in chapter 4, "Electrical Design," which is more specifically winding design.

Both chapters 3 and 4 also cover the better-known basics of magnetic components, though some extra derivations are included such as an accurate formula for determining the winding length needed for toroidal windings, of approximating magnetic saturation, of the thermal advantage of distributed cores, relative advantages of aluminum or copper conductors (Charles Sullivan also has a paper on this), and interlayer and interwinding capacitance approximation. All design formulas are derived so that the reader knows what they are and where they came from.

My fourth question was how to choose the optimal operating frequency for minimum core loss and maximum power transfer. The derivation is based on the *generalized Steinmetz equation* and not the simplified "classical" equation with ΔB^2 and f^2 factors. The result is in chapter 5, "Optimization." It also includes a rather extended analysis of power transfer through the transductor—the magnetic component of multiple windings (whether coupled inductor or transformer.)

Two methods of power transfer optimization are given in prior books. The first, based on subtly faulty calculus, is the application of the maximum power-transfer theorem (which might better be called the "maximum output-power theorem.") It concludes that core and power loss should be equal for maximum power transfer. This is true only in the special case where no transfer actually occurs and is otherwise only approximately true.

In my book, the analysis is taken a small step at a time by first using one-sided models (referring secondary winding resistance to the primary or vice-versa, so that all the winding resistance is on one side or the other), and then showing why one-sided models are not adequate because referral of winding resistance does not allow for derivation of power transfer in the general case when core loss (in core resistance in the model) is included.

The algebra is challenging for the general, though simple-looking, transductor circuit model, as shown in Fig. 1, with secondary winding circuit referred to the primary. When the math is worked out, some new and useful quantities result such as the *power-loss ratio*, β and α (reminiscent of BJT β and α) for winding/core resistance ratios, and efficiency, η, which is the same as the power-transfer function to be maximized, subject to other constraints. In practice, an acceptable η is chosen (of perhaps 98% or 99%) and winding design optimization (the next question) is based on it for setting a winding resistance goal.

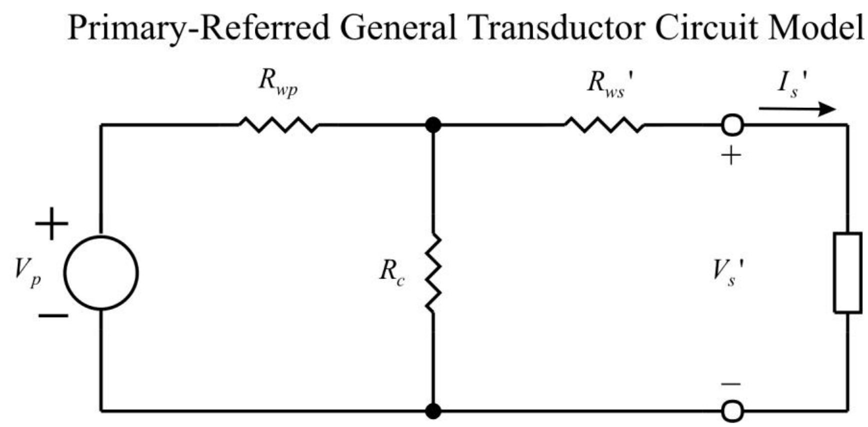

Fig. 1. General circuit model for a transductor having primary and secondary winding resistances, R_{wp} and R_{ws}, referred to the primary as R_{ws}'. The core circuit-referred resistance is R_c. The load is to the right, on the secondary circuit. Primed quantities are the secondary quantities referred to the primary through the turns ratio squared, n^2.

Maximization of *power transfer* is the driving goal of electrical (winding) design just as maximization of *transfer power* is the goal of magnetic design for coupled inductors (and in a different way, for transformers).

An alternative given in the literature for optimizing winding design is the minimization of power loss or the K_g method. This might be a primary goal in itself for some designs, and minimum loss is presented in the book. However, minimizing power loss does not necessarily maximize power transfer from primary winding port to secondary port, and the book shows why.

The fifth and final question leading to what I suspect most of you will find is the biggest contribution of this 16-month effort concerns how to optimize the winding design itself while taking into account eddy-current effects. These effects can be neatly summarized by the Dowell equation for resistance, where the ratio of winding resistance normalized to static (dc) resistance is F_R for constant wire size. This is the winding-resistance multiplier caused by eddy currents.

However, what is more useful is F_r, the ratio normalized for constant frequency, which can be derived from F_R (as shown in chapter 4 on "Electrical Design.") F_r is more useful than F_R because the optimal frequency is determined in the magnetic part of the design and is fixed for the winding design. Dowell's equation is thus used in the form of $F_r(\xi, M)$ where ξ is the wire size normalized to $\delta(f)$, the skin depth at frequency, f ; and M is the number of layers (not necessarily an integer) of conductor.

Various details complicating matters somewhat (such as shape of wire: foil, square, or round) are derived or explained in the book, in chapter 4. (The *How2Power Today* series on eddy-current effects also presents it.) When explained as simply as possible, these concepts clear the way for winding optimization as described in chapter 5. The novelty here is the derivation of the equation for layers as a function of the winding window geometry and (round) wire size of conductive radius, r_c, as $M(r_c)$.

For instance, for a given bobbin width, w_w, and wire size, only so many strand turns can be fitted per layer in the bobbin width. This poses a simple algebraic constraint on M that can be substituted into Dowell's equation, along with $\xi_r(r_c)$. When rectangular or toroidal window geometries are applied as constraints, the loci of F_r trace out plots on the $F_r(\xi_r, M)$ graph that have interesting design operating-points, usually at minima. To minimize (or constrain to some maximum value) the winding resistance, which is the ultimate winding design goal, the *bundle* $F_r = f_r = F_r/N_s$ is minimized, where N_s is the number of strands per winding bundle.

In the Fig. 2 graph below, the black plots are derived from the unconstrained Dowell-equation F_r with M as a parameter. The points on the plots can be thought of as magnetic operating-points (op-pts). The interesting op-pts are those that minimize winding resistance and are the f_r minima.

For an instance of a geometrically-constrained f_r, by holding N_s constant, a minimum of f_r occurs at a given $\xi_r = \xi_{rN\text{min}}$, as shown by the solid green plot, at a value of ξ_r somewhat greater than 1. The dotted red plot results from holding the cross-sectional window winding area, A_{ww}, constant. Its asymptotic minimum is at an f_r value somewhat above 0.01. It also has a higher minimum for large wire at about $\xi_r = 20$, and a suboptimal value at the maximum of about $\xi_r = 1.5$, where eddy-currents have their maximum effect on winding resistance.

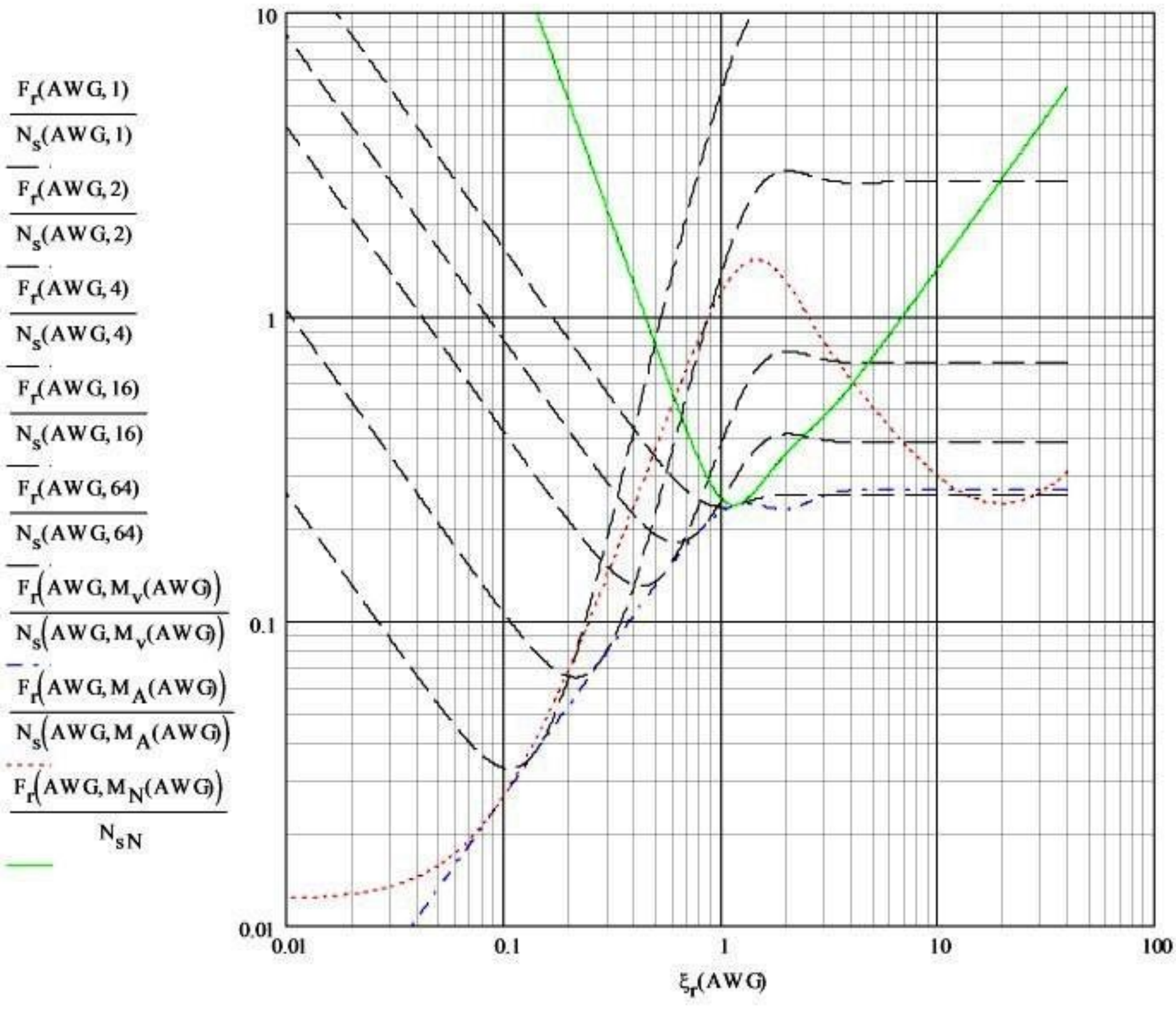

Fig. 2. Plots of the bundle $F_r = f_r(\xi_r, M) = F_r(\xi_r, M)/N_s$, where N_s = number of strands per bundle. When winding constraints are held constant, the f_r plots have different loci than those with constant M. The solid (green) plot holds N_s constant and the dotted (red) plot holds winding area, A_{ww}, constant. The constant-N_s minimum is a design operating-point of interest as is the low-ξ_r asymptote of the constant-A_{ww} plot. Also, at high-ξ_r, it has another minimum.

The Dowell equations can be approximated algebraically for low-ξ_r and high-ξ_r regions, and these equations can be used to find close approximations for the op-pts of interest in the Fig. 2 graph. The book works these out for both linear layering (rectangular windows) and toroids.

Finally, chapter 6 ends the book with "Design Procedures and Examples." A general transductor design procedure, based on the derived optimizations, is given in detail. Although examples are given in earlier chapters, the last part of this chapter provides detailed design examples as *templates* that can be used to guide similar designs, with the relevant equations and tabulations of alternative solutions for a variety of different core materials and some different converter circuits.

Before this, however, the text solves the practical problem of how to determine a power rating for magnetic components when the input voltage is not fixed but can be anywhere within a range. Having input voltage ranges (rather than a fixed input voltage) usually increases the power requirement and size of magnetic components, but by how much? This problem is solved for both inductors and transformers for the three PWM-switch configurations. This chapter is followed by a 10-page index, 5.5-page list of symbols and their page references, and lists of magnetic materials and tables and MathCAD programs (there are two), all page-referenced.

To this point, I have concentrated on the questions that motivated me to write this book and described how the answers to these questions are presented in chapter 3 and beyond. However, before those discussions can be broached, an understanding of first principles is needed and I have endeavored to explain these principles in the opening chapters.

Chapter 1, on "Waveforms," introduces the important waveform parameters that characterize magnetic component behavior. Average and RMS values are worked out for sine- and square-waves. Waveform performance parameters are also described including the important ripple factor.

The second chapter, "Transductors," covers transductors from a circuit standpoint and begins by giving simplified explanations of Maxwell's equations, magnetic-electric analogies (magnetic Ohm's and Kirchhoff's Laws), inductance from geometry, mutual and leakage inductance, transductor circuit models, how to measure model parameters, circuit transforms of them, and also the often-neglected discussion of terminology—both good and bad—in magnetics. All of this provides the foundation for venturing within the devices.

My quest to find answers for design was fulfilled and the results are a new and different set of design equations, procedures, and rationale for understanding power magnetics design optimization.

Reference

A list of my magnetics articles published in *How2Power Today* can be found in How2Power's Power Magnetics section. In this section, click on the link for "designing magnetic components," as that calls up article titles, summaries and links to the articles. Note that these results also include articles by other authors. For a list of just the articles I have written, see the How2Power Today Newsletter Authors page, and open the listing for "Dennis Feucht." This listing contains issue dates, titles and article links. Among the relevant articles listed here, you'll find titles such as "Utilizing Full Saturation and Power Loss To Maximize Power Transfer In Magnetic Components.")

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.