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Power Magnetics Text Delivers Depth, Breadth And Fresh Ideas

Inductors and Transformers for Power Electronics, Alex Van den Bossche and Vencislav Cekov Valchev, Taylor & Francis Group (www.taylorandfrancis.com), an imprint of CRC Press (www.crcpress.com), 2005, 447 pages, hardback.

The title of this book describes precisely what the latest instantiation of the book contents is about. Dr. Bossche is a professor at the U. of Ghent, Belgium and Dr. Valchev, who worked in the Electric Energy Laboratory at the U. of Ghent is at the Technical U. of Varna, Bulgaria. This book adds to the growing list of books on power magnetics for switching conversion, but is by no means just a rehash of familiar material. Even for those familiar with the magnetics literature, it may offer some pleasant surprises.

The book begins logically with an overview of magnetic theory. Then a simplified ("fast") design procedure is described for both transformers and inductors. Chapter three goes into detail on soft magnetic materials and the next chapter covers quasistatic details of the electrical side of transformer and inductor design. Chapter five takes on the winding dynamics: skin and proximity effect and eddy-current losses in conductors, including rectangular conductors. This chapter is long. Chapter six turns to the "Thermal Aspects" of design, venturing more deeply in heat transfer and rate processes than most electronics books.

With chapter seven, we are leaving pavement and hacking into the bush of the magnetics frontier. The authors have the courage to take on the question of what is the intrawinding and interwinding capacitances. With chapter eight, we are back to inductor design, beginning with air coils. Gap fringing is treated less than superficially and we are treated to another round of dynamic winding loss from a design standpoint. Design examples are given for three common converter circuits.

Chapter nine continues with transformer design. Various transformer models are introduced and magnetizing and leakage inductance for them is discussed. Use of parallel and Litz wires for winding design includes a section on half turns, then interleaved windings and the expected appearance nowadays of the topic of nonsinusoidal waveforms.

Chapter ten discusses *optimization* of winding and core losses. (More on this below.) Chapter eleven turns to the bench in treating temperature and power-loss measurements. Both are difficult to measure and this chapter is useful in addressing these difficulties. Among the measurements covered here are inductance, parasitic capacitance, and core loss.

The first appendix of the book gives RMS values for various waveforms—a useful compendium of waveform formulas. The second appendix reiterates some magnetic core data for cores of various commonly-used shapes, followed by an appendix of wire tables. The final appendix is math functions. This is briefly the contents of the book.

Now, for some specific comments; I perked up at chapter ten (not that the preceding chapters were boring!) when it ventured upon design optimization. This is a nontrivial topic, as can be seen by the varied approaches to it in the power-electronics literature. There is no *one* optimization criterion. Some choose to minimize total loss—winding (electrical) plus core (magnetic) losses. Chapter ten starts out this way with a derivation (pp. 368, 369) that has the goal of minimizing total power loss,

$$P_t = P_w + P_c$$

which is the sum of the winding and core losses. The assumption is made that the winding volume is to remain constant. That is, the winding window area that is filled with wire remains unchanged. Then the winding volume, $A_{cwp} \cdot l_w$, is constant, where cross-sectional wire area = A_{cwp} (taking into account packing factor) and winding length = l_w. In the search for minimum P_t, wire size can be varied so that as turns, N (and l_w) increases, A_{cwp} decreases. P_w varies proportionally with l_w. However, to maintain constant winding volume, A_{cwp} decreases with an increase in l_w, and

$$P_w = R_w \cdot i^2 \ , \ R_w = \rho \cdot \frac{l_w}{A_{cwp}} = \rho \cdot \frac{N \cdot \bar{l}_c}{A_{cwp} / N} = N^2 \cdot \left(\rho \cdot \frac{\bar{l}_c}{A_{cwp}} \right)$$

where $\bar{l}_c$ = average turn length which, with a constant winding window, generally remains constant with varying A_{cwp}. P_w varies with N^2.

Then the argument proceeds that P_c varies (according to the "classical" Steinmetz formula) with $\hat{B}_{\sim}^{\,2}$ and flux-ripple amplitude, $\hat{B}_{\sim}$ varies with field (or core) flux, $\hat{\phi}_{\sim} = \hat{B}_{\sim} \cdot A$ which varies with circuit flux, $\hat{\lambda}_{\sim}$, where

$$\hat{\lambda}_{\sim} = N \cdot \hat{\phi}_{\sim} \Rightarrow \hat{B}_{\sim}^{\,2} = \frac{\hat{\lambda}_{\sim}^{\,2}}{N^2 \cdot A^2}$$, A = magnetic-path cross-sectional area.

Consequently, P_c varies (for constant switching frequency) by

$$\frac{P_c}{P_{c0}} = \frac{1}{N^2} \cdot \left(\frac{\hat{B}_{\sim}}{\hat{B}_{\sim 0}} \right)^2$$

where the 0 subscripted constants are the values for N = 1. In other words, P_c varies with $1/N^2$. Then the total power loss can be expressed as

$$P_t = P_w + P_c = N^2 \cdot \left(\rho \cdot \frac{\bar{l}_c}{A_{cwp}} \right) + P_{c0} \cdot \frac{1}{N^2} \cdot \left(\frac{\hat{B}_{\sim}}{\hat{B}_{\sim 0}} \right)^2 = N^2 \cdot P_{w/N} + \frac{P_{c/N}}{N^2}$$

where the $/N$ subscripted parameters are the single-turn values and are constant with N. Take the derivative relative to N to find the minimum P_t. The resulting condition is

$$2 \cdot N \cdot P_{w/N} = 2 \cdot P_{c/N} \cdot \frac{1}{N^3} \Rightarrow N = \left(\frac{P_{c/N}}{P_{w/N}} \right)^{\frac{1}{4}}$$

and for N = 1, $P_{c/N} = P_{w/N}$. For N > 1, core loss exceeds winding loss for minimum total loss. The minimum loss occurs under the above assumptions for equal winding and core losses. The book presents an equivalent presentation (with different notation) of the optimum condition. To the authors, this "means that the minimum power losses, or optimal efficiency … [is] obtained." However, a different analysis by the reviewer in an upcoming *H2P* series on magnetics optimization shows that maximum transfer efficiency does not occur under this condition—not exactly. Maximum power transfer has a somewhat different condition.

The authors are not unaware of other optimization criteria, including equal core and winding temperatures, and include them in the book. This illustrates the value of the book; it contains various useful derivations not commonly found elsewhere.

A second particular strength of the book is its in-depth coverage of fields approximations for other than round wire. The eddy-current losses for square and rectangular wire and for foil are included at some length. For those not fluent in fields math, the authors have enough graphs and pictorial illustrations to explain the intuitive meanings of the mathematical derivations. The authors have analyzed the errors in Dowell's equations (reminiscent of the work of magnetics research engineer Charles R. Sullivan at Dartmouth C.), which are the mainstream equations used to calculate winding loss for dynamic currents. They propose their own improved approximation. I leave it to the reader of this review to assess how it compares to Sullivan's improvements, in papers downloadable from his Dartmouth C. Thayer School of Engineering website.

Overall, this book has enough depth and coverage of topics not found elsewhere that I am thankful to have a copy. Anyone who is serious about magnetics should invest in one. It is hardly old material warmed over and shows that the authors have a good grasp of magnetics.

The English is quite acceptable, though one of the authors must have had an equation editor that does not include Greek letters! It is somewhat annoying (and in a CRC Press book) to have a courier-font m appear instead of μ, for instance, in some equations. They need a re-edit. Secondly, the book retains older, inaccurate jargon such as *MMF*, *magnetizing force*, "copper" instead of "winding", and *ac*, and *dc*. However, the content of the book more than makes up for such distractions.

To their credit, the authors use SI (metric) units—no Oersted and Gauss. The illustrations are well-designed, well-drawn and informative, and references are given at the end of the chapters. No problem sets appear; this is not a textbook but a resource for engineers—a resource worth having for power-electronics design efforts.

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 doing current-loop converter modeling and converter optimization.

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