Power Magnetics Text Is Strong On Theory, Yet Distinctly Practical And A Source Of Fresh Design Ideas

Transformers and Inductors for Power Electronics, W. G. Hurley and W. H. Wölfle, John Wiley & Sons, Ltd., Chichester, West Sussex, PO19 8SQ, UK, (www.wiley.com/go/hurley_transformers), ISBN-978-1-119-95057-8, glossy hardback, 344 pages, 2013.

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This is a long review. This book deserves it. A former student of MIT professor John Kassakian, and now a professor, Ger Hurley, and his student at the National U. of Ireland in Galway, Werner Wölfle, have written a book on magnetic component (transformer and inductor) design. This book has the style that made MIT a leading engineering school: it builds the basic concepts, step by step in logical order, and then develops everything else from this solid foundation.

The first chapter introduces, in a somewhat historical context, the basic equations of Maxwell, major ferromagnetic properties, eddy-current and core losses, and materials. Before chapter one there is a nomenclature list, showing that mechanical and chemical engineers are not the only ones who define their symbols at the outset.

The Basic Principles

Section one on inductors begins with chapter two, a tutorial on inductance, magnetic circuits, and how inductance relates to coil geometry and fields including air-gap fringing. Each chapter has a problem set, as might be expected for a textbook. Chapter three continues with inductor design. The basic design equations are derived or laid out and the strategy for design is given, based on the area-product method, one of the simpler but least optimal methods. As shown in a flowchart (Fig. 3-2, p. 63), this method is not iterative. Design examples for it are given. Core selection and winding design are discussed. Then the design is related to its circuit context. Three example designs have MATLAB program segments for doing design calculations.

Section two on transformers begins with chapter four, beginning with transformer circuit theory involving the winding referral ratio for the ideal transformer: the turns ratio. The more-detailed transformer modeling then includes leakage inductance with secondary-referred equivalent circuits using turns ratio as the referral ratio. Electrical (winding) and magnetic (core) losses are included. The importance of current waveshape begins to appear in the book at this point in the form of power factor. In Chapter five, transformer design begins with the equations and then gives the design process in another flowchart (Fig. 5.3, p. 129.) It is also based on the area product but proceeds in the usual design sequence by picking a core, then deriving the consequences.

The area-product method of design is suboptimal because it makes too many assumptions, which are often not accurate enough for an optimum result. The method of applying the maximum power-transfer theorem (such as is found in Erickson and Macsimović's book, *Fundamentals of Power Electronics*) is only one optimization criterion. A major and often overlooked aspect is the full *utilization* of the core material, driving it to both an acceptable saturation and core power loss. Under full utilization, there is nothing more that can be extracted from the core. Yet no textbook written to date (to my knowledge) presents this straightforward method. (See the *How2Power Today* article, "What Is to Be Optimized in Magnetics Design," D. Feucht, May 2014.)

The chapter continues with design examples, which are not only good for students in covering the various considerations in the design but also for practicing engineers, showing when and how to apply design equations. In the examples, some attention is paid to the importance of the waveforms, though obscured somewhat in the power factor, a quantity that applies to sine waves.

Intermediate Concepts

Chapter six begins to move into the finer points of design with a consideration of high-frequency effects in the windings. The skin-effect equations are derived and the proximity effect with multiple winding layers is presented in typical fashion. The authors do not shy away from deriving the rather math-intensive modified Bessel equation for the ratio of dynamic to static resistance (one indicator of the attention to rigor in the MIT tradition), which is the resistance factor known as Dowell's formula. When this equation is plotted with number of layers as a parameter, a very useful design chart results that can be used for manual (calculator) magnetics design.

The proximity effect for other than sine waves has an entire section. Optimization of wire size or foil thickness versus number of layers, in view of the proximity effect, is developed. Still in chapter six, winding interleaving is shown to reduce proximity effects. Finally, a complicated formula for leakage inductance is presented.

Chapter seven turns to the magnetic high-frequency effects in the core. Numerical approximations of eddy-current loss are accompanied by frequency-dependent core-loss equations. Complex permeability and laminations finish the chapter.

Section three is titled “Advanced Topics”. Chapter eight is the first, that of measurements. Various methods of measuring inductance for power components are time- and frequency-domain-oriented. This material should appeal to the bench-oriented power-electronics engineer. B-H loop measurement is followed by transformer losses.

Moving closer to the edge of the unknowable, a brief model of winding capacitance is presented, then attention is turned to how to measure it instead using a method not unlike that proposed years ago by H-P for measuring series inductance of capacitors. In this case, however, a capacitor is driven with a current source (a large R from a voltage source) and a switch discharges the capacitor into the winding. This causes the voltage across the source capacitor to step downward by an amount determined by the capacitive voltage divider formed with the winding C. The winding inductance is large enough that it has no immediate effect on the negative voltage step. A simple C-divider formula gives a value for winding C. To make a measurement of the voltage step, the source C should be comparable in value to the winding C.

An interwinding capacitance model is also developed based on windings as coaxial cylinders. In many cases, this can be simplified to a parallel plate approximation. An example is worked out given transformer geometry. These capacitance approximations can be quite useful in power-circuit design, for it is often parasitic capacitance that causes the power-circuit engineer trouble. With some anticipation of capacitive effects, time and effort can be reduced. Most power-electronics books do not wander very far into this swamp of modeling parasitic elements, and the authors are commended for taking a sensible approach to an unavoidable topic.

Planar Transformers And Leading-Edge Magnetics

Moving on to chapter nine, we encounter a rapidly developing idea in power magnetics: planar transformers. One of the benefits is the significant departure of their general shape from that of something like a cube or sphere (very 3D) to that of a planar surface (very 2D). This increases the surface area-to-volume ratio which reduces thermal resistance, a fundamental parameter in determining acceptable power loss. Also, windings can be produced using circuit-board or other CAM techniques.

Because circuit-boards are highly repeatable (unlike wire winding configurations), parasitic elements are more precise (repeatable). As for disadvantages, because the windings are relatively few, limited by circuit-board layer stacking, inductances will be relatively low. For low-voltage applications and the use of ferrite cores, this is generally not a major limitation, though for shrinking board size, planar devices use more board area and consequently, interwinding or interlayer capacitance is high relative to wire windings.

The authors state (p. 248): “The circuit models [for planar transformers] have not necessarily changed, but the new layouts of windings and cores require new models for inductance and loss mechanisms.” The authors then embark on an exposition of inductance models for spiral windings, a topic reminiscent of wideband amplifier design (such as oscilloscope vertical amplifiers) which make use of them for inductive bandwidth extension compensators known as *T coils*. Many of these have been used in Tektronix oscilloscopes and have the same spiral characteristics as planar transformer windings. History has an odd way of repeating itself. The authors apply fields theory to planar coils on a magnetic substrate—a topic actively researched at MIT by Prof. David Perreault and others.

We then return to the bench for the “Fabrication of Spiral Inductors” (section 9.2) using circuit-board windings and also thick-film and thin-film processes, which result in highly integrated transformers. From page 275 to 298 are MATLAB program listings for examples in chapter nine.

Besides the Appendix, which has a wire table and list of magnetics manufacturers, chapter ten ends the book on the topic of variable inductance caused by core saturation. The engineering adage once again applies: If you can’t fix it, feature it. Instead of a fixed value, L, the inductor has an inductance of $L(i)$. This results in a nonlinear circuit and has been used to good effect by controlling the saturation characteristic in such applications as “swinging” inductors, which have stepped air gaps. This causes inductance to be large at low currents and at a current value that causes excessive saturation in a fixed-gap core, the wider section of the gap extends the usable current range by causing a reduction in the inductance. With higher *L* at lower *i*, CCM is maintained near the zero-scale end of the power range, with its advantages.

One of the applications that appears in this chapter is a solar charger with maximum power regulation. Because of the wide input voltage range that varies with insolation of the PV panel, the converter circuit flux has a wide range. The core material example chosen is a laminated electrical steel. By using data on a particular material, the *L*(*i*) function can be approximated from a circuit standpoint. Another example uses a Micrometals 52 material iron-powder core and shows how to find the effective *L*(*i*).

Then two-stepped air gaps for swinging inductors, with more equation derivation, show an *L*(*i*) function with a noticeable hump in the curve caused by the step. Finally, the sloped air-gap case is worked out and it has the widest range of *L* over current.

The book ends with interesting application examples that should cause those of us stuck in the fixed-*L* design mode to think "outside the box." One application is in passive power-factor correction for a rectifier followed by an inductive-input filter. Another reduces harmonics because of the increased *L* where the total harmonic distortion (*THD*) is derived. Yet another is maximum solar input power regulation through input resistance matching (from the maximum power-transfer theorem), by extending the range of matching with *L*(*i*). This keeps a boost converter in CCM, thereby reducing current form factor (and shape factor) at low insolation.

Conclusion

Overall, this book receives high marks. Unlike too many other books on magnetics, this one does not gloss over topics that require some Bessel functions, yet does not become buried so deeply in the trees that the forest is lost sight of. This is due in part to the many examples showing how to use the derived theory. The authors have a long history of magnetics research and this book excerpts to some significant extent from already-published *IEEE Transactions* papers of theirs. The excerpting is not noticeable except by their references to it. The book is conceptually seamless, flowing smoothly from beginning concepts to variable inductance in a progressive, logical sequence.

As for weaknesses, as previously stated, I would have preferred a different inductor design method than the area-product method, which has too many hidden assumptions. Either equal core-winding loss (max power transfer) or maximum core utilization, or both combined, would be preferred. If students can handle derivation of the Dowell proximity-loss equation, they can engage a more-optimal method. Yet it is good to know about area-product design, if for no other reason than to reflect upon its shortfalls as one develops greater understanding of magnetics design.

Second, the authors do not seem to have discovered yet the central importance of power-circuit waveform performance parameters such as form factor and crest factor (for inverters) or its relationship to core utilization as a design criterion. The current waveshape is typically a driving factor in optimization of converter design, including magnetics design.

I recommend for serious power-electronics engineers, to obtain a copy of this excellent book, if for no other reason than to be current on planar and integrated magnetics, to have the winding proximity- and skin-effect loss theory worked out in one place for design, and on the advantageous incorporation of variable inductance in circuit design.

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.

For more on magnetics design, see the How2Power Design Guide, select the Advanced Search option, go to Search by Design Guide Category, and select "Magnetics" in the Design Area category.