HOW2POWER TODAY
Your Power Design Newsletter

Focus on Magnetics
Sponsored by Payton Planar

ISSUE: September 2020

Why Magnetics Design Has Progressed So Slowly

by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

This article contrasts the development of the magnetics industry, particularly power magnetics as applied in electronic power supplies, with that of the semiconductor industry by giving an overview of the history of each. The objective of this comparison is to analyze why the semiconductor electronics technology has grown so much quicker than the magnetics technology. Why have the theory, terminology and industry practices underlying power transformer and inductor design and development for power electronics failed to keep pace with that of power semiconductors and ICs, and semiconductors in general?

We begin by reviewing the early history of transistors and ICs, and device models, and how these led to development of modern day power switches, the PWM switch model and modern switched-mode power supplies. We recall the era of circuit innovation and how it gave way to semiconductor process advancement. Then we step further back in time to the origins of magnetics technology in the electrical power field, and see how concepts from that era have lingered even up until the present and impacted power electronics.

We'll discuss how the magnetics (transformers and inductors) of power electronics diverged from the magnetics (transformers) of the electrical power industry. I'll also explain how my attempts to answer some "obvious" questions about magnetic component optimization led me to develop some new terms and approaches to magnetics design, which hopefully underscores the need for more engineers to lend their talents to this endeavor.

The Dawn of the Solid-State Electronics Era

The semiconductor industry began in earnest in the late 1950s. With the change from germanium to silicon transistors and the introduction of integrated circuits (ICs) in the early 1960s, solid-state electronics reached the steep knee of the progress curve. The bipolar junction transistor (BJT) was not well-understood at first and hybrid- or *h*-parameter models were applied to it. The *h*-parameter model is a two-port "black box" model—a behavioral and not a structural model.

Structural models tell us what is inside the "box", and in electronics, they appear as equivalent circuits, where the elements of the circuit are all well-defined and their properties are independent of the circuit of which they are a part. The circuit is independent of its surroundings, hence is *modular*, and can be inserted as such into any other circuit. This is what all general circuit simulators require. Devices in the circuit have a fixed model independent of the larger circuit of which they are a part.

Two-port models are instead *behavioral* and not structural models. They can have the form of a circuit but they capture device behavior under the constraints imposed on them by the larger circuit, such as open and shorted port terminals. That is why each of the three BJT configurations has a different *h*-parameter model. How the BJT behaves under different circuit conditions requires different *h* parameters. This black-box modeling is clearly inferior in its usefulness to structural models. Then why are they even used at all?

When a breakthrough technology is new, it is so poorly understood that to characterize its behavior under some imposed conditions is all that can be achieved. As the internal mechanisms of the device are discovered, structural modeling commences. Solid-state electronics, driven by solid-state physics, has culminated in detailed structural modeling of BJTs such as the Ebers-Moll 3 or Gummel-Poon BJT models. The quest for complete BJT models was largely accomplished by the 1980s.

When the FET—both JFETs and MOSFETs—became more commonplace in the 1970s, and then dominated digital ICs by the 1980s, the effort in electronics focused on circuit innovation. In the mid-1960s, Barrie Gilbert at Tektronix discovered a new class of circuits based on IC junction matching, that of *translinear* circuits. Various clever combinations of transistors resulted in new circuits and improvements in electronics during the 1970s and '80s.

But such developments slowed in the 1990s, as new circuit ideas were displaced by improvements in IC processing. High-performance transistors of both polarities, both BJT and FET, were able to be made on a single IC. Circuits on chips were shrunk, making them lower in power dissipation and faster. The emphasis on miniaturization set in. So did the opposite trend toward devices capable of handling ever more power.

© 2020 How2Power. All rights reserved.

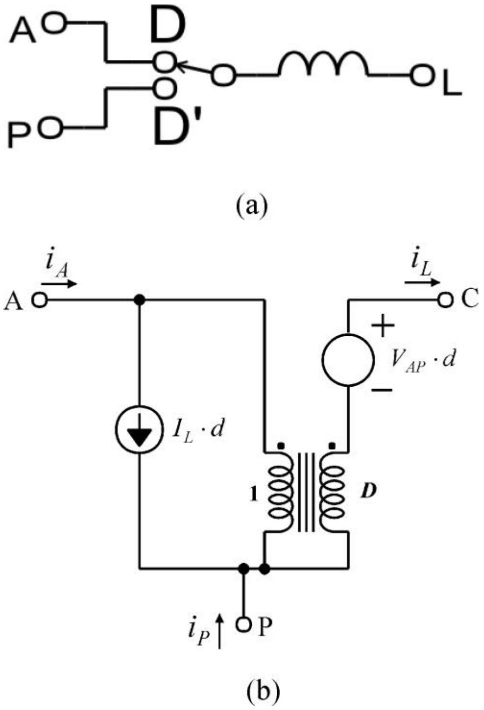
The Arrival Of Power Electronics

With the ongoing improvement in solid-state technology, power transistors led to solid-state power electronics. Some power circuits existed in the electron tube era, but were rarely applied to power conversion or motor drives. Radio and television transmitters were where tubes with cooling fins could be found.

Analog or *linear* power supplies were also commonplace in tube instruments such as analog oscilloscopes (AOSs). In a feature-rich AOS, electron-tube supplies occupied a significant fraction of the instrument and typically supplied over 100 W of power. With low (<60%) efficiency, the power supply also contributed significantly to instrument heating.

With the advent of the power MOSFET, a new era of power circuits and power electronics emerged. Despite switching noise, AOS power supplies became switching converters, contained in a metal EMI enclosure. These supplies were also regulated, as were their analog forerunners, with a feedback loop.

With switching, nonlinearity was introduced into circuits with feedback loops. What can be more nonlinear than a switch? Another round of new device modeling began, that of the PWM-switch, shown in Fig. 1a. Around 1990, at VPI, Richard Tymerski did his PhD thesis under Vatché Vorpérian on the PWM-switch model. At first it seems incongruous that a circuit with a switch can be approximated with a linear model, but the model is shown in Fig. 1b. It will not be derived here, though the rationale for it is simple.



(a)

(b)

Fig. 1. The PWM-switch, conceptually a power-electronics device, switched at a given frequency and duty-ratio comprising its operating-point (a), and its linearized model for average currents and voltages over the switching cycle (b).

A PWM-switch is a SPDT switch with its common terminal in series with an inductor and switched by a steady-state square-wave having a fixed frequency and duty-ratio, *D*. Then over a switching cycle, the currents and voltages of the three terminals of the switch are averaged, and the linearized model is constructed from these averages. The resulting model does not have continuous waveforms but almost; they are *piecewise-continuous*—continuous over each cycle, with discontinuities where switching occurs.

The PWM-switch equations apply in whatever configuration in a circuit it is placed; the model in Fig. 1b is a structural model. Like the transistor, it has three terminals and for a given two-port (input and output) configuration, one of the three terminals must be common to both ports. Hence, the PWM-switch also has three configurations corresponding to the three basic converter configurations of common-passive (CP, buck), common-active (CA, boost) and common-inductor (CL, or buck-boost).

© 2020 How2Power. All rights reserved.

The Long Road For Power Supply Magnetics

All the while that great strides forward in power circuits had been taking place, the magnetic components—single-winding inductors and multi-winding magnetic components that I call *transductors*, were taking a very different path in their historical development.

The names *transformer* and *coupled inductor* both name behaviors: in transformers the winding fields oppose and in coupled inductors they aid. These names describe the behavior of a *structural* device that can function behaviorally as either a transformer or coupled inductor, yet has not ever been given a name! Consequently, I suggest that it be called by the mnemonic neologism *transductor* to avoid confusing a device structurally with its possible behaviors.

All multi-winding magnetic components are *transductors.* This distinction in nomenclature is especially important when considering Ćuk-derived converters because their transductor operates at the boundary of transformer and coupled inductor behaviors, crossing between them during switching cycles.

This lack of refinement of the terminology of magnetics, even at this basic level, is indicative of what its history discloses. Magnetic components had their beginning in the mid-19th century, with Michael Faraday's experiments with magnetic induction. By the late 1800s, practical uses of these discoveries were being applied in the construction of electric power distribution systems. An important engineering decision had to be made; should the distribution lines, which for standardization of loads needed to have the same form of electricity, be "ac" or "dc"?

The optimal choice for the pre-electronic technology of the 20th century was that of Westinghouse and Tesla—ac—and not Edison—dc. The decision reduced down to the existence of one component, the transductor, which in all earlier power distribution applications always behaved as a transformer. Consequently, it was simply called by that name without confusion. We have now advanced in the use of magnetic components to where the structure-behavior distinction is necessary.

The transductor itself, as a *transformer*, began a long development and refinement history. General Electric and Westinghouse were at the center of it, and it involved 60-Hz power distribution. With the advent of power electronics, a divergence from *electrical* use of transductors led to the possibility of switching converters, switching at electronic speeds. The faster the switching, the more power is conveyed from input to output port each cycle.

At first, transistor switches merely chopped the constant (dc) input source so that the resulting square-wave could pass through a transformer, to be rectified and presented as a fixed (dc) voltage at the output port. While this is an advancement, a *chopper* stores power only in the output capacitor, and any transient overcurrent at the output would immediately—within a cycle—overcurrent the input-port power switches, leading to failure. Many low-cost inverters on the market have this failure mode because adding an inductor to make them a PWM-switch converter adds cost to the design.

With the possibility of switching frequencies much higher than 60 Hz, industry attention shifted from circuits to magnetic cores and windings. For decades, the optimal core material for 60-Hz applications has been *electrical steel*—steel with 3% silicon. It is a rather wonderful material at 60 Hz, with a very high saturation value for field density, B_{sat} of around 1.5 T (Tesla, $T \equiv V{\cdot}s/m^2$).

In contrast, ferrite cores used in electronic power conversion typically saturate rather abruptly at 350 mT, at only about 23% that of electrical steel. A higher B value increases power density, for at a switching frequency, f_s, the power dissipation limiting a transformer core varies directly (though not proportionally) with it. Average field intensity, $\overline{H}$ is limited by saturation but ΔB, flux ripple, is limited by core heating.

Furthermore, at 60 Hz, the other part of transductors—the windings—begins to dissipate power from eddy-current losses. At 0+ Hz or even 60 Hz, the skin effect in conductors is negligible (though this does not quite apply to the high-power transmission lines of today). At 100 kHz, the increase in resistance of conductors from the intra-wire (skin) and inter-wire (proximity) eddy-current effects causes losses that can be a decade or more than conductive loss at 0 Hz.

This is where the departure of electronic magnetics from electrical magnetics occurs. The development of magnetics for power electronics has followed the development of power circuits, but with the difference of a long pre-electronic history. Core materials for electronics must be selected that have lower loss—mainly

© 2020 How2Power. All rights reserved.

hysteresis loss—at high frequencies, and winding design must be altered significantly to minimize high-frequency resistance.

Unlike electronics, electrical technology has transformer design that has been refined since the late 19th century. Language and design customs of earlier times were inherited, and settled into the engineering world. Unrefined jargon that arose early in the electrical power field, such as *ac* and *dc*, are ambiguous and partially nonsensical, though they are so entrenched in electrical language that they continue to be used. Electronic circuits language carries some residual 19th-century electrical language, but it is more prevalent in magnetics terminology. For instance, Faraday's mysterious "magnetic force" is now distinguished as magnetic field intensity, whether it produces any force or not.

The radical new application of magnetics to electronics also had to overcome the precedent of how magnetics is designed and built. Solid-state electronics had essentially no previous history, no established way of doing things, except in electron tube technology. Even so, tubes are in some ways so different to design with than transistors that solid-state active-device circuit design was nearly like starting over. Yet with magnetics, the difference was not so stark, and we still have outdated concepts, obsolete terminology, and suboptimal design practices that continue to impede the field.

Seeking Answers To Fundamental Magnetics Questions

One of the reasons the magnetics field has not advanced as quickly as semiconductor electronics is its smaller size; fewer people are involved and still fewer of them creatively push the field forward. When I set about to design an optimized inverter over a decade ago (as an engineer whose style is to optimize design), I asked myself some seemingly obvious questions about magnetics design and sought their answers in magnetics textbooks and papers, but to no avail.

I then spent the next decade finding answers by doing theoretical magnetics research culminating in a book on it[1] and numerous articles in *How2Power Today*. I also discovered that some of the truisms of magnetics design are not really true under all conditions. A few examples of unanswered "obvious questions" will suffice for this article. There are others.

The first question is how to maximize power density in a coupled inductor of a PWM-switch converter. The inductor is the means of conveying power from input to output, and to minimize its size or maximize its power density, how do I find the magnetic operating-point, (B, H) where this occurs? The equation for power transfer and energy storage in the core is

$$\overline{P}_{xfr} = [(\Delta B \cdot \overline{H}) \cdot V] \cdot f_s = \Delta W_{xfr} \cdot f_s$$

where the average per-cycle transfer-energy change is ΔW_{xfr} , V is the core volume, ΔB is the flux change in core magnetic field density (in V·s/m^2), and $\overline{H}$ is the average core field intensity (in A/m).

For maximum energy transfer through a given size (V) of core at f_s, ΔB and $\overline{H}$ are maximized. ΔB is limited by allowable core power loss and $\overline{H}$ by maximum acceptable saturation.[2,3] This simple fact seemed to be implicit at best in the literature as the basis for maximizing core transfer-power density. It is an optimization question and not the main goal of textbooks covering fundaments of magnetics.

The ΔB and $\overline{H}$ constraints set upper and lower limits on the turns range. Minimum turns, N_λ is determined by the $\overline{p}_c$ value of maximum allowable core power-loss density and is a thermal consideration. Maximum turns, N_i is determined by acceptable core fractional saturation, k_{sat}. When both ΔB and $\overline{H}$ are maximized, the core transfers the maximum power that it can. However, this optimal condition also places a constraint on the circuit input voltage and current, and determines input resistance, $R_g = V_g/I_g$. Knowing this, however, allows the circuit designer to optimize both circuit and magnetics for an overall optimum design. None of this is made explicit in any previous magnetics literature I have found.

A second "obvious" question is: what is the f_s at which maximum power is transferred? This is a frequency optimization unpublished until the 2010 decade in *How2Power Today*[4] and earlier in reference 1. From the above equation, power transfer is maximized by maximizing f_s, yet core material power loss increases with frequency and places a bound on it. The derivation of the answer resulted in a new core performance parameter, like the unity-power-gain frequency, f_{MAX} of transistors, and named that by analogy.

© 2020 How2Power. All rights reserved.

This f_{MAX} term also has yet to appear in commercial core specifications. It is the frequency at which the change in core power loss equals the change in core power transfer so that any increase in f_s above f_{MAX} causes more power to be lost than is transferred. It is the breakeven frequency for power transfer benefit. f_{MAX} can be derived from the core power-loss equation, the generalized Steinmetz equation, with exponents α for f_s and β for ΔB. The answer reduces to a simple relationship between α and β.

A longstanding misconception in transductor design is that maximum power is transferred between windings according to the *maximum power transfer theorem* of basic passive-circuits theory. (This theorem might more generally be called the *maximum output-power theorem.*) The usual answer is when the core power loss equals the power loss of the windings.

However, that derivation is based on a simplified and incorrect circuit model. The core resistance added to the equivalent circuit to account for core power loss adds a third resistance to the source-load resistance scheme of the power-transfer theorem, and the answer becomes more difficult to find (more algebra), though the hard work only needs to be done (correctly) once.[5,6]

The answer is that for high transfer efficiency, the $P_c = P_w$ condition closely approximates the exact condition. But as the transductor is operated over a range of currents, efficiency can change significantly, and as it decreases, the approximation becomes less accurate, and maximum power is transferred when winding loss is slightly greater than core loss.

For electrical applications of transformers, the waveforms are sinusoidal, not square, and lead to a somewhat different optimization. The large size of electrical transformers (those used on the power grid) scales design into a different region of optimization where magnetizing current is often negligible, as is the core loss it causes, with a simplified transductor model. Readjustments of this practice have not become commonplace for electronics where smaller magnetic components have significant core and winding losses.

A final example and a holdover of tradition from electrical transformer design is sequential winding design. Windings are laid down on the core in sequence. This results in a lower coupling coefficient, more leakage inductance, and greater eddy-current effects. It also makes core winding more difficult, often requiring a winding machine. In some cases, a sequential winding design is optimum, but often it is not.

An alternative scheme is multifilar design, where the windings have an integer difference in ratio of turns, and can be placed in a single bundle and wound on the core. Multifilar windings reduce leakage inductance, increase coupling coefficient, decrease interwinding capacitive currents, and can decrease eddy-current effects significantly. In terms of transformer construction, multifilar windings move most of the work in winding into bundle construction, require that bundle strands be sorted out and some strands connected in series for different turns ratios, and reduce wire packing factor. This last effect causes the winding window to be more filled than in sequential winding.[7]

With these tradeoffs, and no need for a winding machine, many magnetic components can be built in-house by power electronics companies rather than farmed out to magnetics specialty houses for construction. Multifilar windings are not always optimal for high-voltage applications where safety compliance considerations apply, yet many electronics applications nowadays are low voltage and integer multiples of turns ratios are acceptable. In such cases multifilar windings have advantages, though this is not a widespread practice. Sequential windings from electrical use need not constrain magnetics in electronics, yet often do.

Conclusions

Magnetics terminology refinement, design optimization, and simplified construction practice has come late in the development of the field. Why? Probably because, unlike semiconductor power electronics, magnetics has a long history steeped in electrical power distribution thinking and practice. These (and other) "obvious" magnetic component design questions illustrate that "If you want it done at all, do it yourself" and think "outside the box" of familiar and established design habits.

Therefore, if you have an idea and nobody else is doing it, then either 1) it is a bad idea; find out why, or 2) you have an opportunity to contribute to the advancement of magnetics for electronics. The lesson to be taken from this is to not assume that power magnetics design is in a mature, finalized state of development or that widely-assumed beliefs within it are always correct. Hopefully, you or others will continue to contribute to the refinement of the body of knowledge comprising optimized magnetics design. I hope to also continue. Perhaps we can eventually reach the same state of progress as semiconductor power circuits!

© 2020 How2Power. All rights reserved.

References

1. *Power Magnetics Design Optimization*, by D. L. Feucht, Innovatia, 2016. PDF copies of this book are available on request through the website.

2. "Match Circuit And Field Resistances For Optimal Magnetics Design" by Dennis Feucht, How2Power Today, March 2011.

3. "What Is to Be Optimized in Magnetic Component Design?" by Dennis Feucht, How2Power Today, May 2014.

4. "Determining Maximum Usable Switching Frequency For Magnetics In CCM-Operated Converters" by Dennis Feucht, How2Power Today, April 2015.

5. "Magnetics Optimization," a multipart series by Dennis Feucht, How2Power Today: "Part 1: Equal Core And Winding Losses Do Not Maximize Power Transfer," September 2015, "Part 2: Maximum Power Transfer Of The Primary-Referred Circuit," October 2015; "Part 3: Maximum Power Transfer Of Magnetics Circuit Model," April 2017; "Part 4: Minimization Of Transductor Power Loss," May 2017.

6. "Optimizing Transformer Winding Design For Max Efficiency Over Output Current Range" by Dennis Feucht, How2Power Today, September 2018.

7. "Single-Bundle Windings Make It Easier To Build Custom Magnetics In-House" by Dennis Feucht, How2Power Today, March 2014.

About The Author

Dennis Feucht has been involved in power electronics for 35 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.

For more on magnetics design, see these How2Power Design Guide search results.

© 2020 How2Power. All rights reserved.