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Design Your Inductors For More Efficient Applications

GREEN ENERGY APPLICATIONS such as hybrid vehicles, wind energy, and solar energy stand to reap big benefits from regulated electronic power conversion common to switch-mode power supplies (SMPS).

Insulated gate bipolar transistor (IGBT) advances are now facilitating the development of switched-mode power in the 5- to 50-kW range, putting switched-mode power solidly in the realm of these green energy markets.

At these high power levels, the demands on all passive components, including inductors, are increasing dramatically. This trend is going to create new requirements for the inductor designer.

Historically, SMPS inductors were designed using low-cost, relatively high-loss core materials and solid wire or foil for their windings. Designers have been able to get away with this for three reasons.

First, ripple currents are typically low in this class of inductor. Second, low-volume cores can support higher loss densities. And third, smaller gauge conductors can support high-frequency ac ripple current with lower losses than very large conductors.

As power levels increase along with frequency, these old rules of thumb no longer apply. The larger cores required at these high power levels simply cannot support high loss density, and even small ripple currents can lead to core overheating.

1. This SMPS inductor suits applications in the lower-kilowatt power range.

SMPS BOOST INDUCTOR SPECIFICATIONS	
Inductance	10-µH minimum under peak load
Idc	40 A
Core geometry	E core; each core half is 71 by 33 by 32 mm
Core material	Variable
Turns	15
Gap	Varies depending on core; gap chosen to achieve equivalent effective unloaded permeability with all the core materials
Ripple current	1% to 25% of dc current
Frequency of operation	10 and 100 kHz

Also, high absolute values of current require very large copper cross sections, which in turn lead to high ac copper losses. As a result of these factors, the design becomes far more complex.

UNIQUE ASPECTS OF SMPS INDUCTOR DESIGN

Switch-mode inductor designs are demanding for a number of reasons. One reason is there are many core options to choose from. An SMPS transformer is almost always a core-loss-limited design, and the designer is limited to a soft ferrite.

But inductors can employ many different types of cores, including powdered metals, stripwound cores, ferrites, and even laminated cores. Within each of these classes of core, there are further distinctions between the base metals and methods of manufacturing that greatly affect core properties as well as the cost, size, and electrical performance of the inductor.

Another reason for the difficulty in designing switch-mode power inductors is that they are typically dc-biased components requiring energy storage, involving biasing the switched current and voltage to one side of the zero point.

As a result of this dc bias, inductors are operating all or part of their duty cycle in the saturable region, and it's essential to understand their performance under saturating conditions.

In particular, it's essential to understand how inductance drops with dc current (Idc) as the core enters saturation. This can be a make or break failure mode for some power-supply designs, and often there is no good way to predict inductor performance in this region.

A final cause for inductor-design hardships is the tricky task of predicting copper losses, which, in an inductor, are a combination of dc and ac losses. We can calculate dc losses quickly and easily based on the direct current resistance (DCR) of the inductor.

But ac losses resulting from ac ripple depend on a complex relationship between the core geometry, gap location or locations

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if a gapped core is used, the type of conductor (solid wire, litz, or foil), and the positioning of the wire in the core window.

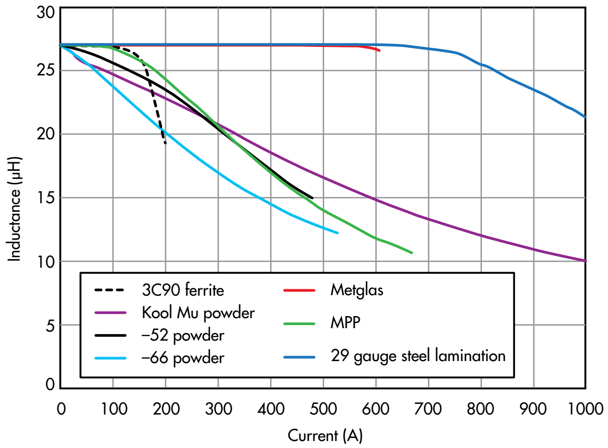
DESIGN EXAMPLE

To highlight some of the variables entailed in an inductor design, our specific design example focuses on an SMPS inductor for deployment in a low-kilowatt power application *(Fig. 1)*. The Table shows the properties of this inductor. Inductor design typically starts with the choice of a core.

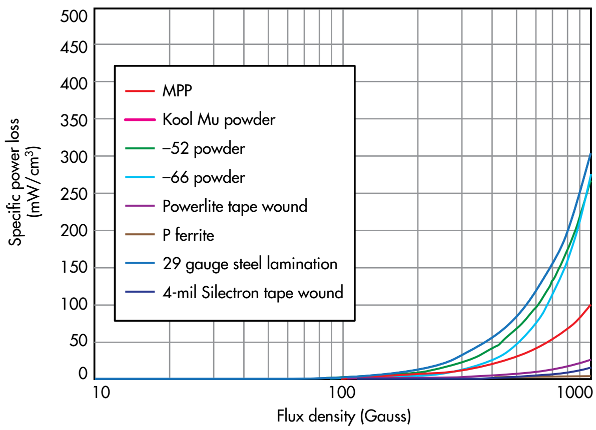
Pressed from nickel and iron powder, powdered cores exhibit low permeability and gaps effectively distributed throughout the core. Majority iron blends, i.e., Micrometals -52 and -66 materials, offer relatively low cost and high effective perm.

Kool mu is a marginally higher-cost blend, but with significantly lower losses. Molypermalloy powder (MPP) has the lowest losses and the best temperature stability, although it's too costly for most applications.

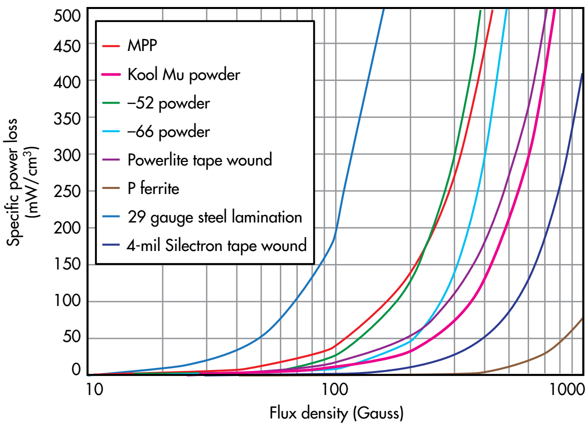
Powdered cores in general find employment in applications at 10 kW and lower because they aren't available in larger sizes due to manufacturing challenges. Magnetics Inc. is addressing this



2. Based on simulation models, low-Bsat core materials exhibit a loss of inductance as Idc increases.



3. Taking frequency into consideration, each core material exhibits a different level of power loss at 10 kHz. The data from this chart comes from the core manufacturer's loss curves.



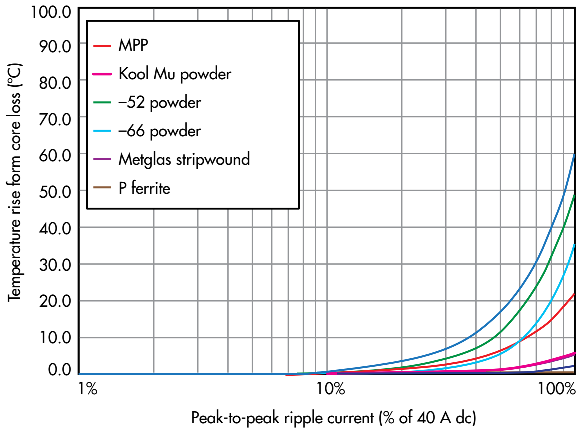
4. Core losses for various materials widen as frequency jumps to 100 kHz. The data from this chart comes from the core manufacturer's loss curves.

scaling problem to some degree with its Race Track cores, which permit the assembly of discrete blocks of Kool mu material into larger core sizes. Nevertheless, as they are readily available in large sizes, tape-wound cores tend to be the material of choice at higher power levels.

Silectron and Metglas are commonly used tape-wound core materials. Tape-wound cores are high-perm, high-Bsat (saturation flux density) materials, and they must be used with a physical gap. This leads to some difficulty in predicting the roll-off of inductance (L) versus Idc, unless the core manufacturer has published gapped core data. It also leads to even greater difficulty in predicting losses in the vicinity of the gap since there is no simple method for such predictions.

Ferrite cores used for SMPS power have very low losses, but also very low Bsat. Since most inductor applications don't require low-loss cores, ferrites aren't a common choice for inductors due to their lower saturation flux density. However, ferrites do have their place in core-loss-limited designs at high ripple current and high frequencies.

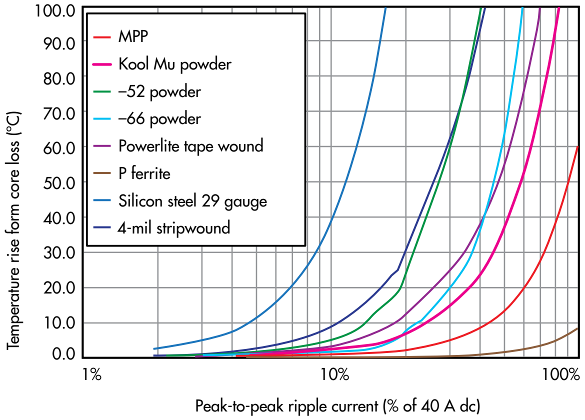
Laminated cores are available in silicon steel in large sizes. They offer relatively low cost in very large sizes and high saturation flux density, which supports high levels of dc current. Yet they also offer high losses at frequencies of 10 kHz and higher.



5. Factoring temperature rise and peak-to-peak ripple current into the mix, common core materials perform well at 10 kHz.

L VERSUS IDC

As previously noted L vs Idc is a critical design parameter. West Coast Magnetics has developed a program to model L vs Idc, and we used that model to predict the performance of the inductor shown in Figure 1 for different core material options. Looking at Figure 2, which shows the results, it becomes apparent



6. When contrasting temperature versus ripple current at 100 kHz, the choice of core material becomes more critical since designs are constrained by core losses at ripple currents as low as 3%.

that a relatively low-Bsat material such as the ferrite will lose inductance very quickly as Idc ramps up.

On the other end of the spectrum, when using a very high-Bsat material such as silicon steel, the core can support a very high level of dc current. For the designer, choosing a low-loss ferrite for an inductor design requires characterization of the peak current conditions as well as a check of the performance of the power supply under worst-case conditions, simulating the loss of inductance at high peak loads.

When higher-Bsat materials are the choice, this aspect of the design becomes less important. In the case of silicon steel, the highest-Bsat material, it is rare as well as difficult to drive enough current through the inductor to saturate the core if the gap is large enough. Under these conditions, the inductor would have an excessive temperature rise.

CORE-LOSS COMPARISON

In addition to dc bias, switch-mode inductors will see an ac current ripple that will lead to core losses. Values of B (gauss) typically are quite low. But in some high-ripple designs, core losses are one of the factors that limit the design.

This becomes especially true as frequency increases since core losses are typically proportional to F^x where x varies from as low as 1.36 for a typical ferrite at frequencies under 100 kHz to more than 2 for iron powder. Figure 3 shows the relative core losses for each of the inductor materials at 10 kHz, while Figure 4 shows the same data at 100 kHz.

The data on core losses versus ripple current is easy to interpret if we take the inductor example from above and plot temperature rise due to core loss alone versus ripple current. Displayed in figures 5 and 6, this data reveals that any of the core materials identified in this report are adequate to handle all but the greatest ripple currents at a 10-kHz operating frequency.

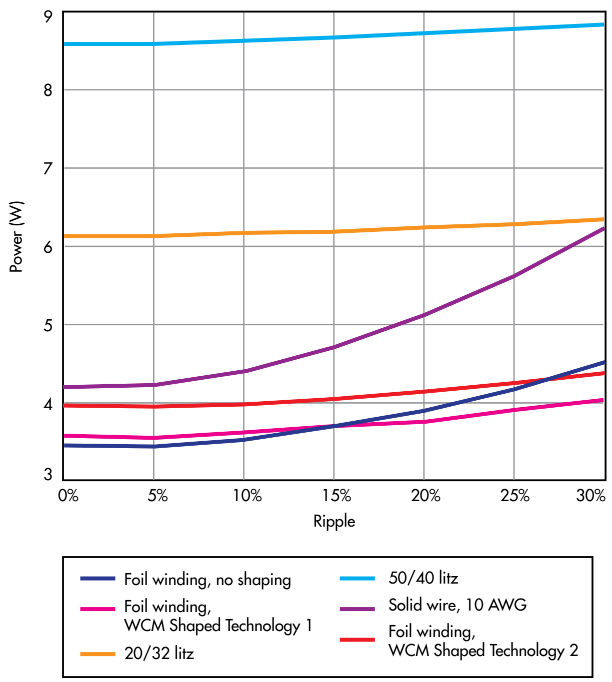
But by the time we reach a 100-kHz operating frequency, the choice of cores is much more critical as the designs are constrained by core losses at ripple currents as low as 3% for the higher-loss core materials.

WINDING LOSSES

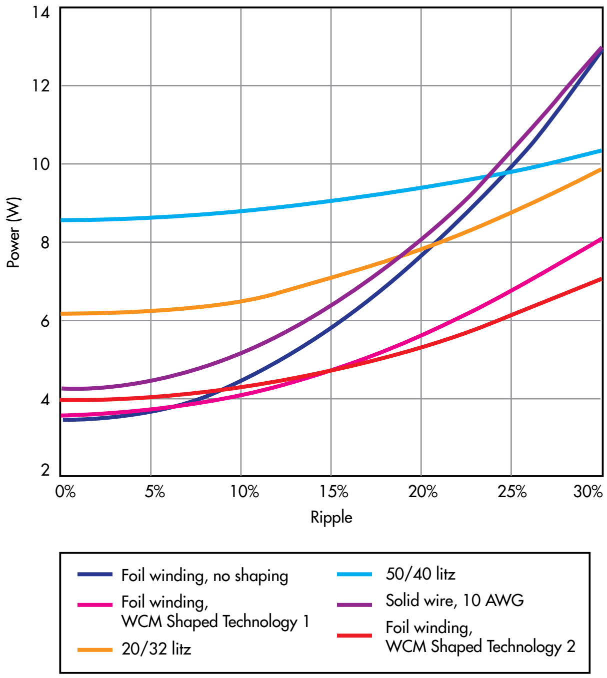
Winding losses result from dc and ac losses. We can easily determine the dc losses with reasonable accuracy from the dc current and resistance, two apparent parameters. The ac winding losses in inductors result from ripple current at the fundamental frequency of the inductor, and they increase with both frequency and ripple current. At high frequencies and high ripple current values, ac losses can dominate the design.

Figures 7 and 8 show winding losses at 10 kHz and 100 kHz, respectively, as a function of ripple current for the inductor detailed in the table with a 40-A dc current and a ripple superimposed. Losses shown in these figures come by way of constructing and testing the E71/33/32 sample inductor with six different windings, including solid wire, two litz wire options, a foil wound option, and two options using patented Shaped Foil Technology from West Coast Magnetics.[1]

It is apparent from the data in figures 7 and 8 that the type of winding has a significant effect on winding losses. Solid wire performs reasonably well at low values of ripple current and



7. As a result of ac ripple currents at the fundamental frequency, power losses through the inductor winding increase with both frequency and ripple current. Compare the losses here at 10 kHz with those at 100 kHz in Figure 8.



8. At 100 kHz, power losses through the windings jump significantly over those at an operating frequency of 10 kHz.

lower frequency, but it loses ground very quickly at higher ripple values and at higher frequencies. Challenging conventional wisdom, the results tallied with our sample inductor show that solid wire or litz wire was never the lowest-loss winding option. At 100 kHz with ripple values of 10% and higher, WCM's shaped foil technology has lower losses than all other competing technologies.

CONCLUSION

The demands placed on SMPS inductors are increasing along with the power levels demanded by green energy applications. The inductor industry players have been slow to keep up with these demands, and they will face far more complex design problems over the next decade.

In particular, green energy applications are benefiting from switching power in the 5- to 50-kW range. Within this power band, switching frequencies are increasing beyond 10 kHz. As a result, the inductor design problem is becoming a multivariable interplay been core losses, winding losses, and inductor performance in the saturable region of the core. With many different core and winding options to choose from and very few tools available to the designer, the challenges are formidable. ed

REFERENCE

1. Shaped Foil Technology is a patented technology developed by the Thayer School of Engineering at Dartmouth and under exclusive license by West Coast Magnetics.