WCM designing
high power, high frequency magnetics

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RoHS compliant

shaped foil™ WCM

EDN INNOVATION
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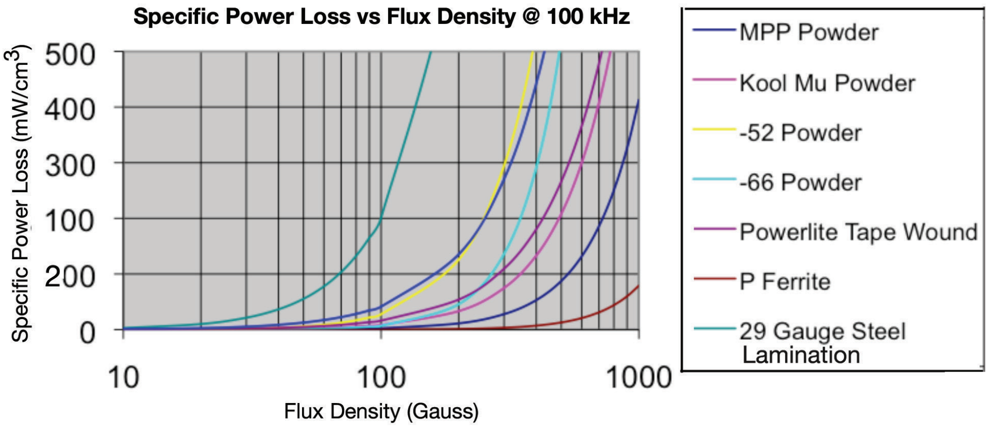
FINALIST 2009

The demands on switch mode power supply (SMPS) power transformers and inductors are increasing rapidly. High frequency power electronic equipment is being designed for power levels that are moving into the medium to high kilowatt range. Exciting new applications driving this trend to high power levels include hybrid vehicle power trains, electric drives, industrial equipment drive trains, large scale solar converters and power grid level energy conversion including wind energy. This trend to higher power levels is leading to some unique challenges in the design of the magnetic components.

CHOICE OF A CORE FOR HIGH POWER: required core volume does not scale linearly with power

One of the fundamental problems facing the designer is power density in the core. Higher power levels require more core volume per unit of power than is typical for lower power levels and this result is independent of frequency. There are two reasons for this, the most obvious being the choice of core material itself. Ferrites typically have the best cost/size/performance tradeoff because ferrite losses are typically lower than alternative core materials (see Figure A below). However ferrites are not widely available in sizes that can deliver 10 kW and higher power levels. Even assuming the availability of ferrites at this high power level, there is a concern with the mechanical properties of the core. Many high power applications take place in an environment subject to shock and vibration, and ferrite is an inherently brittle material that is subject to fracturing, particularly in larger sizes. The alternatives to ferrite cores are lossier and more expensive.

Figure A



Specific Power Loss vs Flux Density @ 100 kHz

WCM WEST COAST MAGNETICS

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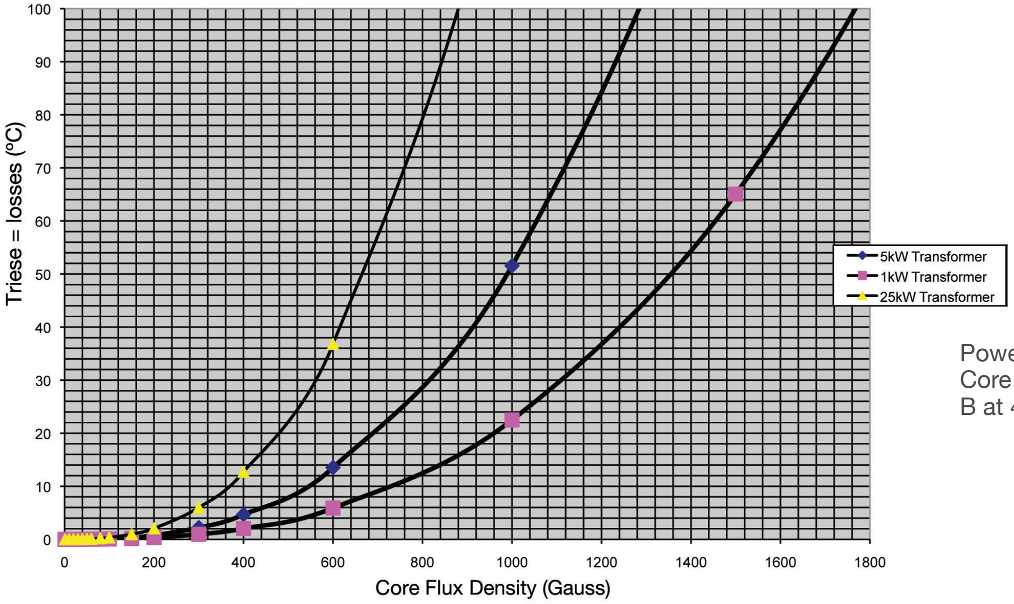
A second concern with high power designs, is that larger cores cannot support power densities as high as smaller cores and as a result, gauss levels must also be lower. By way of example look at the three transformers illustrated below, a 1 kW PCB mount transformer, a 5 kW chassis mount transformer, and a 25 kW chassis mount transformer. In Figure B we compare the estimated transformer hot spot temperature rise caused by core losses alone to the core gauss level. The frequency is set at 100 kHz and each transformer uses the same low loss 2000 perm ferrite core material. It is clear from this plot that the smaller core can support a significantly higher gauss level without an excessive temperature rise. This trend continues as the transformer power level increases and it is independent of core material and frequency of operation.

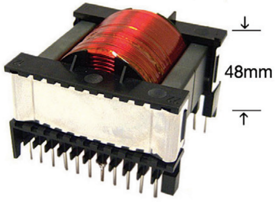
Figure B

Temperature Rise Attributable to Core Loss (Frequency = 100 kHz)



1 kW

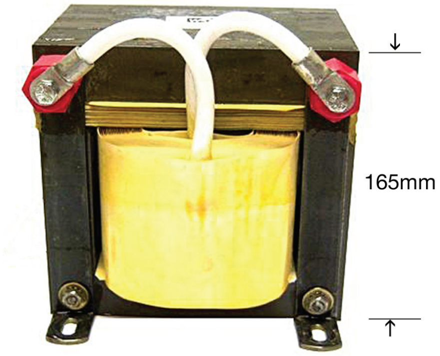
PCB (WCM408)



Power at 100 kHz = 1000 watts
Core Loss Density at 40°C T rise = 140 mW/cm3
B at 40°C T rise = 1240 gauss

25 kW

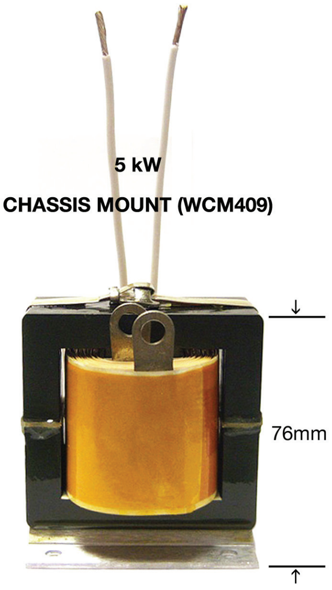
WCM5277



Power at 100 kHz = 25000 watts
Core Loss Density at 40°C T rise = 22 mW/cm3
B at 40°C T rise = 612 gauss

5 kW

CHASSIS MOUNT (WCM409)



Power at 100 kHz = 5000 watts
Core Loss Density at 40°C T rise = 61 mW/cm3
B at 40°C T rise = 920 gauss

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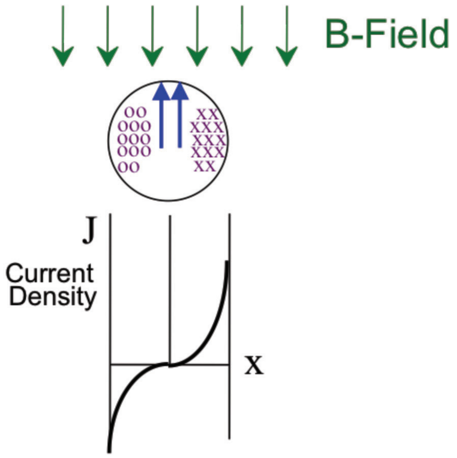
High power SMPS designs require a greater knowledge of and comfort with the many types of core materials available to the designer. Industry players representing all of the major core alternatives are developing new shapes and core materials to position themselves for entry into the high power SMPS market. For the designer, the choice of a core is quite challenging, as there tend to be more shape and material options that present viable design solutions.

CHOICE OF A CONDUCTOR FOR HIGH POWER

Copper losses for high power, high frequency magnetics are a major concern to the designer. Copper losses consist of both AC and DC losses. At SMPS frequencies AC losses are amplified by the tendency of eddy currents to concentrate on the surface of a conductor at higher frequencies. AC winding losses can very easily equal or exceed DC winding losses in both transformers and inductors, although the mechanisms leading to current concentration in inductors and transformers are very different. In transformers, the mmf driving current concentration is created from the flux linkage between the windings, while in an inductor the linkage is between the winding and the core. The following Figure C shows how the mmf resulting from the B-field drives the current to the surface of the conductor.

Figure C



For both inductors and transformers however, the basic problem at high power levels is the same. Conductor cross section must increase with an increase in RMS current, but the forces driving the current to concentrate on the surface of the conductor are purely a function of winding mmf and frequency. Eddy currents do not care how big the conductor is, they will move to the same distance from the surface of a conductor for a given mmf.

In Figure D, (next page) the usable portion of a circular conductor is plotted as a function of frequency and conductor size for both foil and round wire. The usable portion of the conductor is defined as that portion of the conductor that resides within one skin depth of the surface of the conductor. While this definition is arbitrary it is a good proxy for many if not most designs.

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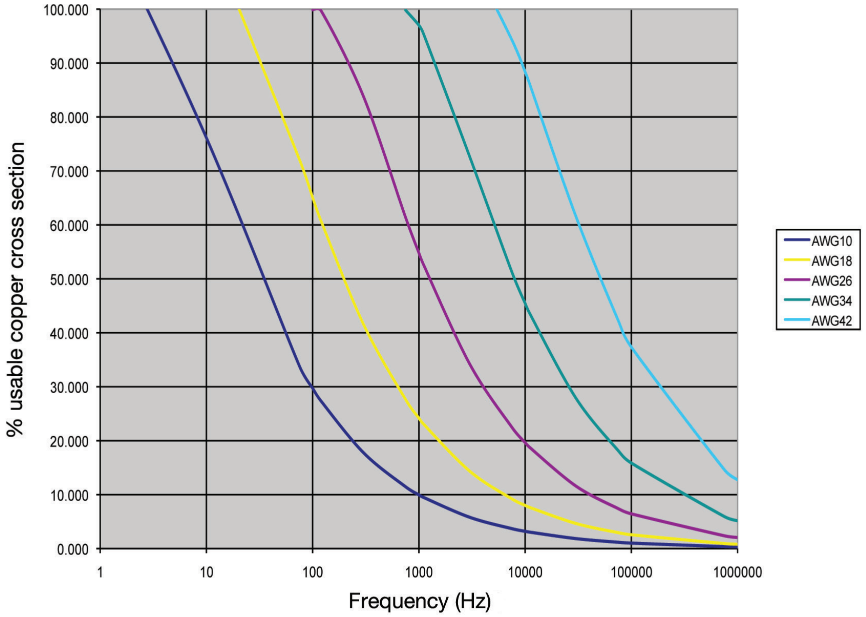
Figure D

Plot for Percent Usable Copper Cross Section vs Frequency



The largest conductor in this plot, 10 awg, is typically only good for a maximum of 50 amps, on the low side for many kilowatt power applications. And this conductor has less than 10% usable copper cross section at frequencies above 1 kHz. It is clear from this that one of the factors driving high power SMPS designs to lower frequencies is eddy current effects and the need to achieve full conductor utilization.

Litz wire does present an easy, if expensive solution to the problem of high frequency winding losses in both transformers and inductors. If the individual strand diameter of Litz wire is chosen to be fine enough, the problem of eddy current losses effectively goes away and winding losses are simply the product of RMS current squared and the DCR of the conductor. In the table below a number of different 10 awg Litz strandings are compared. Solid 10 awg wire is clearly the least costly alternative, but it begins to have very significant AC copper losses at frequencies as low as 1 kHz. For frequencies over 10 kHz, 24 awg and finer Litz gauge will limit AC winding losses, but the price climbs significantly as the gauge of the individual Litz strands is reduced, see Table 1.

Table I

Comparison of Litz Stranding for 10 awg Equivalent Litz

Stranding	*Cost/lb*	*Frequency at which Skin depth = conductor diameter*	*Frequency at which Skin depth = ½ conductor diameter*
10 awg solid wire	$ 6.50	0.65 kHz	2.62 kHz
10 strands of 20 awg	$ 12.10	6.60 kHz	26.50 kHz
26 strands of 24 awg	$ 17.73	16.80 kHz	64.40 kHz
66 strands of 28 awg	$ 20.79	42.80 kHz	171.10 kHz
110 strands of 30 awg	$ 21.21	67.90 kHz	271.60 kHz
210 strands of 33 awg	$ 22.51	138.00 kHz	554.40 kHz

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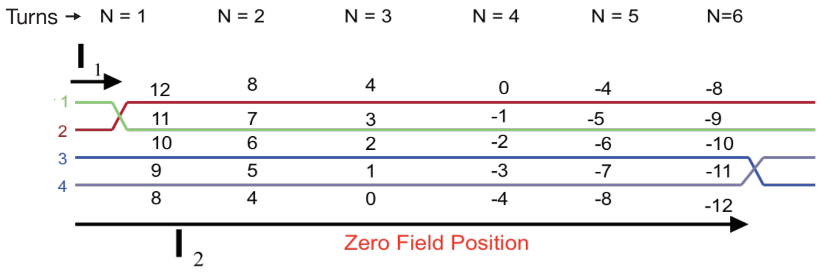
Another approach to minimizing winding losses is to use copper foil for the winding. Copper foil has two properties that make it useful for SMPS applications and it is much cheaper than Litz wire. With a rectangular cross section, it is easy to achieve a high window utilization. However while this may help to reduce the size of the device, it does not actually lead to lower losses in and of itself. Another property that does help with losses is that the mmf of a foil winding is normal to the plane defined by the foil width, and therefore eddy currents concentrate on the top and the bottom of the foil. Since the foil width is much greater than the thickness, the usable portion of a foil cross section can be very high compared to magnet wire. But foil windings do suffer from the fact that each turn of copper is in fact a single layer, and multiple turn copper foil windings also have multiple layers and this again increases AC copper resistance in both transformers and inductors.

West Coast Magnetics, in conjunction with researchers from the Thayer School of Engineering at Dartmouth, has developed two new technologies to further reduce AC winding losses in foil windings. The technique is different for inductors and transformers, but the end result is the same. The ripple current density in the winding cross section is equalized and the AC winding resistance is similar to Litz wire. The compromise in DCR is minimal, so the winding has lower overall losses than either a solid wire or a Litz wire winding.

For transformers, the key to this new foil technology is the use of multiple parallel foil conductors that are interleaved. For this technique to work, the parallel foil conductors are swapped at precise points throughout each winding. In the case of inductors, a single conductor is used, but it is modified prior to winding. In Figure E below, a four parallel foil conductor winding with six turns has been optimized to reduce losses by 50%.

Figure E

Parallel Foil Conductor Winding Diagram



Interchange Locations:

- I_1 = 58.4 mm
- I_2 = 1231.4 mm

Theoretical Loss Reduction = 50%

For inductors, the foil winding is prepared in such a manner that the field in the area of the core gap is used to steer the current inside the winding, and prevent current concentration on the surface of the copper foil.

CHOICE OF A CONDUCTOR FOR HIGH POWER

WCM, in conjunction with Dartmouth researchers, has demonstrated that for high power, in high ripple buck and boost inductors using gapped core assembly, the shaped foil technology is the lowest loss winding when compared to unshaped foil, solid wire and Litz.

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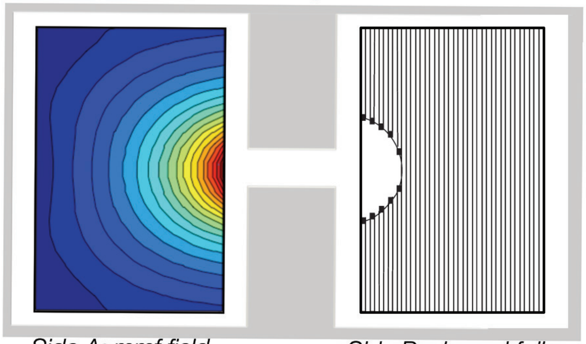
Figure F

Inductor Winding Cross Section



Side A: mmf field due to gap fringing

Side B: shaped foil construction

OTHER DESIGN TIPS

The holy grail of optimal magnetics design for high power SMPS requirements is loss minimization. The magnetic components can quickly become the largest and mostly costly items in a high power design if they are not designed properly. While it is possible to remove heat from a device, lower losses will always advantage the design.

For transformers there are a couple of useful rules of thumb to minimize losses. To keep winding losses to a minimum, the winding mmf should also be minimized. To accomplish this it is important to minimize the number of layers for each winding, and interleaving or swap the primary and secondary windings. As for the choice of a core, SMPS transformers are typically not Bsat limited so the choice of a core will normally be based on the core losses and cost only.

Inductors are usually saturation limited, and therefore advantages can be gained from choosing a material with higher saturation flux density. In fact, high Bsat cores sometimes permit the design to be loss limited, and in this case it may be possible to achieve a higher inductance than specified. This has the advantage of reducing the AC winding losses as a result of lower ripple current.

It is important to make a careful estimate of the worst case RMS load on the inductor or transformer over a period which is reasonably close to the time for the device to reach equilibrium temperature. Large transformers and inductors will take 60 minutes or more to reach equilibrium temperature. So if there is no chance of the device being fully loaded for an hour or more there is no reason to estimate losses based on continual use over this period. Magnetic components are relatively robust and they are capable of handling high peak power and current levels over a short period of time.

For further information
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