Embedded Magnetic Power Transformer

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Abstract — Inductors and transformers are basic building blocks in power systems. Their attributes are critical to the function and performance of a switch mode power converter (SMPC). Embedded magnetics provides a new approach for fabricating transformers and inductors. A key benefit of this approach is that it provides a practical means for employing toroid (ring) cores in power designs. Essentially, the fabrication is done with a Printed Circuit Board (PCB) line. Ferrite elements are embedded into an FR4 substrate and the device windings are realized using printed circuit techniques. Rather than fabrication one-at-a time, devices are fabricated in a batch format. Automation also brings the benefit of improved consistency and reliability. This paper describes the device composition and fabrication on a printed circuit line

1.0 Introduction

Over the past few decades, Switch Mode Power Conversion (SMPC) has overcome traditional linear conversion. This is primarily due to the better efficiency of the SMPC architecture. The power transformers used in these systems are often based on E-style ferrite core structures, where two E-shaped elements are clamped around a wire-wound bobbin. This construction is conducive to semi-automatic winding and has been refined over the decades to provide a relatively low cost construction. Labor content, however, is still considerable. Bobbins are wound one at a time and require manual content to dress wires, apply tape between windings, clamp and glue the ferrite cores in place. Often the device wires are soldered to the package leads, which accounts for additional manual content.

Planar transformers rose to prominence over the past decade, as a means for improving automation and device integration. Rather than clamp two E-cores around a bobbin, the ferrite elements are clamped around a multi-layer PCB. Typically 8 or more PCB layers are employed the achieve the required windings and turns ratio. The inductive windings are printed in a spiral configuration and implemented different PCB layers. Two ferrite E-core segments are then clamped onto the PCB. This produces a device with many of the same characteristics as the bobbin-wound E-cores in terms of efficiency, weight, size, leakage inductance and radiated emissions. The main difference is that the planar construction offers a higher degree of automation. The windings are fabricated on a PCB line, in a batch process and elimination of many of the manual steps associated with providing isolation and terminating wires. A constraint is that the conductor line widths and spacing must follow PCB design rules. With a wire wound bobbin, one can always cram more wire into the core's window area and apply more windings to the core than the planar construction..

2.0 Embedded Magnetics

Embedded magnetics is the next advancement in power magnetics. The technology makes it practical to use toroid shaped cores, which offer many benefits to power systems. The toroid is inherently the most efficient shape for transferring inductive energy. They provide the shortest path for magnetic flux to flow within the core. In its basic form, the flux path does not have any discontinuities, allowing inductors and common mode filters to use the full capabilities of the ferrite material. With an SMPC power transformer, however, it is often necessary to insert a "gap" in the flux path[1]. The gap will reduce the inductance per winding, yet stabilize the cores performance over temperature and under DC bias. E-cores have three gaps while a toroid will have one. Fewer discontinues provides for more inductance per turn. In a toroid, gaps can be precisely cut with either a diamond wheel or laser. E-cores requite that the interfacing surfaces are machined and polished.

Where toroids excel is in low loss. The length of the windings is shorter, resulting in lower AC loss and resistance. Core loss is lower, due to the smaller volume or ferrite. Both conditions make it practical to operate the transformer at higher switching speeds. When implemented with the embedded magnetic construction, the windings can be carefully shaped to control the AC impedance and minimize the inter-winding capacitance. The windings of a Planar or wound EFD-style transformer cover only a small portion of the ferrite core. In comparison, the windings on the embedded device can be evenly distributed around the toroid to minimize leakage inductance. Full coverage also reduces radiated emissions and dissipates heat. Finally, toroids have the advantage of cost. Cores are basically

[1] Gapping places a discontinuity in the magnetic flux path and often reduces the cores effective permeability by > 80%.

stamped-out in "cookie cutter" and don't require the machining and polishing as E-style cores do.

With all of their benefits, why haven't designers traditionally employed toroids for power transformers? The issue is with the winding and lead termination. There are automated machines that can readily wind toroids with diameters of 8 mm or greater. However, SMPC applications provide some unique challenges. The designs use large winding ratios and different gauge wires, between the primary and secondary windings. Both characteristics are problematic for automatic windings. If the design requires a gapped core, it is also difficult for an auto-winder to distribute wires around the core and avoid pulling wire into the gap. To date, bobbin winding and the planar PCB construction have been better suited for the power transformers. Embedded magnetics now makes it practical to use toroids in SMPC application Figure 1 shows a comparison of different power transformers. The bobbin-wound device is the popular EFD20 package, while the planar device is based on an EQ20 size core. The embedded magnetic transformer was fabricated using a 15.8mm (0.625") diameter core. Each package is similar in footprint and height.

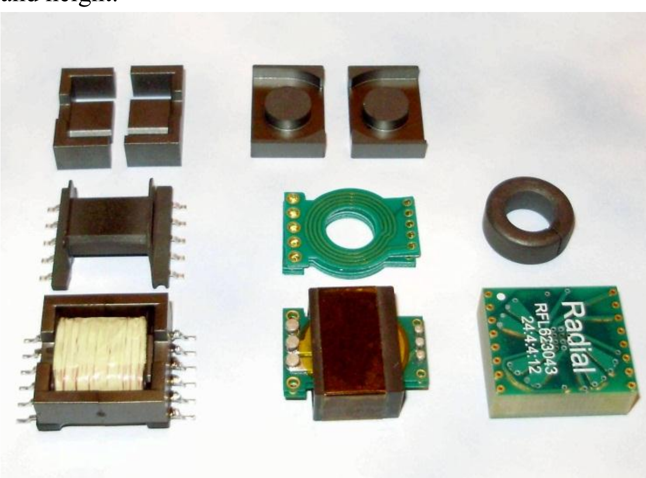

Figure 1, Comparison of EFD, Planar and Embedded Packages

3.0 Construction

As with the planar construction, embedded magnetics provides consistency and reliability unmatched by wire-wound construction. Photolithography is used to define the device windings, allowing the designer to carefully control line widths and spacing. Figure 2 shows a cross section of the construction. As depicted, the windings can be shaped to reduce resistance and AC loss. Implementing broad conductors over the embedded core also improve the distribution of heat and provide a greater surface for conductive and radiated heat dissipation. In comparison, the windings are usually bunched and concentrated in in the middle of a planar or bobbin wound design.

There are actually a couple of alternatives for producing the embedded magnetic device, each having varying degrees of complexity and cost. The most-straight forward approach uses Plated-Through-Hole (PTH) interconnects between the different winding layers. Figure 2 depicts a 4 layer design, where the primary and auxiliary windings are implemented on the inner layers and the secondary winding is implemented on the outer layers.

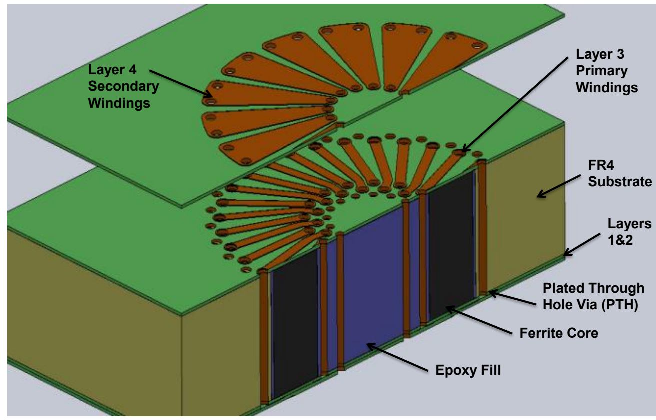

Figure 2, Cross Section of Embedded Transformer

To begin, cavities are routed into an FR-4 or G10 substrate. Ferrite cores are inserted and encapsulated with a low shrink epoxy. Winding layers are then disposed on the top and bottom surface of the substrate and vias are mechanically drilled to interconnect the layers. Most bobbin based designs use layers of Mylar tape between the winding layers to provide a certain degree of electrical isolation. This is often applied manually. With embedded magnetics, primary and secondary windings can be placed on different PCB layers. Voltage isolation is controlled by line spacing and the FR-4 thickness separating the layers. FR-4 has a withstanding voltage >13kV/mm (500 V/mil). 3kV of voltage isolation can be accomplished with merely 6 mils of FR-4 separation between layers. To minimize winding resistance, the copper thickness should be 1 oz. or greater. Vias are drilled and plated to a thickness consistent with the laminate foil. The panels are then imaged and etched with the winding arrays. The benefit of this construction method is that it that it readily fits within the capabilities of most PCB shops. The primary limitation is the aspect ratio of the vias. This aspect ratio dictates the via diameter and number of windings that may be applied within the core window, for a specific core thickness. Similar to the planar construction, PCB design rules limit the number of windings that can be applied. The advantage in this case, however, is that the toroid core shape allows one to achieve more inductance with fewer windings. Regarding manufacturing cost, the trade-off is to employ drilling and plating instead of winding wire. Drilling time is significant, yet not prohibitive. Modern PCB drill systems have multiple spindles and can create the PTH interconnects at a competitive cost. More significant is the cost savings that comes from using a single toroid versus two E-style cores.

Given the different core shapes and construction techniques, it is difficult to make a direct comparison between the different topologies. At best, one can compare cores of similar volume and package footprint. Table 1 compares the properties the popular EFD20, Planar EQ20 and a 15.8 mm toroid core.

Table 1, Comparison of properties for EFD, Planar EQ and Toroid Cores

	EFD Ferroxcube EFD20	Planar Ferroxcube PLT14/5	Embedded Toroid, Ferronics 11-277
Core Dimensions, mm	L=20, 2•W= 20 H= 6.65	L=20, W=14, 2•H=8.12	OD =15.8, ID=8.8, H= 6.3
Package Footprint	29 x 20 x 9.9	22.9 x 20 x 8.4	22 x 20 x 7.6
Path Length, le, mm	23.5x2= 47	26.4 • 2 = 52.8	36.8
Cross Section Area, Ae, mm^2	31.0	47.3	21.1
Core Volume, Ve, mm^3	730 • 2=1460	625• 2= 1250	747
Core Weight, g	3.5 • 2 = 7.0	3.8 • 2 = 7.6	4.4
Al value, nH/T^2 μ=2.3K	≤ 1300	≤ 2500	≤1830
Al, nH/T^2 μ=2.3K, gapped	≤ 160	≤ 230	≤ 250 (0.15 mm gap)
Core Loss, 2.3K perm material, 100 KHz, B=2000 Guass	584 mW	500 mW	298 mW
W_aA_c Product , cm^4	2 • 0.078 = 0.157	2 • 0.082 = 0.164	0.125
Core Factor Σle/Ae, mm^{-1}	1.52 • 2 = 3.04	0.563 • 2 = 1.12	1.70
Relative Material Cost	2.0x to 2.5x	2.0x to 2.5x	1x

Wa = Window area in cm^2
Ac = core area in cm^2
C = current capacity, cm^2/A
4.05x10-3 cm^2/A square wave & toroids
5.07x10-3 cm^2/A square wave & E-U-I cores
e = efficiency
B = Flux in Guass
f = frequency in Hz
K = winding factor
(0.2 toroids, 0.3 for E-U-I cores)

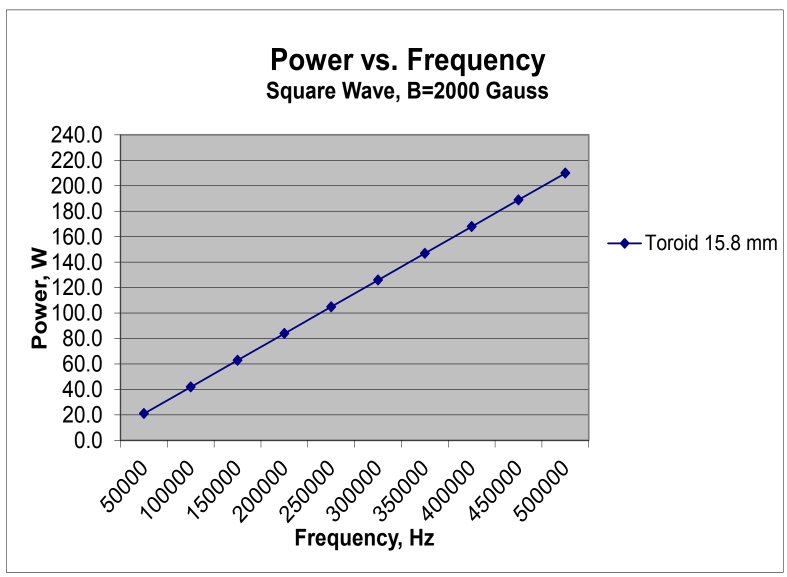

Figure 3, Power vs. Frequency for 15.8 Embedded Torodi

The power handling capability of a transformer can be determined by the product of the window area and cross section area of the ferrite core (W_aA_c). Based on Faraday's law[2], on can derive the equation:

$W_aA_c = (P_o \cdot C \cdot 10^8) /(4 \cdot e \cdot B \cdot f \cdot K)$

[2] Faraday's Law, E=4 • B • Ac • N • f • 10^8 (volts)

The chart in figure 3 shows Power vs. Frequency 15.8mm embedded toroid. Similar to the EFD and Planar devices, the design is suitable for applications ranging from 20 to 100W, depending on the switching frequency. The equation considers core size and saturation. In actual applications, winding resistance and heat dissipation are likely bigger factors in determining the constraint on power deliver. Heat dissipation of the embedded device warrants further investigation. The broad conductors and full coverage of the windings can be advantageous for spreading and dissipating heat.

4. Measured Data

Table 2 summarizes the parametric data for Embedded Magnetic prototype transformers developed by Radial Electronics. The ferrite material had an initial permeability of 5000 and the core height was 0.250”. Before insertion, the cores were prepped with a gap cut with a YAG laser. Gap width was about 0.005”. Primary and secondary windings were implemented with 2 oz. copper. Measurements were taken at 10 KHz.

Table 2, Average Parametric Data, Embedded Transformers

Core OD	Windings	L, Primary	R, Primary	R, Secondary	Cww
0.500”	24:3:3:12	152 uH	0.49Ω	0.03Ω	22 pF
0.625”	32:4:4:12	238 uH	0.57 Ω	0.04Ω	56 pF
0.870”	48:4:4:12	532 uH	0.99 Ω	0.05Ω	67pF

These devices are useful for flyback converter designs, operating with a 38 to 72V input and in the frequency range of 200 to 400 kHz. Inductance values can be improved with refinements to the gapping and encapsulation process. Winding resistance can be reduced further by optimizing the winding design and using a higher copper weight.

5. Conclusion

Embedded magnetics provide a practical method for implementing power inductors and transformers. The toroid core shape provides the shortest path length for magnetic flux and is optimal for producing transformers with minimal ferrite material. The embedded magnetic construction makes it practical to implement high winding ratios and different copper weights on the primary and secondary windings. The technology is useful for fabricating transformers and inductor that can operate in the 6W to 60W range. Beyond that, copper foil and plating thickness will begin to constrain the winding resistance. The following is a summary of the salient benefits:

1. Automated batch process; fabrication on a PCB assembly line with minimal labor content
2. Practical implementation toroid shaped cores
   a. Low Cost
3. Higher efficiency
   a. Shorter windings for lower AC impedance and DC resistive loss
   b. Low core loss
   c. Low leakage inductance
4. Good shielding and low radiated emission
5. Good heat spreading and thermal management
6. Low profile package
7. Consistent performance that can be modeled and optimized
8. Reliability consistent with PCB technology

Finally, the product package is essentially a PCB, which allows for the placement of other passive and active components. Vertical integration can be used to reduce the overall system footprint. It also provides short interconnects between devices, which is beneficial for high frequency performance and minimizing I^2R loss.

References:

1. Ferroxcube Product Selection Guide 2007
2. Magnetics Inc. Product Catalog, 2008
3. Switching Power Suppliers A-Z, Sanjaya Mankiktala, Elesevier Publihing, Bulington MA. 2006