Embedded Magnetics for Power Applications

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Abstract — Inductors and transformers are basic building blocks in electronic systems. In power applications, their functions include energy storage, noise filtering, voltage isolation, and impedance matching. Embedded magnetics provides a new approach for fabricating transformers and inductors. In DC-to-DC and AC-to-DC converter implementations, they are useful in minimizing switching noise, parasitic losses and reducing the device size and footprint. Current power magnetics are constructed one at a time, by winding wire around a magnetic core structure. Often, the wires are manually dressed and soldered to I/O pins. Embedded magnetic devices are implemented on a standard printed circuit board line in an automated and batch process. The magnetic device becomes the printed circuit board, upon which other active and passive devices can be populated to implement the power conversion function. Integration into the system module can shorten interconnects between components and improve the circuits efficiency. Also, heat can be distributed by the PCB winding layers while voltage isolation and safety concerns can be maintained through careful selection of materials and construction of the layer stack. This paper describes the device planning and construction. In addition, it discusses constraints and shares design rules for fabricating of embedded power magnetics on a printed circuit line. A design example is provided to show the viability of the technology

Background

The pursuit of energy efficiency is driving innovation in electronics and electronics packaging. In the past, Energy Star and other efficiency standards only applied to large appliances like refrigerators and washing machines. Now, most electronics appliances, whether it is a battery charger or LED light, are subject to regional efficiency standards. In particular, power conversion efficiencies are being driven above to > 80% and there are requirements for minimal energy draw during no load and standby conditions. To meet these requirements, designers have embraced, Switch Mode Power Conversion (SMPC). Power converters based on SMPC architectures offer much higher efficiency then the linear regulators that preceded them. An SMPC circuit often employs a number of transformers and inductors. These elements provide voltage isolation, voltage level conversion, filtering and impedance matching. The magnetic components are critical for meeting efficiency targets and Electro-Magnetic Compliance (EMC). Figure 1 shows a block diagram of typical SMPC AC-to-DC converter. The power transformer is central to the design. It steps down the voltage level and provides voltage isolation between the input and output. It works in conjunction with the switching transistor, whose frequency and duty cycle controls the transfer of energy across the transformer windings. Also, at the input of the power converter there is a common mode inductor (choke) that blocks switching noise from emanating onto the power source. Similarly, a filter at the output to minimize noise being from conducted to the load.

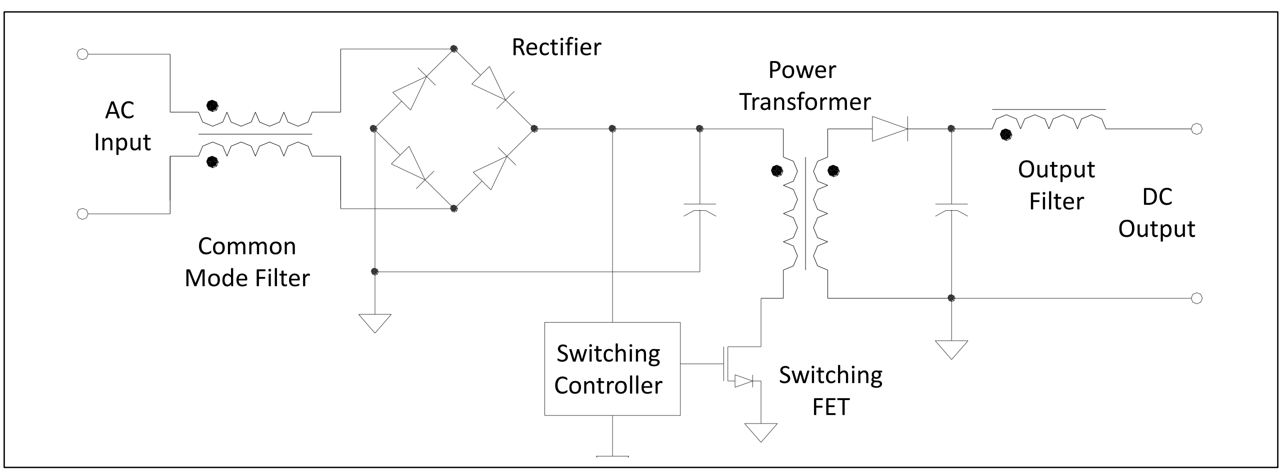

Figure 1, Block diagrams of AC-to-DC power converters

The power transformers used in these systems are often based on E shaped ferrite core structures, where two E shaped elements are clamped around a wire wound bobbin. Coiling wire onto a plastic bobbin is relatively easy to automate, which has made this construction the industry standard. However, bobbin winding still requires some manual labor to dress the wires, apply insulation tape between layers and solder wires to the package I/O pins. Devices are still constructed one at a time and the labor content is still considerable.

Planar magnetics emerged over the past few decades as a means to improve automation and efficiency of power transformers. Rather than clamp two E-cores around a bobbin, inductive windings are implemented on multiple PCB layers and the ferrite elements are clamped around the PCB. Typically 8 or more PCB layers are employed to achieve the required windings and turns ratio. This produces a device with many of the same characteristics as the bobbin wound devices in terms of efficiency, weight, size, loss and noise emissions. The planar construction offers a higher degree of automation and eliminates of many of the manual steps associated with providing isolation and terminating wires.

Embedded magnetics offers another means of automation and improving efficiency. Much like planar magnetics, embedded magnetics may be implemented on a standard PCB line using conventional processes. Devices are arrayed on a panel and fabricated in a batch process. The main differences are that embedded magnetic devices may be implemented with a fewer number of a PCB layers and can utilize more efficient toroid (ring) shaped cores. Figure 2 compares E shaped cores to the ring shaped toroid. Where toroids excel is in low loss. When an alternating voltage is applied to the inductive windings, a magnetic flux is induced inside the ferromagnetic core material. With the E cores, the windings only cover and stimulate the center leg portions. Magnetic flux then loops around the legs to complete the magnetic circuit. In doing so, the flux energy has to cross 3 discontinuities in the ferrite material. With the toroid, the path length of the magnetic flux is shorter with no discontinuities. Consequently, for a given volume of ferrite material, the toroid will have a higher inductance factor[1] and will require fewer windings to deliver the same amount of inductance. This means that the toroid based design will be smaller and lighter weight. Another consideration is the power loss. Toroids can achieve the same inductance with a smaller volume of ferrite material. Core loss is a function of the ferrite volume. When the magnetic flux is switching within the ferrite material, some of the power is lost in the core material and dissipated as heat. A smaller more efficient core will also have shorter conductive windings and less winding resistance. Both conditions improve efficiency and make it practical to operate the transformer at higher switching speeds. When implemented with embedded magnetic construction, the windings can be carefully shaped to control the AC impedance and minimize the inter-winding capacitance.

Whether a planar or bobbin wound construction, the windings cover only a small portion of the ferrite core. The exposed areas surfaces of the cores contribute to leakage inductance and radiated emissions. In comparison, the embedded toroid has conductive windings evenly distributed around the core to minimize leakage inductance. Leakage inductance is contributes to loss during AC switching. Noise is another concern in power converter design. Again, the toroid's advantage is a continuous flux path and windings that cover their full circumference. Thus, they are preferred when radiated emissions is a concern. Finally there is cost. Toroid cores are stamped out in "cookie cutter" fashions. Molding E cores is a bit more involved and requires that the interfacing surfaces be machined and polished. Consequently, toroid cores can be fabricated at a fraction of the cost of E cores.

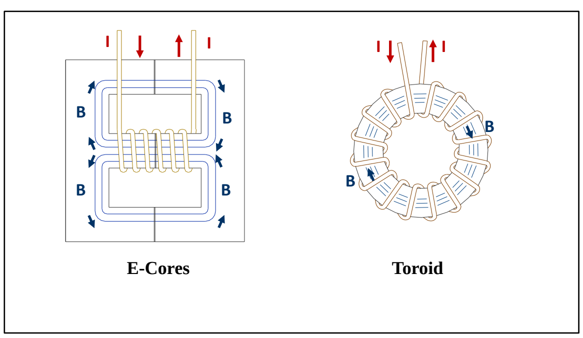

Figure 2, Comparison of E shape and Toroid

With all of their benefits, why have E cores been the standard for implementing power transformers? The issue has been the winding equipment and lead termination. There are automated machines that can wind toroids with diameters of 8 mm or

[1] The inductance factor, AL, is expressed in Henrys per winding turn squared, H/T^{2},

greater. However, SMPC application provides some unique challenges. The designs use large winding ratios, between the primary and secondary connections, which can be problematic for automatic windings. Different wire gauges are also used on the different windings, which add further complexity for an auto winding. Finally, many power applications actually require that a small gap[2] (slot) be cut into the core. Winding around the gap is difficult. To date, bobbin winding and the planar PCB construction have been better suited for the power transformers.

Construction

Embedded magnetics takes away all of these winding issues and makes it practical to use toroid's in SMPC applications. In fabricating the devices, there are actually a few alternatives with varying degrees of complexity and cost. The most-straight forward approach uses Plated-Through-Hole (PTH) interconnects between the different winding layers. A power inductor or common mode filter can usually be implemented with 2 layers. Power transformers are best implemented on 4 layers to provide voltage insulation between the primary and secondary windings. Figure 3 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. FR-4 laminate provides voltage insulation between the primary and secondary windings. To fabricate the device, cavities are first milled into a substrate made of FR-4 or G-10 Sheet stock. The ferrite cores are inserted and encapsulated with a low shrink epoxy[3]. Once the ferrites are loaded, the panel is sanded and cleaned for lamination. At that point, the panel can follow a standard process flow. Pre-preg and copper foil is laminated to the top and bottom surfaces. Hole arrays are drilled and plated to interconnect the top and bottom surfaces. Next, the windings patterns are imaged and etched to produce the primary windings. The lamination sequence is repeated again to produce the secondary windings.

One of the functions of the transformer is to step down the voltage. To achieve this, the device is designed with a winding ratio between the primary and secondary. Winding ratios can range from 2 to 20. During each switching event, current flowing in the primary winding induces a magnetic flux in the ferrite core. The primary has relatively high inductance and is driven by large voltages and relatively low current. Since the current is lower, the primary windings are placed on the inner layer. As mentioned above, coverage around the full circumference of the underlying core provides the most efficient stimulation and minimizes leakage inductance. During the switching cycle, magnetic flux in the core induces current in the secondary windings, effectively transferring energy to the secondary windings of the transformer. The secondary winding then delivers current to the load. Here, it is important to have low resistance and minimize I^2R power loss. The secondary is designed with broad conductors and multiple vias can be used to help manage resistance. The windings can also be designed extra wide to spread and dissipate heat.

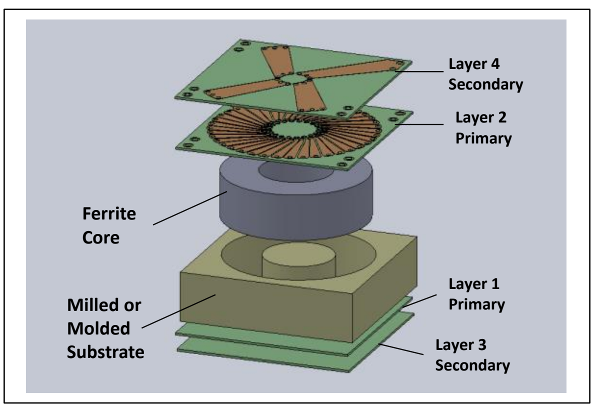

Figure 3, Exploded Assembly View

Winding resistance is a key parameter in power magnetics and copper weight will have much bearing on the power converter's efficiency. Copper weights should be 1 oz. or greater. In addition to managing the winding resistance, copper selection also impacts the separation between conductors and the density of the PTH via arrays. Table 1 lists common copper weights and their associated design characteristics. When all of the winding elements are linked together with PTH vias, the lengths of the primary windings can easily exceed 50 cm in length while the secondary windings can reach 10 cm.

[2] Gapping often improves the cores power handling capability and temperature stability, while reducing the material permeability by > 50%.

[3] Hysol 3145/3165 two part epoxy or equivalent.

The designer should work with a PCB trace width calculator to understand the tradeoffs between copper weights and trace width, for their particular design.

Table 1, Copper foil weights and design characteristics

Cu Weight oz.	Thickness µm (mils)	Minimum line width/ spacing mm (mils)	Winding Resistance per square mΩ
0.5	17 (0.68)	0.1/0.1 (4/4)	1.000
1.0	34 (1.36)	0.13/0.13 (5/5)	0.500
2.0	68 (2.72)	0.15/0.15 (6/6)	0.250
3.0	103 (4.08)	0.20/0.20 (8/8)	0.167
4.0	137 (5.44)	0.25/0.25 (10/10)	0.125

Another important function of the transformer is to provide voltage isolation between the primary and secondary windings. Depending on the application, the isolation requirement can range from 500 to 5000 volts. With wire wound devices, isolation is achieved primarily through wire insulation. Typical wire insulations materials include enamel, polyurethane, polyamide, polyester, polyvinyl and polyimide. Magnet wire with a *heavy* insulation will have a film thickness in the range of 25 to 50 um (1 to 2 mils). To enhance isolation, Mylar tape is usually applied manually to enhance insulation between the primary and secondary windings. Fortunately, the materials and geometries used in the PCB construction can readily exceed the isolation provided by magnet wire. Fist, one has to realize that the materials used to insulate magnet wire have dielectric properties very similar to the polymer and polyimide materials used in PCB construction. FR-4 has a withstanding voltage >13kV/mm (500 V/mil). With PCB construction, the separation between conductors exceeds 100 um (4 mils). Over 3kV of voltage isolation can be accomplished with merely 0.15 mm (6 mils) of FR-4 separation between layers. Beyond the material properties, there are a number of industry standards for "creepage clearance". They are often classified by applications, whether it is military, telecom, industrial, medical or consumer applications. One must also consider the working voltage of the circuit when deciding what spacing is required. UL 60950-1 and IPC-2221 are two of the more prominent documents concerning creepage and clearance. Per UL 60950-1, inner layers conductors should be ≥ 0.4 mm (0.016") apart for working voltages up to 250Vpk. IPC 2221B provides other guidelines for separation between high potential conductors. Table 2 is derived from columns B1, B2, B3, B4 and IPC 2221B Table 6. It lists the minimum recommended spacing between internal and external conductors[4], for different peak working voltages. Note that IPC only provides spacing's for up to 500 V working voltage. To complete the table, an online creepage calculator[5] was used to determine the values up to 2 kV

Table 2, Working voltages and recommended conductor separation

Working Voltage Vpk	Internal Layers		External Conductors Coated	
	mm	inch	mm	inch
30	0.05	0.002	0.05	0.002
50	0.6	0.024	0.13	0.006
100	0.1	0.004	0.13	0.006
150	0.2	0.008	0.40	0.016
250	0.2	0.008	0.40	0.016
300	0.2	0.008	0.40	0.016
500	0.25	0.010	0.80	0.032
1000	1.5	0.060	2.33	0.092
2000	4.0	0.158	5.38	0.220

Note that the voltage listed in table 1 are working voltages, which implies that the material will maintain its integrity under these voltages over extended time and within temperature limits. Voltage breakdown of a transformer, however, is typically characterized through hipot testing. Hipot testing is intended to stress test the insulation and is typically done at voltage

[4] For devices intended for use under 3050 meters (10,000 ft.)
[5] http://www.smps.us/pcbtracespacing.html

levels much higher than the working voltage. Voltage levels can range from 500 V to 6kV, yet for periods of 60 seconds or less. If one follows the IPC guidelines for conductor separation, hipot requirements are easily met. For instance, most telecommunication applications require that isolated devices pass 1500 Vrms, for 60 seconds. With 0.16 mm of FR-4 separation, an embedded magnetic transformer can easily pass hipot levels exceeding 6 kV. Figure 3 shows an example of a layer stack for a power transformer. Four layers of 2116 pre preg is used to provide 0.4 mm separation between the primary and secondary windings.

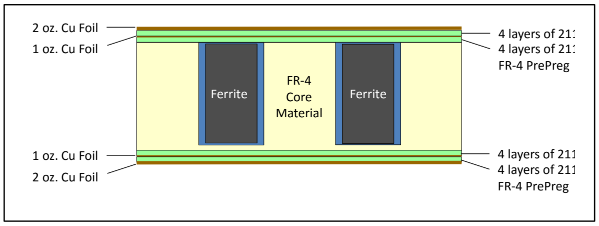

Figure 4, Cross Section of 4 layer Power Transformer

With hipot, one has to pay particular attention to the distance between covered conductors and exposed pads on the outer layer. Polymer solder masks can provide good insulation and typically exhibit breakdown voltages exceeding 13kv/mm (500 V/mil). Screen printing application can result in inconsistent thickness and the material will drain down the via barrels. This creates sensitive areas at the edge of the conductors and the annular rings of the vias. Problems occur when the air surrounding the exposed pad begins to ionize, due to the high voltage potential. Solder mask may be applied at 0.025 mm across the panel, but be much thinner at the edge of the conductors and vias. When the ion cloud gets large enough and extends over the opposing trace it can breakdown the thin film of solder mask. Generally, it is advised to polymer fill the vias and to apply at least 2 layers of solder mask. The second layer increases the thickness and fills any pin-holes in the first layer that might have been caused by bubbles or impurities. If signals are routed under the embedded magnetic transformer, the designer should consider either applying a polyimide cover lay (Kapton[6]) to the bottom surface. Kapton has a dielectric strength of 236 kV/mm (6000V/mil). Depending on the thickness, cover-lay can improve voltage isolation by 1000 to 6000 volts.

As a design example, a 15W power transformer will be considered. The device is designed for a Flyback AC-DC power converter and is suitable in implementing a battery charger for a cell phone or another portable appliance. The transformer is designed to have a 120 VAC input, 5 volt output and operate at a switching frequency of 100 kHz. To design the transformer, a number of variables need to be considered and it is an iterative process. The calculations are guided by the equations for magnetic flux density, both in terms of the drive voltage and drive current. The calculations can be rather lengthy and exceed the scope of this presentation. For reference, the flux density design equations are shown in Figure 5, along with the transformer schematics. and derived specifications for number of turns (windings) and inductance. For this application, an auxiliary winding is included to provide feedback information to the switch mode controller.

$$Bpk = \frac{0.25 \cdot Vpk \cdot 10^9}{f \cdot N \cdot A_e} \text{ mTesla}$$

Peak Flux Density in Terms of Voltage

$$Bpk = \frac{L \cdot Ipk}{N \cdot A_e} \text{ mTesla}$$

Peak Flux Density in Terms of Current

Vpk = peak switching voltage
Ipk = peak current voltage
L = Inductance, Henrys
f = frequency, Hz
N = number of turns, primary winding
Ae = cross section area of transformer, mm^2

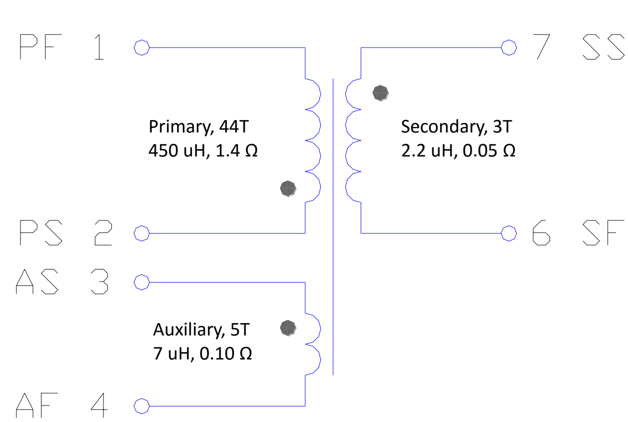

Figure 5, Design Equations and 15W Power Transformer Specification

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[6] Kapton is a Dupont product

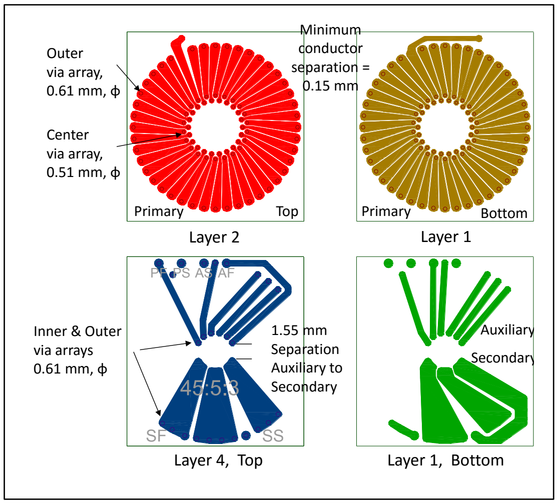

Figure 6, Artwork for Primary and Secondary

Figure 6 shows the artwork for the 15W power transformer. The primary was implemented with 45 windings (turns), 3 on the secondary and 5 on the auxiliary. This design is implemented with 1 oz. Cu on the primary and 2 oz. Cu on the secondary layers. Minimum conductor spacing on the primary windings is 0.15 mm (0.006"). The conductors are shaped to minimize resistance and enhance coverage to the underlying ferrite core. Normally, the auxiliary windings would be placed on the inner layers. For this design, the core ID was not large enough to fit the auxiliary, so they were placed on the outer layers with the secondary windings. Separation between the secondary and auxiliary windings is larger than 1.55 mm, enough distance to meet hipot and creepage requirements. Figure 7 shows some of the finished prototypes. The Transformer primary inductance was measured to be 463 uH at 100 kHz and has a winding resistance of 1.7Ω. This can be improved by increasing the copper weight in future builds. One can also see that the solder mask is thin at the via rims and isolation can be improved by adding a polymer fill step to the process.

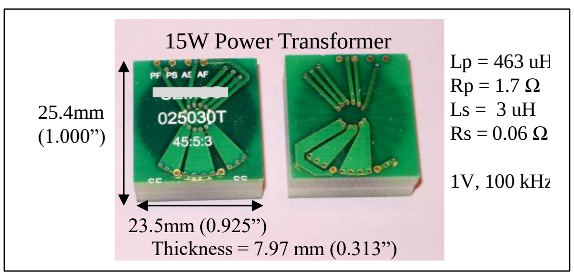

Figure 7, Prototype 15W Power Transformer

Conclusion

This paper described the construction on embedded power magnetics and key design considerations. A summary of a 15W power transformer was presented as a design example. The primary constraints for implementing this technology are the conductor resistance and size of the magnetic cores. While not necessarily suited for 100W applications, embedded magnetics is useful for applications in the 5W to 60 W range, which applies to a wide range of electronic appliances.

References:

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3. Sanjaya ManikTala, *Switching Power Supplies A to Z*, 2006 Elsever Inc. Burlington MA.

Authors Biography: Jim Quilici has over 30 years of experience developing microelectronics. He has designed and developed magnetic components for Pulse Electronics, Belfuse and Wurth Elektroniks. Presently, Jim does design consulting and process development through Radial Electronics. He also is a part time lecturer in Network Analysis and Microelectronics at California State University Sacramento. He can be reached at jquilici@radial-e.com