A Review of Planar Magnetic Techniques and Technologies

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Abstract – This paper presents an extensive survey of techniques and technologies used to implement planar magnetic structures in modern dc to dc converters. The survey emphasises the practical applications of these devices. The trends are analyzed in the context of the marketplace and some predictions of future direction are attempted.

I. INTRODUCTION

The drive towards higher power densities and overall lower profile in switch mode power supplies has exposed a number of limitations in the use of conventional magnetic structures. In particular achieving higher power densities has meant increasing the converter switching frequency to achieve passive component size reduction. However for conventional wire wound magnetic components this led to problems of increased loss due to the skin and proximity effects in the round conductors particularly at frequencies above 100 kHz. The earlier applications of planar magnetics [1-4] demonstrated the use of flat wide conductors to reduce skin and proximity losses in windings (compared to round wire), and illustrated the control of other parasitics such as leakage inductance. The repeatability of component characteristics also proved of considerable importance, particularly for use in resonant topologies being used for converters switching in the 1-10 MHz range [5,6].

The windings of the planar magnetics were essentially formed using common interconnection technologies, such as printed circuit boards (PCB), thick film and flex. Many early designs used thick film technology [5,7-9] for the realization of the windings but by far the most popular approach was the use of PCB, flex or stamped copper turns.

The early 90's saw many investigations into the characteristics, modeling and optimization of planar magnetics with the result that the pros and cons became clearer and some design guidelines became accepted.

The disadvantages of using non-standard low profile cores were addressed in the mid 90's when core manufacturers introduced ranges of standard planar cores, e.g. planar EE and EI cores, and low profile versions of conventional cores, e.g. RM cores. More recently planar ER and EIR cores have been introduced, thus contributing to the more widespread acceptance of planar magnetics.

However the widespread use of converters switching in the 1 – 10 MHz range, which were investigated in the late 80's never materialized, mostly due to limitations imposed by losses in the semiconductor devices [10]. Consequently, although planar magnetics have gained use in some areas they have not completely replaced conventional magnetic components.

In this paper the characteristics of planar magnetic structures as used in medium power (10-500W) applications are reviewed. This includes investigation of some of the more widely quoted characteristics of planar magnetics as described in the literature. Particular issues which arise in typical applications are also discussed. A section on manufacturing and safety requirements illustrates some practical limits in the application of planar devices. Methods for modelling and designing planar components are described, and finally issues which need to be addressed are outlined for further development and acceptance of planar magnetics.

II. CHARACTERISTICS OF PLANAR MAGNETICS

What is a Planar Magnetic Structure?

A comparison between a typical planar magnetic structure as shown in Fig. 1 and a conventional wound magnetic similar to that of Fig. 2 best illustrates the main differences. The core of the planar device has a lower profile than that of the conventional device. Also, windings on the conventional device are stacked so that they are successively further from the center leg, i.e. winding build up is in the x and y dimension. Windings on the planar device are, instead, stacked in the z-direction. Technologies used to produce such flat windings are discussed later in this section along with a review of suitable core structures.

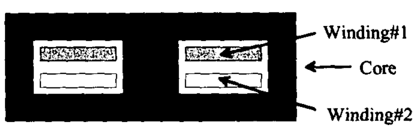

Fig. 1 Practical Planar Device

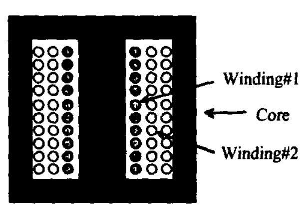

Fig. 2 Conventional "Wound" Device

The major characteristics which sparked interest in the use of planar magnetics for high-frequency power conversion are discussed below. These include:

- Low profile structures,
- A reduction in high frequency winding losses,
- Controlled leakage inductance.

Because a technology such as PCB easily allows the interconnection of arbitrary layers interleaved primary and secondary windings can be implemented much more easily than with conventional magnetics. This provides the means to further reduce leakage and high frequency winding losses [11], both of which have obvious advantages for high frequency square wave switching. A further advantage of the planar magnetic is the enhanced thermal performance possible because of the greater surface area to volume ratio, thus providing more area to contact to the heat sink. This is illustrated in the smaller value of thermal resistance quoted for planar cores over conventional cores [12].

The characteristics of planar magnetics are, of course, not all advantageous. In particular the planar format, although improving thermal performance, increases footprint area. The fact that windings can be placed close together thus reducing leakage inductance has the usually unwanted effect of increasing parasitic capacitance. The repeatability of characteristics obtained from PCB windings also comes at the price of having a greater portion of the winding window filled with dielectric material, thus reducing copper fill factor and limiting the number of turns.

Low Profile

The term "low profile" is often used to describe planar magnetics. However, not all low profile magnetics are planar. In particular low profile cores, such as the EFD type, use conventional wire wound technology. These components lack many of the characteristics of planar magnetics described in the following section.

The effect of core height on power density has been studied in several of the references [13-16]. In particular, some of these studies have compared planar magnetics to more conventional low profile magnetics and found that the low profile magnetics can have better volumetric efficiency [15] and higher power density [16] for certain applications.

High Frequency Winding Losses

Some earlier studies assessed winding configurations [11,17], investigated the optimum placement of windings [18], compared different winding technologies [11] and optimized layout of turns to minimize overall dc winding resistance [19].

In an analysis of different winding configurations involving the use of solid wire, litz wire, PCB and foil windings at 500 kHz [11], PCB windings had lower AC resistance (approximately 85 – 90 %) than similar solid wire windings but higher than Litz wire windings (approximately 115%). Leakage inductances of the PCB implementations were lower than both the wire and Litz wire implementations.

It also became evident that circularly wound planar windings can have significant 2D field effects in the winding window [15], which give rise to losses not accounted for by the traditional approach to the winding loss computation [20]. These effects were also investigated for foil windings and conclusions drawn as to how these 2D or "edge effects" might be minimized [18]. The conclusions were that winding losses were minimized for equal width primary and secondary layers, and for minimum spacing between winding end and core center leg. The work also indicated that there was an optimum spacing between primary and secondary layers which minimized losses.

Leakage Inductance

The ease with which interleaving can be implemented in planar structures allows the minimization and control of leakage inductance within the winding [11].

However, because the leakage inductance of planar components can be so low, particular attention should be paid to the termination of the windings. For example, depending on the secondary termination method used, the leakage inductance presented to the circuit can be up to three times that computed by the classical short circuit secondary approach [21].

It is obvious that the benefits of careful transformer design can easily be nullified by a lack of care in the connection of the transformer to the rest of the circuit. Inappropriate termination design can also account for as much as 75% of the short circuit ac resistance of a planar device [11].

Planar Winding Technologies

Various technologies can be used to implement the planar windings. The most popular of these have been compared in the literature [11], i.e. Printed Circuit Board (PCB), flex circuit and stamped copper. Windings fabricated in thick film and LTCC have also been used primarily in lower power applications.

The use of PCBs gives a highly repeatable and manufacturable means of implementing planar windings. In principle the windings can be an integral part of the system interconnection substrate thus totally eliminating all terminations, however in practice the interconnection substrate rarely has sufficient layers to fully accommodate the magnetic component windings. The disadvantage of PCB is that the window utillization factor can be quite low (typically 0.25 – 0.3 compared to 0.4 for conventional magnetics) due to a typical interturn spacing of 150 μm and minimum dielectric thickness of 100 μm.

Flex circuit (copper on a thin, flexible polymer substrate) gives an improved utilization factor as the dielectric thickness is as low as 50 μm [22]. Many layers of flex circuit can be laminated together resulting in a rigid structure similar to a PCB but with increased utilization factor [23]. Alternatively, it can facilitate the use of techniques such as the "z-folding" method [24,25]. This folding method can be used to implement a large number of layers without the need for vias or soldering for layer interconnects. Similar to PCBs, flex conductor thickness may be limited to standard thickness, typically 17, 35, 70, and 105 μm, with minimum conductor spacing increasing with increasing thickness. Unlike PCBs, the flex technologies are more suited to much heavier copper weights, e.g. 210µm (6 oz.) or larger.

Stamped copper windings provide a low cost means to implement high current, thick, single turn windings. The main disadvantages are that insulation layers must be separately applied and layer interconnection provided by some external means.

Planar Cores

Cores for planar components come in several forms. Probably the most popular is the planar EE or EI core, which is a core specifically designed for planar magnetics and is now offered by most manufacturers in about eight industry standard sizes. Other planar cores include low profile versions of standard cores such as RM, ER, PQ and pot cores. Because of its rectangular center leg, the EE core requires the use of a relatively long turn which must extend a considerable distance beyond the core, thus giving rise to issues of space usage and possibly EMI. Cores with circular center legs such as the RM, ER, PQ, etc. allow for shorter turns, and possibly improved shielding. However most of these low profile cores have a smaller winding window area to core area ratio than the EE core, thereby limiting the number of winding turns.

It is interesting to note that optimization studies on planar components have shown that there exists an optimal component height which maximizes power density for any set of specifications [13] and that higher power densities can be achieved by using custom cores [17]. Thus the limited range of standard planar cores is unlikely to offer the optimum solution for a particular design, so that if cost constraints permit, custom core designs should be investigated to maximize performance.

III. Applications in Power Electronics

The application of planar magnetic structures is wide-ranging across power levels and magnetic functions [26-33]. The common characteristics of these structures have been discussed in the previous section. This section concentrates on the desired characteristics that are application dependent.

Power Transformers

Planar transformers designed for power applications must satisfy the same requirements as conventional power transformers including the minimization of loss mechanisms and the provision of an acceptable cooling strategy. The task of minimization of the core losses is similar to that of a conventional wound magnetic. It requires suitable choices of the switching frequency, core shape and size and core material. The main difference lies in the choice of core shape and size.

Minimizing copper losses at high frequencies requires a good understanding of the principles of skin effects and proximity losses. Interleaving is a well-known technique used to minimize high-frequency effects contributing to winding losses within planar turns. However, the level of interleaving is limited by considerations of capacitive effects and the concerns of providing adequate levels of isolation between the windings. Application of these principles means that filling the core window with copper is usually not the best solution. In fact, in many applications high levels of interleaving of relatively thin layers results in a high insulator to copper cross-sectional ratio. This makes the use of printed circuit boards particularly suitable for transformer winding structures despite the upper limit of approximately 45 to 50% on copper utilization of the window (see Fig. 3a). In some very low profile applications, the copper utilization factor can be increased through the use of thinner insulation systems, shown in Fig. 3b [23]. In the case of single-turn, single-layer secondary windings designed to carry high current, thick external copper stampings can augment or replace PCB layers. In some applications where further interleaving is undesirable or not practical, thicker copper may be used for improved thermal transfer without a loss or efficiency penalty.

1-D analysis is sometimes sufficient for predicting high frequency transformer effects [20,34,35] but in many cases 2-D, and even 3-D, analysis is required as discussed below in the section on modeling.

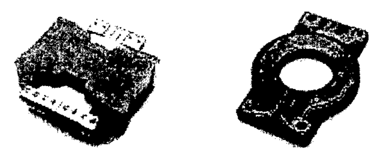

Fig. 3 (a) Transformer with FR4 PCB Winding (b) Rigid Flex Winding

It has also been previously mentioned, reductions in leakage inductance and winding resistance can be offset by poor termination design [11,21] resulting in a poorly designed transformer.

Power Inductors

Depending on the application, the requirements of planar power inductors can be very similar or very different to those of power transformers. For simplicity we limit our discussions to two categories. The first category is inductors where the ripple current is a small percentage of the average dc current component (say, less than 5% on a rms basis). The other category is where the ripple current is large relative to the dc component (say, greater than 20%). Of course, many applications are somewhere in between and tradeoffs are required.

In the case of the small ripple, we can assume that the current is a dc current and that skin effect and core losses can be ignored. The design of the planar inductor then reduces to choosing the lowest resistance winding possible based on the constraints of the core size and gap. Minimizing the number of turns on the inductor is the first step towards achieving a low winding resistance. The next and, probably, more difficult challenge is to maximize the copper utilization of the core window.

Unlike planar transformers, printed circuit boards are usually not suitable for inductor windings because of the inherently large insulator thickness. The exception would be at lower current levels where the size of the core window doesn't require full window utilization. A number of different approaches have emerged depending on the number of turns required.

Clockwise from Top Left:
(a) Stamped and Pinned Winding (courtesy of Pulse Engineering)
(b) Helical Winding (courtesy of Schott Corporation)
(c) Watchspring Winding (proprietary to Artesyn Technologies)
(d) Staples through Core (courtesy of Pulse Engineering)

Fig. 4 Examples of High Current Planar Inductors

In the case of fewer turns a helical structure offers a good solution. This can be in the form of copper stampings which are pinned in series [36] (Fig. 4a), folded copper winding structures [24] or a true helical winding from a single piece of conductor [37] (Fig. 4b).

As the number of turns increases, the thickness of the conducting materials decrease. This can lead to difficulty in forming and maintaining terminations in some of the helical structures. In these cases a watchspring-type winding may be more suitable (Fig. 4c). If the core window is wider than it is tall, then the copper conductors will be thicker and more easily workable although terminations may require difficult bending or forming. Some approaches involve solder or welding operations to implement the terminations [38]. One alternative to these complex bends and solder operations is to use a rigid-flex circuit board [23] (see Fig. 3b). These circuit boards offer increased copper utilization over FR4 material due to the use of thinner insulating materials.

Other approaches to implementing windings on a low profile planar magnetic core involve incomplete turns (often called staples) as shown in Fig. 4d [36]. The turns are completed by copper etch on the converter's PCB.

In inductors where the ac ripple content is high, the design of the winding has issues very similar to that of transformer winding design with one more difficulty. There usually is no secondary winding that can be used to reduce proximity effects through interleaving.

With regard to core design, there is now a significant ac flux component causing core losses and potentially contributing to eddy-current losses if the gap and the winding are in close proximity. This is not an unreasonable assumption in planar devices as two of the primary goals are small size and high power density. In these cases, a lumped gap may result in unacceptably high losses in the winding and alternative gapping strategies (e.g. distributed gaps) may merit consideration [39].

Pulse Transformers

The use of planar magnetic structures for implementing pulse transformers has been minimal. Relative to power transformers and inductors, devices such as gate drive and current sense transformers are small in size. Because the devices are already low-profile, even when built using conventional wound magnetic techniques, any further reduction in height increases the footprint unnecessarily. Some uses have been reported [29] but in most practical applications, there is usually little to gain by using a planar construction for pulse transformers.

Some research continues to develop coreless transformers using windings buried in circuit boards [40] and experiments burying the windings and cores in circuit boards [41].

Integrated Magnetics

A discussion of planar magnetics would not be complete without the consideration of integrated magnetics structures. These devices combine multiple magnetic functions on a single core structure. With the exception of the flyback transformer and some coupled-inductor applications [42], integrated magnetic devices have been slow to gain widespread use in the power supply industry. While these devices offer many advantages, e.g. reduced parts count and improved performance [42-44], potential gains have usually been offset by the complexity of the winding structures and the associated cost.

The maturing of the technologies associated with planar devices has helped overcome some of these complexities and the associated costs. Examples now abound where the advantages of planar devices have allowed the practical implementation of magnetic structures that were previously very difficult or unfeasible. The advantages range from repeatability and reproducibility, which help control manufacturing cost [45,46], through improved thermal performance and the minimization of interconnections between devices [30,47]. The minimization of interconnects is obviously very advantageous in low voltage high current applications for efficiency reasons.

Some converter topologies are well documented and analyzed [42,44-46,48] for their applicability to planar technologies. Most of these suitable topologies appear to have an obvious symmetry from the perspective of the magnetic devices, e.g. push-pull primaries, current-doubler secondaries and center-tapped secondaries.

However, not all converter topologies are necessarily suitable for planar magnetic structures. As an example, consider the integration of the isolating transformer and the output inductor of the forward converter. The optimization of this device can severely compromise the low-profile feature of planar devices. The evolution from discrete devices to the integrated magnetic structure on a three-legged core is well documented [42,49]. Optimization of this structure is somewhat problematic when planar magnetics are considered. For example, one option is to locate the transformer windings on the outer legs and the inductor winding on the center leg. While this results in a symmetric structure, the magnetic path length associated with the transformer, and its large ac flux content, can be very long resulting in high core losses. The need for a wide (i.e. low resistance) inductor winding exacerbates this problem by further increasing the magnetic path length. The other option is to locate the transformer windings on adjacent legs and locating the inductor winding on an outside leg. Unfortunately, flux-splitting no longer occurs and if window height is to be maintained the core height will have to grow. Thus, the low-profile advantage of planar structures is immediately compromised.

Some of these issues have begun to be addressed through the use of multi-chambered structures [50]. A stacked multi-chamber approach appears to be very flexible from a design standpoint but probably has limited usefulness in low profile applications. The side-by-side (or concentric) approach appears most promising for low-profile applications but access to the inner windings could be problematic especially for surface-mount applications.

IV. Other Issues

Manufacturability

The simplest way to introduce planar devices in a manufacturing facility is to use stand-alone components which are available both off-the-shelf and customized. An example of such a stand-alone planar transformer is shown in Fig. 5.

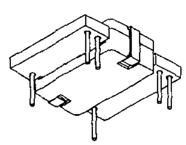

Fig. 5 Stand-Alone Planar Transformer

Stand-alone planar magnetic components are used with various types of terminations. The most common termination types include PCB edge connectors, J-leaded and T-leaded terminations. The stringent SMT co-planarity requirements (typically 100um) can be alleviated by using pin-through-paste terminations or press-fit terminations. Shown in Fig. 5 are terminations compatible with both pin-through-paste (also known as intrusive reflow) or wave-soldering processes. The main drawback of non-substrate-integrated magnetic components is compromised electrical performance due to additional losses in the terminations.

For optimum circuit performance and lowest cost it is sometimes desirable to utilize the main substrate of the electronic assembly as an integral part of the planar magnetic component. An example of such a planar transformer is shown in Fig. 6.

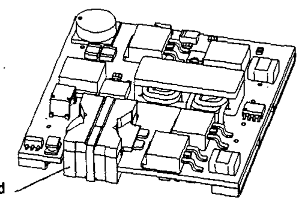

Fig. 6 Substrate-Integrated Planar Transformer [51]

When moving from conventional magnetic components to substrate-integrated planar magnetic components manufacturers of electronic assemblies (e.g. dc/dc converters) essentially become manufacturers of magnetic components facing new challenges. The magnetic core must be assembled during the manufacturing process of the electronic assembly. The core halves must be either clipped or glued together. Cost comparisons between clipping and gluing are complex involving numerous factors (material cost, manual labor, curing and batch processing of glued parts, repairability). In a high-volume production environment clipping can be automated and typically turns out to be the more cost-effective solution.

Ferrites exhibit wide mechanical tolerances. As a result there will be a loose fit between the core of planar magnetic components and the substrate (a problem known as "core rattle"). Multiple solutions have been identified to address this problem (gluing the core to the substrate, using soft pads between core halves, interference fit between core and flex windings etc.).

A substrate testability issue arises in substrate-integrated planar magnetic components. In this case the magnetic component is not readily testable as a separate entity. Defects in the magnetic component manifest themselves late in the manufacturing process and usually lead to costly scrappage of the complete assembly. With a typical track-to-track spacing of around 200um and multi-layer PCBs with 20 layers and more, intra-winding shorts as shown in Fig. 7 are common reasons for such defects in the planar magnetic components.

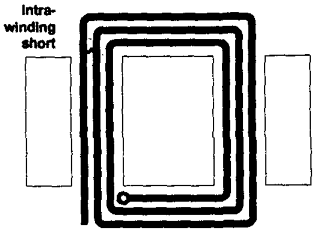

Fig. 7 Intra-Winding Shorts in Planar Coils

It should be noted that such intra-winding shorts will not be uncovered by standard PCB continuity checks.

In short, PCB planar windings have very different requirements to other circuit boards. These issues are best addressed when a good relationship exists between the PCB manufacturer and the designer of the planar devices.

Meaningful specifications can then be developed which reflect the most up-to-date design techniques and the most current process capabilities of the PCB manufacturer.

Compliance with Safety Standards

In most applications, transformers and multi-coil inductors have to comply with international safety standards [52]. Compared to their conventional wire-wound counterparts, PCB or flex-type planar magnetic components can lead to a significant reduction in size while still meeting these standards.

A cross-section of a typical PCB planar magnetic transformer is shown in Fig. 8. It consists of a low-profile E-core and a four-layer PCB. Here, 8 primary turns are sandwiched between 2 secondary turns.

One or multiple layers of pre-preg with a typical finished thickness of 35um each are used as a bonding material for multi-layer PCBs. The outside copper layers are made of plated copper foil. Depending on the required total number of layers one or more double-sided core laminates are used.

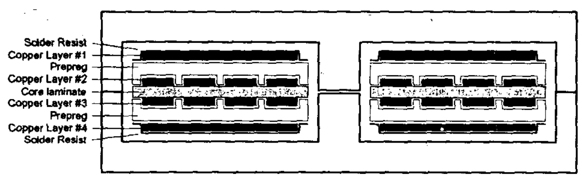

Fig. 8 PCB Planar Magnetic Transformer

Section 2.9.4.3 of EN60950 [52] outlines insulation requirements within PCBs for supplementary and reinforced insulation. If two layers of pre-preg are used no minimum thickness through insulation is required. For operational or basic insulation one layer of pre-preg is sufficient.

According to section 2.9.7 of the same standard [52] the internal insulation of multi-layer PCBs (provided by layers of pre-preg) is considered an insulating compound. Depending on the PCB manufacturer, copper tracks on inner layers can get as close as 400um to the edge of the board (routed edges) or 500um (scored edges). In the given example clearance and creepage distances between primary and secondary coil exist only at the locations where the inner layers are made accessible through vias and terminations. Creepage and clearance distances do not exist from copper tracks on inner layers to the PCB edge, thereby greatly improving utilisation of the available winding area.

Solder resist is not considered a reliable insulator by safety standards. In this example, the core is not considered isolated from the secondary coil and is, therefore, reported to the secondary side of the circuit. The core can be galvanically isolated by not using the outside copper layers at the expense of an increased number of total layers. Alternatively core isolation can be achieved by placing stamped thin sheet materials (e.g. polyimide) between core and PCB.

In conventional wire-wound transformers creepage and clearance requirements are typically complied with using inter-winding tapes and margin tapes. The need for tapes, particularly the margin tapes, considerably reduces the available winding space or increases the physical size of the magnetic component. As an example a transformer for a low-power (10W) telecom dc/dc converter providing basic insulation typically requires 1.0mm margin tapes occupying 25% of the available width of the winding area. Interleaving primary and secondary side coils increases the number of required layers of inter-winding tape further reducing the copper fill factor.

Insulation materials used in conventional transformers need to be approved in combination if the transformer temperatures exceed class A temperature limits. The combination of these materials is called an *Insulation System.* A different interpretation adopted by many safety agencies exists for popular PCB or flex-type planar transformers. Because of their simpler construction they are merely considered "barrier components". Barrier components comply with safety requirements if their insulating materials are individually rated for the temperature stresses they are exposed to. Because of this it is relatively straightforward to obtain a safety approval for planar transformers. Note that this interpretation might change in future.

V. Modeling and Design

As described in the introduction, the main difference between conventional and planar magnetic devices is in terms of their winding structures. As a result of these differences, models for predicting components of impedance for conventional windings are not accurate when applied to planar structures. This is particularly true of components of winding resistance and leakage inductance.

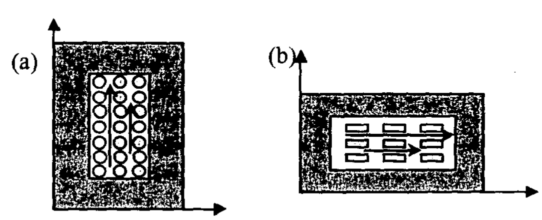

Fig. 9 1-D magnetic fields in (a) conventional windings and (b) planar windings

New methods for modeling planar structures include analytic and numerical techniques. A 1-dimensional (1D) analytic formula is widely used for modeling high frequency losses in conventional windings [20] although significant errors are possible [53]. The formula is based on an assumption of uniform magnetic fields along the height of the core window as shown Fig. 9a, and losses are calculated in each radial winding layer. Planar windings are formed on different axial layers, so that 1D fields may be assumed along the radial direction (see Fig. 9b) and Dowell's formula may then applied to each axial layer [54,55].

By applying the 1D solution to harmonic components of non-sinusoidal current waveforms, the 1D solution provides a convenient method for determining high frequency converter winding losses [34]. However, due to the small window utilization factor in planar structures, significant 2D fields link within the wide conducting sections and cause much higher losses than predicted by 1D solutions. Several analytic techniques have been presented for predicting 2D effects in conventional structures [56,57]. These can also be adapted for modelling equivalent planar structures, but numerical techniques are more widely used [11,21,58]. The development of commercial software simulation tools based on numerical techniques has increased the popularity of this approach.

To illustrate the need for 2D analysis, the use of one such package from Ansoft [59] is applied to predict losses in a planar structure which includes a shield layer between primary and secondary windings. These results are compared with predictions for the primary winding of the same structure using Dowell's formula Fig. 10. The structure could be considered even more one-dimensional than that of Fig. 9(b) because there is only one turn per layer.

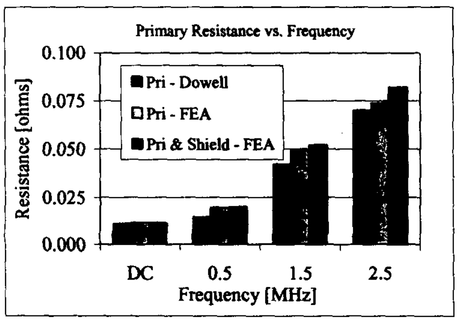

Fig. 10 Comparison of losses calculated using 1D analytic and 2D FEA technique

The effect of increasing frequency on winding resistance is obvious for each method of calculation. However, up to 16% extra losses are predicted by the FEA approach that are missed using the 1-D analysis of Dowell's technique. Additional losses incurred within the shielding layer account for up to 10% of total losses at high frequency. These are easily predicted using FEA models but cannot be included using Dowell's solution.

Leakage inductance can also be predicted from Dowell's 1D solution, but again numerical techniques are more effective for investigating high frequency effects contributing to leakage fields in planar structures. It is interesting to note that values of leakage inductance may be severely underestimated by 2D models [21]. Differences have been found to be due to leakage fields associated with terminations used to short the secondary terminals during measurement. That is, leakage inductance within the planar winding structure is often small enough that it is comparable to that contributed by external shorting connections. Obviously, a 3D model must be applied to include the effect of such terminations.

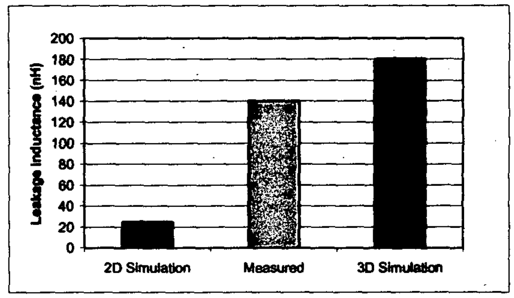

Fig. 11 Comparison of measured leakage inductance with 2D and 3D FEA simulation results

For example, measurements performed on a 100W transformer design are compared with results predicted by 2D and 3D FEA simulation of the structure under short circuit conditions in Fig. 11. As shown, inclusion of the shorting connection between secondary terminals in the 3D model accounts for a high percentage of total leakage inductance in this case where the measured leakage inductance is over 6 times larger than predicted by 2D FEA. In fact, the 3-D FEA modeling overestimates the leakage effects (by approx. 28%). This example further emphasizes the need for careful termination of planar windings.

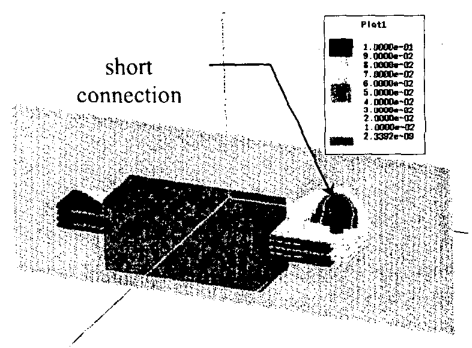

Fig. 12 Magnetic flux density predicted by 3D FEA simulation for planar winding under short-circuit conditions

A plot of magnetic flux density calculated for the structure is shown in Fig. 12 which illustrates the concentration of leakage energy in the vicinity of the short connection.

VI. Future Trends

Current and Future Market Usage

The largest usage of planar magnetic structures is probably in dc-dc converter "bricks" [52,60] and similar products primarily because they offer a means of processing the required power within a given profile while minimizing component count.

Increased availability of standard product from various manufacturers [36-38] is continuing to lower the costs of inductors. However, the standardization of transformers is not as common. This is due, in part, to the plethora of topologies that exists and also due to the fact that the winding technologies and associated costs for these devices are still evolving.

The development of low-cost and high-volume methods for transformer windings continues to be a challenge and the availability of optimal core structures also leaves room for improvement.

If high levels of parallel processing are used conventional magnetic structures can be an economical alternative to planar while achieving the same goals. However, the push for even lower profile converters will make this alternative unfeasible and planar structures will probably win out.

Future technologies

The requirements for future power supplies were recently discussed by Huljak et al. [10] with predictions that future microprocessor power requirements will demand smaller higher density converters operating at higher switching frequencies (e.g. 10 MHz in 2008 for isolated supplies). The achievements of higher power density will demand a greater level of functional integration. The use of integrated magnetic concepts and new packaging approaches goes some way to achieving this [61]. However, in the longer term, new technologies which allow a greater level of integration are sure to figure prominently and most of these technologies suit the use of planar magnetic structures.

For example, there is currently considerable research interest in the integration of magnetic components on silicon and converters have been demonstrated which have inductors, power switches and control integrated on a single IC [62]. For this technology most results to-date have been in the area of low power (typically < 2 W) [31,32], however investigations are on-going on its application to non-isolated converters for the powering of future micro-processors [63]. Other technologies which allow the embedding of magnetic and capacitive components within, for example PCB substrates, [41], [64] also have the potential to increase densities.

Another approach of note is the integrated electromagnetic concept [65]. In this approach the electromagnetic components such as transformers, inductors and capacitors are built up using successive planar layers of conducting, magnetic, and dielectric materials, so as to form part of a highly integrated "energy processing" structure. The concept is illustrated by the diagram in Fig. 13.

Essentially this approach allows the discrete electromagnetic components such as capacitors, inductors and transformers to be replaced by a single integrated component.

It is not clear at the moment what the ranges of applicability of these technologies will be and as with most new technologies their adoption will depend on the techno-economic tradeoffs involved. However what is clear is that if the goals of increased power densities are to be achieved then the integration of magnetics and other components, most likely using planar structures, will become increasingly important.

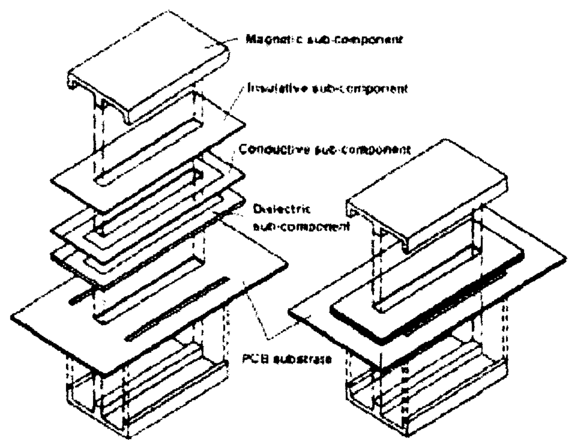

Fig. 13 Integrated electromagnetics [65]

CONCLUSION

A comprehensive review of planar magnetic techniques and technologies has been presented. The history of, and the motivation behind, the development of planar devices has been presented. Issues have been addressed and references provided to allow the practicing engineer evaluate the applications of planar magnetics structures. Finally, some future trends have been predicted for planar applications in the power conversion industry.

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