This paper was originally published in Volume One of the Proceedings of the IEEE Power Electronics Specialists Conference held in Galway, Ireland during the week of June 18-23, 2000.

Multi-Chambered Planar Magnetics Design Techniques

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Abstract **– New planar construction alternatives for blending the various power magnetic components of switch mode power processing circuits and systems are presented. These unique approaches are based on the use of core designs with multiple winding areas and core sections which provide common flux paths for transformer and inductor operations, arranged so as to minimize magnetic interactions and core material required. Construction examples for 125-watt & 50-watt DC-to-DC switch mode converters are detailed, the latter example consisting of a four-piece three-chamber cylindrical planar core structure that houses all power magnetic functions, including input filter inductance. Planar means to control leakage inductances between inductive windings are also presented for control and reduction of AC ripple current magnitudes.**

I. Introduction

ONE of the more interesting magnetic design techniques in practice today by power supply engineers is the "blending" or "mixing" of transformer and inductive functions of dynamic power conversion circuits on a *single* magnetic core structure. This technique has come to be known as **I**ntegrated **M**agnetics (**IM**) design. Although the origin of the technique can be traced to prior work performed in the early part of the last century, IM methods have become increasingly popular since 1977, when "coupled-inductor" assembly concepts and associated converter designs [1][2][3] were more fully disclosed. When implemented correctly, IM techniques can produce a significant reduction of the magnetic core content of related power processing systems, resulting in cost-effective designs of smaller weight and volume. Recently, IM packaging alternatives have been extended to include implementations in planar, or "flat", forms, using modern printed-circuit approaches for windings together with low-profile ferrite core constructions.

It was subsequently demonstrated in 1984 [4][5] for circuit arrangements and in 1987 [6] on a system level that *all* power conversion circuit designs of the switch mode variety have one or more IM forms. Prior to these points in time, it was commonly believed that only those power-processing networks wherein transformer and inductor winding potentials are always dynamically proportional could have IM versions. Such special converter networks include transformer-isolated versions of the Ćuk [2], SEPIC and ZETA topologies. However, by the use of core structures that possess more than one major material flux path [4], IM techniques can be applied to *all* switch mode power processing circuits and systems, and can be extended to include other magnetic elements often excluded. Examples of such elements are second stage input and output filter inductances used for reducing conducted AC current levels.

In this paper, two new approaches [8][9] for using IM techniques in conjunction with planar core and winding construction methods are described. These approaches require the use of core structures with more than one winding window area, and have the distinct advantages of minimal interactions between the various magnetic elements included in the IM assemblies. The full benefits of reduced core system volume and weight by the IM process are also achieved by these unusual approaches. The resulting core structures can completely enclose all windings (except for access slots), providing excellent magnetic shielding capability. In one of these approaches, "off-the-shelf "planar core sections can be used to construct the IM system.

II. Overview Of Conventional Im Methods

IM designs today typically use soft-ferrite E-I or E-E core structures. Fig. 1 is an collection of some of these "traditional" IM designs [1][4][6] for a "single-ended" converter circuit, which differ only in winding locations on the three "legs" of the core structure. For the core leg where inductor windings are situated, an air gap is added to obtain the desired inductance values. Here, the converter topology shown in Fig. 1(a) is a buck-derived "forward" configuration, found in many DC power conversion systems today, where output power needs typically range from 50 to 250 watts.

Effective core leg areas must be chosen in accord with the maximum flux levels that will occur as a result of converter operation so as to prevent saturation of any leg under maximum loading conditions of the system. As can be seen in the alternative designs in Fig. 1, each leg will see different flux levels, depending on winding locations and phase relationships, along with core leg reluctance values. For example, in the "split-winding" version shown in Fig. 1(c), the outer leg to the left of the center leg will see the *sum* of the transformer AC flux and one-half of the DC and AC flux produced by the inductor winding. In the right outer leg, the flux here will be the *difference* between the transformer AC flux and the remaining half of the AC and DC components of the inductive flux generated by the winding(s) mounted on the center leg of the core structure. In this particular IM variation, the window area needs on each side of the center leg are equal. However, in the variation shown in Fig. 1(d), an optimum core design would require *unequal* window areas on each side of the center leg. This disparity is also a possibility for the IM designs in Figs. 1(b) and (e). In the variation of Fig. 1(e), the inductive leg is one of the outer legs of the core structure, and its area would need to be larger than the others, which is not a standard E-E or E-I core configuration. Finally, it is apparent that all of the alternative designs shown in Fig. 1 require winding bobbins that must be fitted on one or both of the outside core legs. Presently, such bobbins are non-standard items, requiring custom manufacturing and added assembly cost.

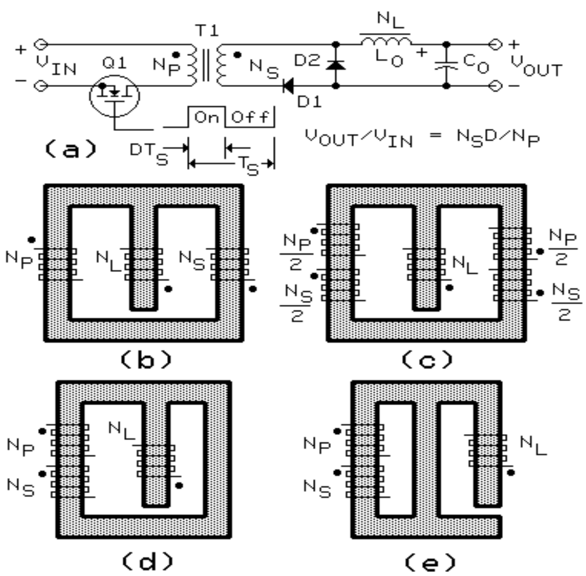


Fig. 1. A discrete-magnetic forward converter circuit (a) and viable integrated magnetic core-and-winding arrangements (b, c, d, e). Winding "dots" shown are relative to winding N_P. Reset means for transformer action not shown (see text below).

For "push-pull" versions of converter circuits where two-quadrant B-H loop operations occur from transformer actions, the centermost leg is used for the inductive part of the converter, with dual primary and secondary windings placed on the outer core legs. In these situations, the window area requirement is balanced, like the core-and-winding arrangement shown in Fig. 1(c).

A variety of methods for core reset [1] due to the "single-ended" transformer action of the converter in Fig. 1(a) is available. Some of these methods utilize resonant reset techniques involving the parasitic capacitances of T1, Q1, D1 and D2 and the self-inductances of the transformer windings.

III. PLANAR IM CONCEPTS

The use of printed wiring methods for the windings of an IM can lower the height profile of the overall package of the magnetic component, and since the windings are mounted on a laminate base, the cost of special bobbins mentioned earlier is eliminated. One example of a **P**lanar **I**ntegrated **M**agnetic (**PIM**) design for a "split-winding" version of the forward converter topology is shown below in Fig. 2.

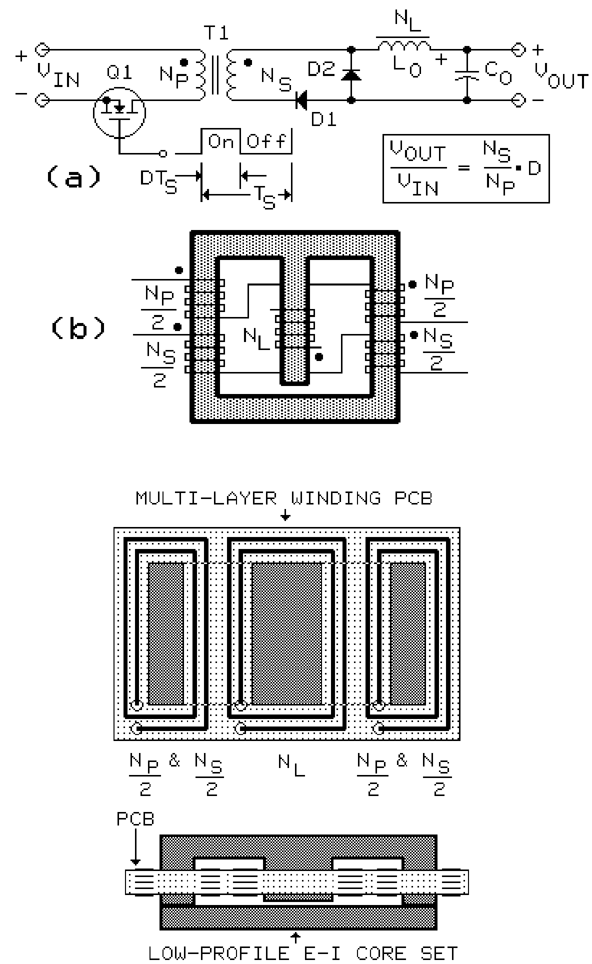


Fig. 2. A PIM construction for a single-ended forward converter (a) using a multi-layer printed-circuit board (PCB) for the windings and a low-profile E-I ferrite core structure (b). Reset means for transformer action not shown.

In the PIM design of Fig. 2, the primary and secondary windings are interleaved using selected layers of the PCB on the outside portions, while the inductor winding is split into parallel sections of the inside layers. Feed-thru vias in the PCB are used to interconnect the various parts of all three windings. Terminations of the winding ends can be accomplished in a number of ways, such as the use of solid pins running vertically from the PCB end patterns down to the PCB of the converter assembly. The use of "gull-wing" leads is another alternative, and this termination method is particularly useful when placing the PIM on a "motherboard" assembly with surface-mounted components.

"Conventional" IM constructions, whether they use PCB-style or wire windings, do have some undesirable limitations. Because windings are required on the outer legs of the core system, it is not possible to completely surround all windings with core material to restrict magnetic leakage levels. This situation is easily seen from the PIM construction example shown in Fig. 2. Also, because conventional constructions using E-I or E-E cores restrict window locations for windings to two locales and material flux paths to a maximum of three, other power magnetic components in a conversion system (like input and added second-stage output filter inductances) cannot be easily accommodated in an IM arrangement without significant topology changes. This, in turn, often leads to undesirable compromises in power processing performance.

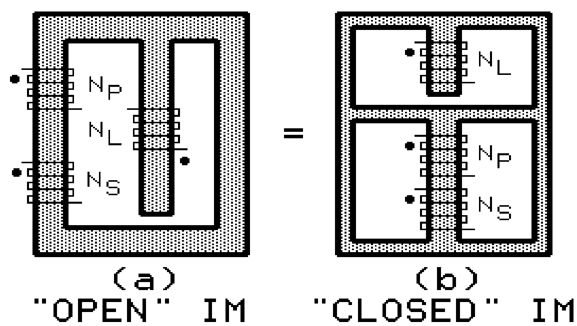


Fig. 3. Conversion of a traditional "open" E-E or E-I IM design (a) into a "closed" format (b) in a "pot" or "box" configuration.

Rather than placing the various windings of a planar IM (PIM) in a conventional "open, side-by-side" manner, they can also be arranged in a "closed, top-to-bottom" core configuration [7][8], as shown in the cross-sectional diagram in Fig. 3(b). In this example, the upper chamber of the core serves as the location for the output inductive windings of the converter, while the lower chamber is reserved for the windings of the transformer. The core piece separating the two chambers provides a material path for *both* inductive and transformer flux elements. With the windings phased as shown in Fig. 3(b), the effective flux level in this common path will be the *difference* between these flux values. Therefore, the core material needed for this common path can be reduced accordingly. Although the center post areas are shown in Fig. 3(b) to be identical, this condition is *not* an absolute design requirement. In fact, optimum size and unit height studies for the PIM form shown in Fig. 3(b) for a particular converter application may indicate otherwise.

A practical construction of the PIM concept of Fig. 3(b) is shown above in Fig. 4. Here, a "pot" format is used, consisting of three separate core pieces, stacked to form the two window areas, or winding "chambers", needed for the transformer and inductor parts of the IM. Within the lower chamber are then placed the PCB assembly for the primary and secondary windings, with the upper chamber reserved for the PCB assembly for the inductor winding. Note that it is possible to use double-sided PCBs in place of a single multi-layer PCB in each locale, and interconnect them by external wiring methods using termination "tabs" on the PCBs. These tab areas are accessed by means of "slots" cut into the core sections, as can be seen in the example assembly in Fig. 4.

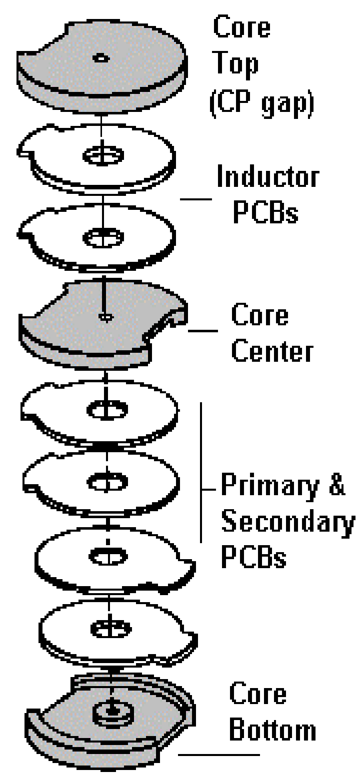
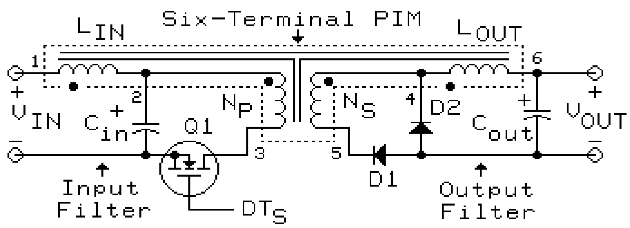


Fig. 4. A "closed, top-to-bottom" PIM assembly, using three separate pieces of magnetic material. Only the center post (CP) of the core top is gapped to provide the desired filter inductance value.

In this construction example, a small hole through the center posts of the cores has been provided to permit a single non-conductive screw-and-nut combination to be used to hold the assembly together.

Adding one or more inductive windings to a "stacked" PIM construction to accommodate additional filter inductances of a converter system is simply a matter of adding a *third* chamber area [7][8] to the core arrangement. This chamber can be located *below* the chamber in Fig. 3(b) where the transformer windings are housed. Fig. 5 is an illustration of this construction, wherein the lower chamber contains the winding(s) for the inductance of an input filter network for the forward converter topology shown in Fig. 1(a). Now the core piece *below* the transformer chamber serves as a differential flux path for the transformer AC flux and the DC+AC flux generated by the lower winding associated with the input filter inductance.



$$V_{OUT} = (N_S/N_P)DV_{IN}$$

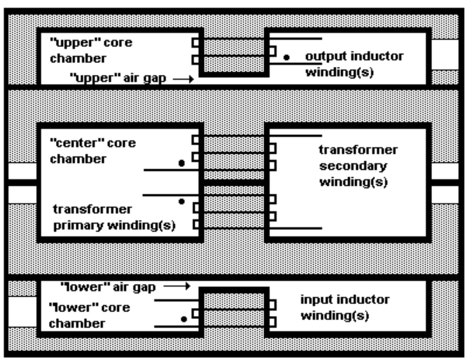


Fig. 5. Adding a third chamber to the PIM of Fig. 3 to house another set of inductive windings, such as one associated with an input filter network.

Because the reluctance of the upper and lower air gaps is *much larger* than those posed by the inner and outer material paths of the core structure, flux produced by the MMF of the transformer section of the PIM is restricted primarily to the inside sections of the core system. Therefore, PIM inductive and transformer-related operations will be largely *independent*, with insignificant magnetic interaction. This situation also implies that there are *no* significant restrictions on turn ratios between transformer and inductor windings, whereas in some IM converter designs [2], such restrictions are required to insure proportionality of winding driving potentials in order to permit their magnetic components to utilize a common core structure.

In the cross-sectional view of the PIM construction in Fig. 5, the unshaded areas on the outside "walls" of the core structure represent open parts of the core for accessing the ends of the PCB windings located in each chamber. Fig. 6 shows the overall construction approaches for viable PIM assemblies of the "stacked" variety [7][8], with typical access locations for PCB winding terminations illustrated.

Another PIM construction alternative is a "side-by-side" arrangement of transformer and inductive windings [9] as depicted in Fig. 7. In contrast to the design of Fig. 3, the inductive portion of the PIM lies in the center of the structure with the transformer windings placed in a second chamber that surrounds the center portion. The core "wall" that separates the two "chambers" of the core system then serves as a common flux path for inductive and transformer operations. Fig. 8 is a sketch of a practical implementation of

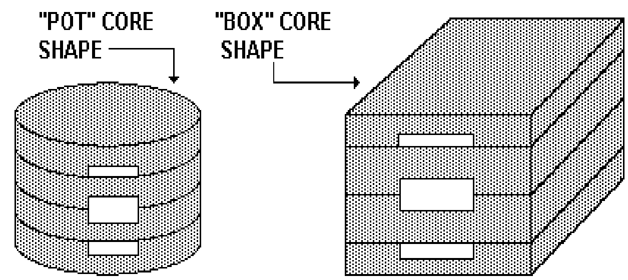


Fig. 6. Typical form factors for "stacked" PIM assemblies, illustrating typical locations in the core "pieces" for accessing PCB winding terminals.

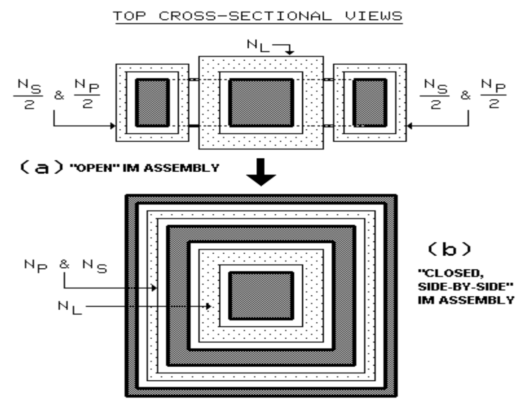


Fig. 7. Converting a traditional "open" E-E or E-I IM design (a) into a "closed, side-by-side" format (b) in a "pot" or "box" configuration.

the PIM concept [9] of Fig. 7, and a cross-sectional view of the design is shown in Fig. 9.

As indicated in Fig. 9, interactions between the magnetic operations of the system can be minimized further by the presence of a small air chamber placed in this common flux path. It is also feasible to place a "shield" band of conductive material in this chamber. This shield technique is similar to a "belly-band" copper screen often added around the outside of a conventional inductor or transformer to reduce radiated magnetic emissions.

The PIM method of Fig. 7 has the advantage of keeping the overall height of the core structure low. However, it is obvious that the surface area of the PIM will be increased over the "stacked" arrangement of Fig. 3, requiring more area for mounting. Also, to access the inductive winding, holes must be placed in the bottom part of the inner core chamber. It is also conceptually possible to add a third outer chamber and associated core walls to the outside part of this core system for another set of inductive windings. However, since the winding lengths will be much longer than those of the innermost chambers, the copper losses will be higher than those in the three-chamber "stacked" design approach illustrated in Fig. 5.

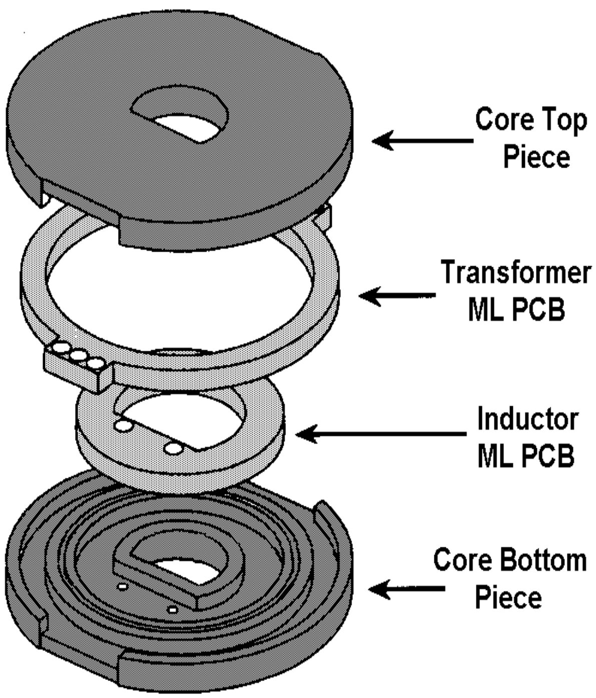


Fig. 8. A practical "closed, side-by-side" PIM construction method [9].

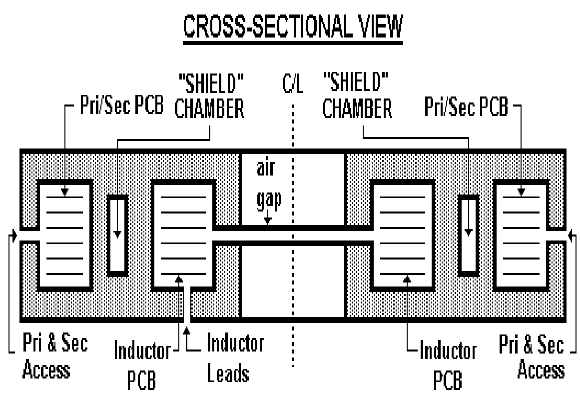


Fig. 9. Cross-sectional view of the PIM system in Fig. 8.

IV. Reluctance Disks

Many power converter systems require multiple inputs or outputs that, in turn, require additional inductances for filtering purposes. These inductances can be placed in a PIM in "coupled-inductor arrangements " [1][3] in the appropriate chambers. For example, in the PIM design shown in Fig. 5, leakage inductance values between windings mounted in the upper or the lower chambers can be well controlled by the addition of thin disks of core material [11], often termed "magnetic shunts", or "reluctance disks" when windings are implemented in PCB formats. Such disks can be used to provide magnetic control and reduction of AC current levels in selected inductor windings [1][2][4]. Examples of reluctance disk forms are shown in Fig. 10. Suitable disk materials include inexpensive varieties of cold-rolled steel and low-permeability soft ferrite. Disks of non-magnetic materials can also be used in those instances where desired leakage inductance values needed are small.

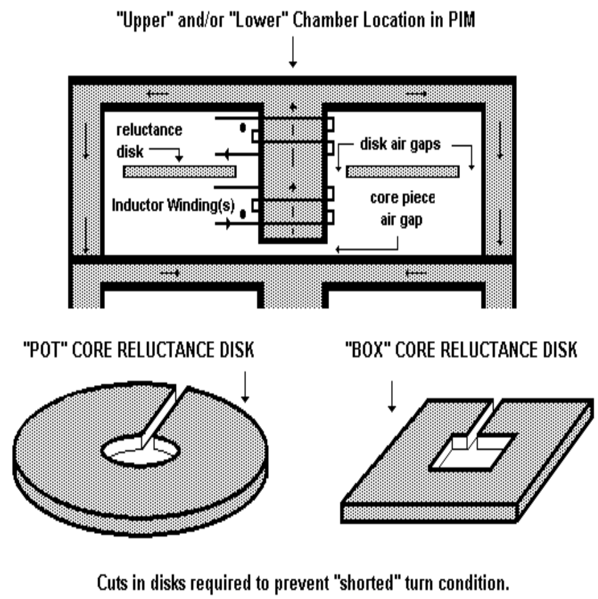


Fig. 10. Sample circular & rectangular "reluctance disk" form factors

V. PIM Modeling Methods

To facilitate a better understanding of the magnetic operations of the PIM designs shown earlier in Figs. 5 and 7, equivalent circuit models can be developed, using the reluctance-to-inductance modeling methods described in Chapter 12 of [1]. These models can then be used to study the dynamics and magnetic interactions between the transformer and inductive sections of a PIM.

For example, using the flux paths and directions defined earlier in Fig. 6 for the three-chamber PIM structure of Fig. 5, a first-order reluctance model of the magnetic system is formed, along with MMF sources. This model is illustrated in Fig. 11. Note that the symmetry of the basic model permits it to be simplified as indicated in this sketch.

With a base reluctance/MMF model established, it can be converted into one involving inductances and excitation sources. This new model is shown in simplified form in Fig. 12. In this model, all inductance values are referred to winding N_P of the PIM system in Fig. 5.

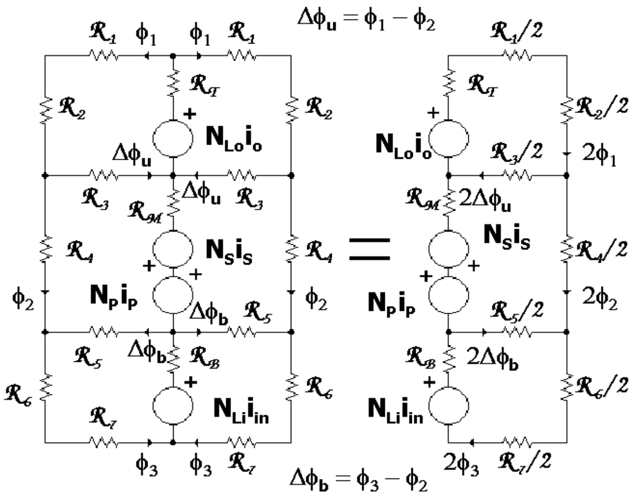


Fig. 11. Reluctance/MMF models for the PIM design shown in Fig. 5.

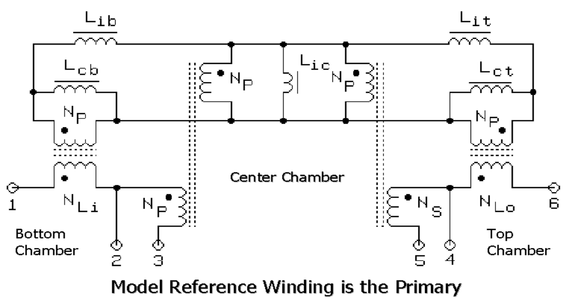


Fig. 12. Simplified circuit model for the 3-chamber PIM design in Fig. 5. This model was derived from the reluctance/MMF arrangement in Fig. 11.

Values for the inductances indicated in Fig. 12 can be estimated, using the first-order reluctance and inductance relationships defined in Table I.

Examination of the resultant circuit model in Fig. 12 shows that that the two inductances (L_{it} and L_{ib}) formed by the two core pieces separating the two inductive chambers from the transformer chamber will be *much larger* in value than those associated with the upper and lower core pieces where air gaps are present (L_{ct} and L_{cb}). For this reason, very little of the flux developed by the transformer actions within the center chamber will appear in the core areas associated with the inductor chambers. This confirms that transformer and inductive operations in this PIM will indeed be largely *independent*, with very little interaction between them.

Finally, as an example of the use of this circuit model in analyzing its use in conjunction with a converter network,

TABLE I.
Approximate relationships between the reluctances of Fig. 11 and the inductances shown in Fig. 12.

$$\Re_T = \frac{l_{airgap(top)}}{m_0 A_{cp(top)}}, \Re_B = \frac{l_{airgap(bottom)}}{m_0 A_{cp(bottom)}}, \Re_M = \frac{l_{mat(center)}}{m_0 m_{mat} A_{cp(center)}}$$

$$\Re_1 + \Re_2 + \Re_3 = \frac{2l_{mat(top)}}{m_0 m_{mat} A_{mat(top)}}, \Re_4 = \frac{2l_{mat(middle,sides)}}{m_0 m_{mat} A_{mat(middle,sides)}}$$

$$\Re_5 + \Re_6 + \Re_7 = \frac{2l_{mat(bottom)}}{m_0 m_{mat} A_{mat(bottom)}}$$

$$L_{ct} = \frac{2N_P^{\,2}}{2\Re_T + \Re_1 + \Re_2}, L_{cb} = \frac{2N_P^{\,2}}{2\Re_B + \Re_6 + \Re_7}$$

$$L_{it} = \frac{2N_P^{\,2}}{\Re_3}, L_{ic} = \frac{2N_P^{\,2}}{2R_M + \Re_4}, L_{ib} = \frac{2N_P^{\,2}}{\Re_5}$$

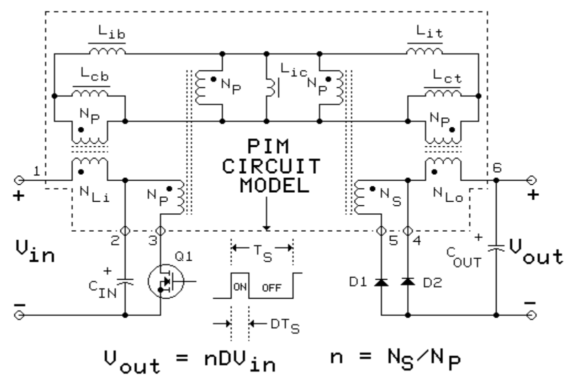


Fig. 13. The forward converter circuit of Fig. 5 with the PIM equivalent model from Fig. 12.

Fig. 13 is a circuit diagram of the forward converter system of Fig. 5, redrawn to include the PIM model of Fig. 12.

VI. PIM PROTOTYPE TESTS

To verify the “stacked” PIM approach illustrated in Fig. 5, a 200 kHz, 20-40VDC in, 5V-10A out, PIM forward converter system was designed, built and tested for performance, as a part of a recent NASA SBIR Phase II proposal effort. In this case, a three-chambered PIM was constructed by using four separate cylindrical pieces of soft ferrite of the MN8CX variety made by Ceramic Magnetics. Overall height of the PIM structure was 16.8 mm (0.661 in) and its diameter was 35.2 mm (1.386 in). Center post area in all chambers was set by design to 53.5 mm^2 (0.076 in^2), with the air gap lengths in the upper and lower chamber center posts cut to 254 μm (0.01 in). The primary and input inductor windings used 3 paralleled 8-turn double-sided PCBs, while the secondary and output inductor windings used 3 paralleled double-sided 5-turn PCBs. Four-ounce copper patterns were used for all PIM PCB windings.

Measured inductance of the primary winding, the input filter inductor and the output filter inductor was 250 μH, 19.2 μH and 7.5 μH, respectively, very close to design projections. The measured efficiency of the power stage under maximum loading conditions was 87%, with total PIM core and winding power losses measured at nominally 1.2 watts. The measured temperature rise above ambient of the PIM was 30°C (*no* heatsink or forced-air cooling). As predicted by design, *no* discernible magnetic interactions were observed with regard to the transformer and inductive functions within the PIM during the testing of the converter. Core volume and weight savings over a conventional converter design having two individual planar inductors and one planar transformer were calculated to be 29.5%.

Similar verification testing of the "side-by-side" PIM system shown earlier in Figs. 8 and 9 have been reported by research engineers in Japan [9][10] with equal success. In one experiment, an off-line 100VAC-to-24VDC, 125W, 350 kHz forward converter system was built and tested. The PIM was constructed using a high-frequency low-loss ferrite of the 2500B2 variety made by TOKIN (Sendai, Japan). The outside diameter of the PIM was 53 mm (2.09 in), and its height was 8 mm (0.315 in). Total center post gap length was set at nominally 300 μm (0.012 in) to yield an output filter inductance of 16 μH. A 5-turn primary winding and a 3-turn secondary winding were used in the outer chamber, with an inner 6-turn inductor winding. Two-ounce copper patterns, nominally 70 μm (0.0028 in) thick, were used for all multi-layer windings to minimize high-frequency copper losses.

The efficiency of the PIM of this converter system was measured to be on the order of 98% at an output power level of 125 watts. Noise reduction tests were also conducted, showing 10 to 20 dB reductions in 100-300 MHz radiated noise over that of a comparable converter design with separate "open-frame" inductor and transformer elements.

VII. Conclusions

The stacked "top-to-bottom" and "side-by-side" multi-chambered PIM constructions presented herein are new, volumetrically efficient IM techniques for blending the many inductors and transformer functions of any dynamic power processing system without compromising electrical performance needs. The constructions can also include simple planar "disks" of magnetic material to control leakage inductances in selected areas of the structures. The form factors for the "top-to-bottom" construction variations can be either "open" or "closed". In the former case, these PIMs can use standard circular core halves (e.g. pot, RM, PQ, DS shapes), or multiple E-I combinations of off-the-shelf low-profile rectangular cores. Research is continuing on these new PIM designs, including investigations associated with direct depositing of windings on selected parts of the core structures to further reduce cost and assembly time.

Acknowledgments

The author would like to acknowledge the funding support provided by the U.S. National Aeronautics & Space Administration (NASA) in the early phase of development [12] of the "stacked" PIM concepts described in this paper. A U.S. Patent [7] was issued to the author's company in 1998 relative to this PIM method and other related enhancements.

The author would also like to acknowledge the unique work performed by Dr. Toru Fujiwara and his associates in the independent development of the complementary "side-by-side" PIM structure [9][10] shown in this paper. Readers interested in obtaining more information about his work can contact him at the National Matsushita Electric Works Ltd. in Kadoma, Osaka, Japan (Email – *fujiwat@ertc.mew.co.jp*).

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