Evaluation of a Quasi Coaxial Printed Circuit Board Transformer

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***Abstract*— Minimization of leakage inductance of a transformer is very often one of the main focus points during the design because of the adverse effects it may have on some power electronics circuit topologies. There are however applications in which the leakage inductance may be used as a circuit element, in which case it should be predictable and easily realizable. Coaxial transformers are known for the ease with which the leakage inductance may be predicted but obtaining these values repetitively is still a problem because of the manner of manufacture. This work investigates the possibility of utilizing printed circuit board (PCB) technology to manufacture coaxial transformers and to increase the accuracy with which the desired leakage inductance may be obtained. Finite element methods (FEM) as well as experimental results are used to support the proposed ideas. A planar transformer is also analyzed in the same way to accentuate the design advantages offered by the proposed quasi-coaxial transformer.**

I. INTRODUCTION

The design of high-power, high-frequency transformers is particularly important from a leakage inductance point of view. Very low values of leakage inductance should be obtained for applications where voltage overshoot on the power switches is a problem [1], [2]. The leakage inductance of a transformer will also often limit the maximum power that can be transferred through the transformer, especially as the frequency increases. In such cases the maximum power transfer may not be limited by thermal considerations. In other applications leakage inductance is a useful circuit component, in which case it should be easy to design and realize in the physical transformer. These applications include bidirectional power converters and bidirectional impedance-adapting transformers used for low-voltage power-line communications (PLC) [2], [3], [4]. Another important aspect driven very hard for the last number of years is the functional integration of modern power electronic components and development of technology which allows automated manufacturing of these integrated components [3], [5]. Coaxial transformers are attractive solutions in many applications due to the low values of leakage inductance that may be obtained [6], [7]. The manufacturing process usually involves a copper pipe used as the primary or secondary conductor of the transformer.
The inner turns are wound through the inside of the pipe to form the second winding. The leakage inductance can be determined very easy, as will be shown later, as long as the inner turns are positioned correctly throughout the length of the pipe structure. This manufacturing technique poses a problem when a predictable leakage inductance is required because the inner conductors may not be distributed ideally as shown in figure 1. Automation of the manufacturing process is also not easy, since it will inevitably involve a split pipe, which needs to be restored to a cylindrical shape after embedding the multiple turn winding. Conventional techniques normally only allow for a single outer winding to be used because of the difficulty involved in insulating multiple outer conductors from one another.

II. PROPOSED CONSTRUCTION

A. Quasi coaxial transformer

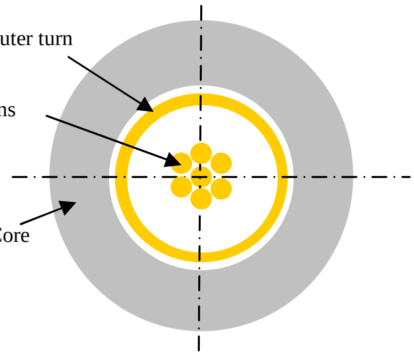


Fig. 1. Conventional coaxial transformer construction

This paper shows how coaxial transformers may be manufactured using a pcb-manufacturing technique. Figure 2 shows a cross section of the proposed pcb-construction of a coaxial transformer. It is shown in a later section that a

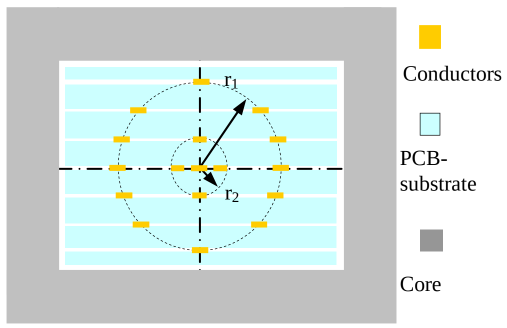


Fig. 2. Coaxial arrangement of conductors on pcb-substrate

finite number of separate conductors may be used to construct the outer conductor without severely affecting the resulting leakage inductance.

Equation (1), used for calculating the leakage inductance per unit length of the structure in a coaxial transformer, is given below [6], [7].

$$L_{Leakage} = \frac{\mu_0 N_{prim}^2}{2\pi} \ln\left(\frac{r_1}{r_2}\right) \quad (H/m) \quad (r_1 > r_2) \quad (1)$$

where μ_0 is the permeability of free space, N_{prim} the number of primary turns, and the dimensions of the structure as shown in figure 2. The primary comprises five turns in the centre of the cross section and the discrete outer conductors are interconnected at the end points to form a single secondary turn. The windings are embedded in a high permeability core. The capacitance between the inner and outer conductors may be calculated using equation (2), where ε is the permittivity of the material in this region [6], [7].

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{r_1}{r_2}\right)} \quad (F/m) \quad (r_1 > r_2) \quad (2)$$

B. Planar transformer

The proposed construction of the planar transformer is illustrated in figure 3.

For the planar winding comprising a number of winding sections, the leakage inductance per unit length of the structure may be calculated using equation (3) where the conductors are made of solid foils or if discrete conductors are spaced close enough to imitate a current sheet [2].

$$L_{Leakage} \approx \frac{\mu_0 N_{prim}^2}{p^2 h_w}\left(\frac{b_{Cu}}{3} + b_i\right) \quad (H/m) \quad (3)$$

where μ_0 is the permeability of free space, N_{prim} is the number of primary turns, h_w is a dimension of the core window, b_{Cu} is the total thickness of the copper layer and b_i is the distance of the insulation between the conductive layers. The symbol p designates the number of interfaces between winding sections and is equal to one in this particular example. For a given value of leakage inductance the dimension of b_i should be calculated.

No simple analytical method for calculating the capacitance of this structure is known to the authors and only FEM-simulations are used for verification of the measured values.

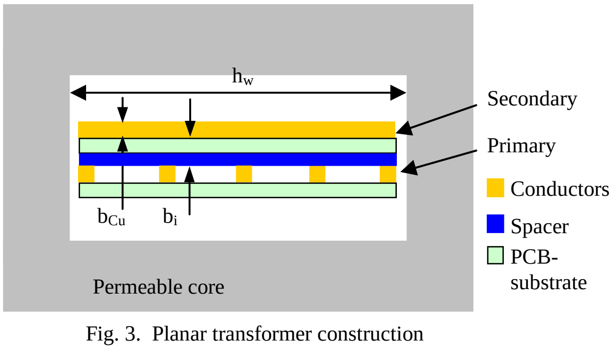


Fig. 3. Planar transformer construction

III. FEM SIMULATIONS

A. Coaxial transformer

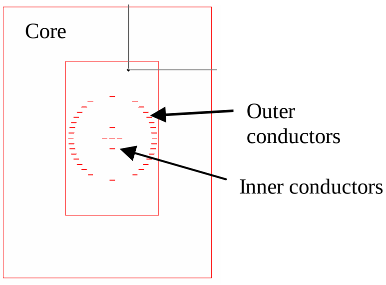
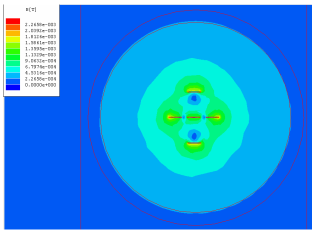


Fig. 4. 2-D model of coaxial windings in core window

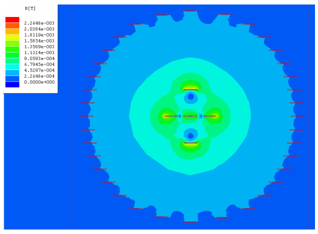
The intended use of the transformer is in a resonant converter with a resonant frequency of 50kHz and the desired leakage inductance value for the proposed coaxial structure and equation (1) are used to determine the dimensions of the proposed coaxial transformer. The width of the conductors is chosen to be roughly twice the skin depth at this frequency. Ideally all the conductors in the coaxial transformer should be cylindrical with diameter roughly twice the skin-depth at the operating frequency. Due to the limitation in the thickness of the copper on standard printed circuit board the conductors are approximately 0.4mm wide and 35μm thick. The diameter of the coaxial transformer outer conductor is roughly 8.5mm to fit into the window of a standard EI42 ferrite core. Figure 4 shows a typical 2-D model of the windings surrounded by a magnetic core that was used to perform the FEM simulations. The leakage inductance and magnetizing inductance is obtained from an eddy-current analysis. The capacitance is determined by performing an electrostatic analysis.

Figure 5 shows a range of flux density plots starting with a coaxial transformer with a solid outer conductor. The rest of the figures show a number of discrete conductors representing the outer conductor. These conductors are connected in parallel at the ends of the structure and the FEM simulations show the effect on the flux density when the number of conductors is reduced or if the conductors are not positioned more or less at equidistance from one another on the circumference of the outer circle.
As a reference value the leakage inductance of a structure with a solid tubular outer conductor analytically determined was used. The difference between the leakage inductance of each structure and the reference value is graphically shown in figure 6. For this particular geometry an error higher than 10% will occur if only eight or less discrete conductors are used to represent the outer conductor. It should be noted at this point that a reduction in the number of discrete conductors may be favourable in terms of manufacturing but the current carrying capability of the winding is reduced in the process. The same figure also presents the difference between the capacitance obtained via simulation and the analytically calculated value of the capacitance between the primary and secondary conductors for a solid tubular outer conductor and a 1 :1 turns ratio. This difference is below

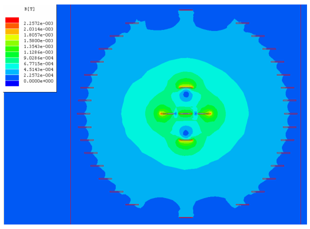
5% for all the cases except where only four conductors form the outer winding.



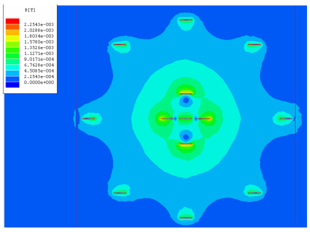
(a) Solid outer conductor



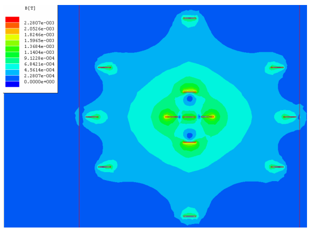
(b) 36 Discrete conductors



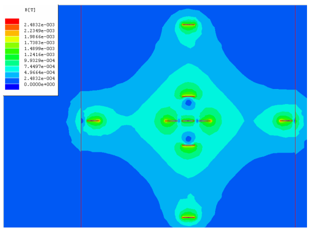
(c) 32 Discrete conductors



(d) 8 Conductors equidistanced



(e) 8 Conductors varying distances



(f) 4 Discrete conductors

Fig. 5. Flux density plots for quasi-coaxial structure

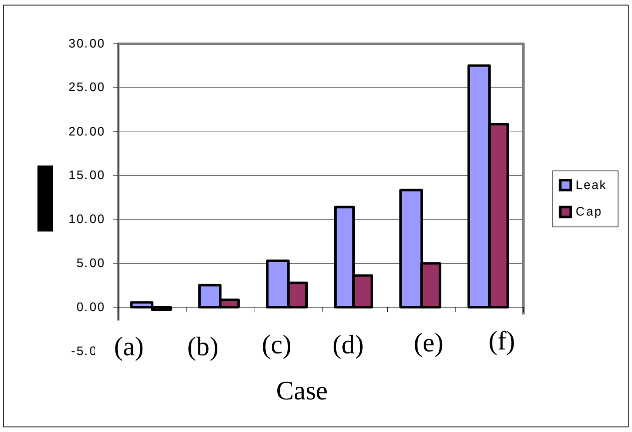


Fig. 6. %Error made in different cases compared to analytical prediction

B. Planar transformer

The graphical representation of the planar structure used for FEM-simulations is shown in figure 7 and the corresponding flux density plot for this transformer is shown in figure 8. The planar transformer comprises a planar spiral winding with five turns and the single turn secondary is represented by a solid pcb-foil. The primary turns of both transformers are of the same dimensions. The structure represented by figure 5c is used for simulation and experimental purposes. The cross sectional area of the planar secondary winding is the same as the combined area of the 32 discrete conductors used as the outer winding of the coaxial construction. The dimensions of an EI64-planar core are used for simulation purposes and h_w = 20mm is the only core dimension required in equation (3).

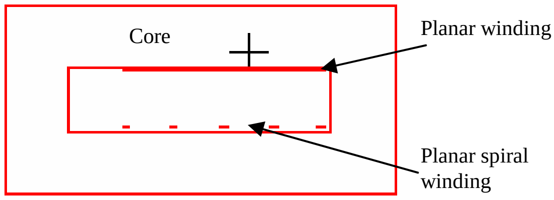


Fig. 7. 2-D FEM-model for planar windings in core window

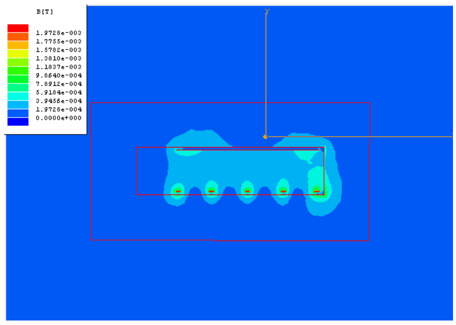


Fig. 8. Flux density plot for planar construction

The leakage inductance per-meter length for the two structures is chosen to be approximately 9µH/m, N_{prim} = 5, b_{cu} = 35µm and for this arrangement there is only one interface between the winding sections, meaning that p=1. The initial value of the distance between the primary and secondary planar windings, b_i = 6.07mm, could only be estimated using equation (3) due to the fact that the conductors of the planar spiral winding are situated too far apart to resemble a current sheet. The leakage inductance associated with this distance in the FEM-simulation is 11.77µH/m, almost 30% higher than the chosen value and intuitive adjustments had to be made until a distance of about 4.5mm yielded the required result.

IV. EXPERIMENTAL RESULTS

The quasi-coaxial transformer is constructed as proposed with the outer conductor comprising 32 discrete conductors as shown in figure 5(c). The pcb-substrate is 0.5mm thick. Figure 9 shows a photograph of a few of the individual pcb-layers. Figure 10 and 11 respectively show the full winding and the winding embedded in the ferrite cores. The leakage inductance, capacitance and magnetizing inductance of the structure are now determined using an analytical approach where applicable, FEM-simulations and experimental measurements.

The planar transformer is constructed using a planar spiral winding with five turns as the primary of the transformer and the single turn secondary is made from a solid pcb-foil.

The primary turns of both transformers are of the same dimensions. The cross sectional area of the planar secondary winding is the same as the combined area of the 32 discrete conductors used as the outer winding of the coaxial construction. The planar windings and full construction are shown in figures 12 and 13 respectively.

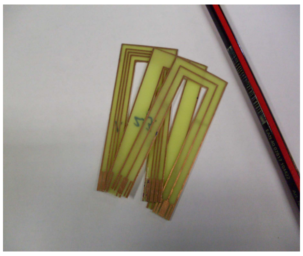


Fig. 9. Individual pcb-layers

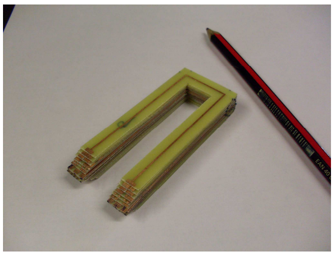


Fig. 10. Winding

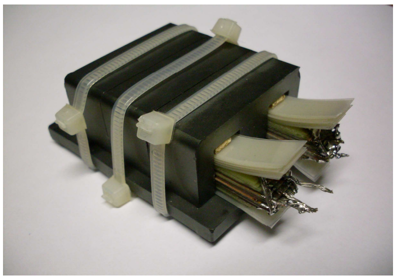


Fig. 11. Winding in permeable core

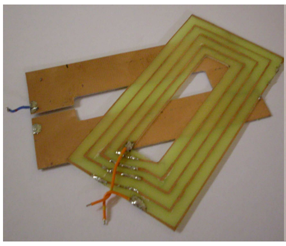


Fig. 12. Planar windings

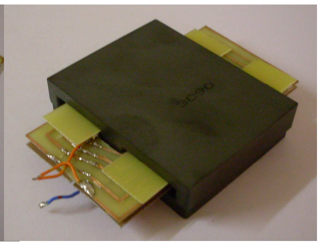


Fig. 13 Planar winding in permeable core

A. Leakage inductance

The leakage inductance of each structure is measured using an impedance analyzer (HP4284A). The discrete conductors may easily be rearranged to reconfigure the transformer. In the coaxial transformer the outer conductors are all connected in parallel to form one single turn secondary winding. If all the primary turns of each of the respective transformers are connected in parallel, a unity turns ratio is obtained. All the parameters of the two transformer structures are measured using a unity turns ratio. All interconnections should be made as short as possible for additional leakage flux in these areas may cause the considerable error in the measurements. The secondary winding is soldered short circuit to force the secondary voltage, and subsequently the voltage on the primary magnetizing inductance, to zero. Measuring the impedance at the primary input terminals results in a direct measurement of the leakage inductance. The analytical values, FEM-results and measured readings for the chosen geometries are listed in table 1 below. The average length of the coaxial winding is 0.143m and the average length of the planar winding is 0.222m. The FEM prediction and measured values for the coaxial structure are respectively 5.4% and 8.4% higher than the analytically calculated value. The measured value is about 2.9% higher than the value predicted using FEM.

For the planar structure, the analytical equation for the leakage inductance with b_i = 4.5mm underestimates the value determined with FEM by 23% due to the reasons mentioned. The measured value in this case is only about 2.5% lower than the FEM value.

TABLE I. ANALYTICAL, FEM AND MEASURED VALUES OF LEAKAGE INDUCTANCE.

Type	Analytical	FEM	Measured
Coaxial (1:1)	335nH/m	352.4nH/m	362.9nH/m
Planar (1:1)	283.5nH/m	369.8nH/m	360.4nH.m

For a different configuration of the primary conductors the new turns ratio is simply used to scale the measured leakage inductance. If the inner turns are separated and connected in series to form a 5 turn winding and the outer conductors are still connected in parallel the new turns ratio is 5:1. The new configuration is accommodated by the analytical solution as well as the FEM-simulations.

B. Capacitance

Although the main focus of the experiment is to calculate the leakage inductance, the capacitance between the inner and outer winding is also measured. This capacitance may be calculated for the coaxial structure using equation (2) [6], [7]. The inner conductors are paralleled for a turn ratio of 1:1 and the capacitance measured between the inner and outer conductors using the impedance analyzer. The respective values obtained from the analytical equation, FEM-simulations and measured values are listed in table 2. The relative permittivity of the pcb-substrate initially assumed to be ε_r = 4.3 [8], is adjusted to 4.7 after constructing a simple parallel plate capacitor using the same material.

TABLE II. ANALYTICAL, FEM AND MEASURED VALUES OF CAPACITANCE

Type	Analytical	FEM	Measured
Coaxial (1:1)	155.9pF/m	162.9pF/m	241.3pF/m
Planar (1:1)	None	209.9pF/m	249.1pF/m

The capacitance predicted with FEM is approximately 4.5% higher than the analytical value for the coaxial structure. The measured value is however substantially higher (48%) than the analytical value.

No analytical equation is available for the calculation of capacitance where the conductors are distributed such as is the case with the planar spiral winding. The measured value of the capacitance in this case is approximately 19% higher than the value predicted using FEM-simulations. The impedance analyzer seems to be well calibrated, for capacitance values higher than 190pF, when checked against a Fluke 5520A calibrator. The expected values are much lower than the 190pF the calibrator can generate and the confidence in the measured values can therefore not be validated. Other measurement techniques may still be explored to remedy this situation.

FEM-simulations and measurement of capacitance for the 5:1 turns ratio transformers should be investigated further. The problem experienced in both cases is that the potential difference between each primary conductor and the secondary winding differs. In the case of the planar structure, the FEM and actual measured values correspond well, but no correspondence could be found for the coaxial transformer.

C. Magnetizing inductance

The magnetizing inductance of the structures is a function of the properties, shape and volume of the magnetic material. If toroidal cores are used, an analytical solution is available for calculating the magnetizing inductance. From a construction point of view it is easier to use EI-cores, hence the data sheet information for these cores is used in determining theoretical values of magnetization inductance for the structures. The results are presented in table 3 for a unity turns ratio.

TABLE III. ANALYTICAL, FEM AND MEASURED VALUES OF MAGNETIZING INDUCTANCE

Type	Datasheet A_L	FEM	Measured
Coaxial (1:1)	83.2µH/m	73.4 µH/m	65.3 µH/m
Planar (1:1)	66 µH/m	75 µH/m	54.1 µH/m

In the case of the coaxial transformer the FEM-prediction is approximately 11.3% lower than the magnetizing inductance calculated using the inductance factor (A_L) of the core listed in the data sheet. The measured value is approximately 21.3% lower than the calculated value but is only about 11% lower than the FEM-result.

The FEM-simulation for the planar transformer produces a value 14% higher than the inductance factor method and the measured value in this case is 18% lower than the value determined from data sheet information and 28% lower than the FEM-result.

These differences are attributed to the tolerances of data sheet information which is ±25% for the A_L values listed as well as some measurement error.

A graphical representation of all the results is shown in figure 14.

D. Conductor losses

The dimensions of the primary winding conductors for both transformers are identical. The total cross sectional areas of the secondary winding conductors are also the same for both structures. Furthermore the conductor thickness in all cases is much less than the skin depth at the chosen operating frequency, resulting in a near uniform current density in all the conductors. The total loss per meter length

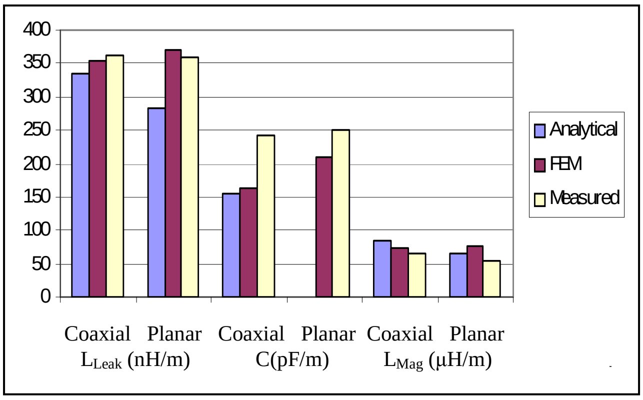


Fig. 14. Graphical representation of results

of the two structures is therefore the same, but the actual power loss for the planar structure is higher, simply because windings in this structure are longer than for the coaxial transformer, a result of the core selection required to fit the planar winding.

Preliminary simulations have shown that if the conductor dimensions are optimized for both cases, the coaxial transformer performance will be better than the planar transformer on a per meter length basis because the current distribution in the planar secondary winding is much less uniform due to conductor-to-conductor proximity effects.

V. CONCLUSION

This work paves the way for further investigation into the manufacturing of coaxial transformers using discrete conductors for the outer winding instead of a solid tubular conductor. Experimental values obtained for the leakage inductance of the proposed structure correspond very well to the predicted values whereas adjustments had to be made in FEM-simulations to accommodate the shortcomings of the analytical calculations performed for the planar structure. Measurement uncertainty exists in experimental values obtained for the inter-winding capacitance for both structures. The large tolerance of data sheet information on the inductance factor of the cores makes a more accurate estimate of the magnetizing inductance very difficult in both the case studies. The matter of core and conductor losses for increased conductor dimensions is not investigated here and will have to be addressed in further work. Much can also be done to increase the achievable conductor dimensions for higher current applications. Proper printed circuit interconnection arrangements should be included, which will not increase the leakage inductance in the structure. The use of isolated or interconnected multiple outer windings is also made possible in the process and should be investigated further.

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