The Design of a Multilayer Planar Transformer for a DC/DC Converter with a Resonant Inverter

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Abstract:
Multilayer planar transformers are widely implemented in power electronic applications (power supplies, inverters, drives, resonant converters). The design process of these elements is complicated due to the complexity of a magnetic circuit and high frequency interactions between windings (leakage inductances, stray capacitances, skin and proximity effects, etc.). Additionally, an analytical approach to the analysis (based on mathematical formulas) can be uncertain. The applied FEM method of the analysis can be a solution to the above mentioned problems and this method was implemented in this paper. The description of scientific problems includes a presentation of a complex geometry of a planar transformer prototype with a ferrite magnetic core and PCB windings. The FEM model of a transformer was developed as the COMSOL 2D axial symmetry case and presented with implemented mathematical formulas, sequences of analyses, meshing aspects and combined with an Electrical Circuit interface. Results of the FEM analyses were compared with laboratory measurements of a transformer prototype.

Keywords: a multilayer planar transformer, a high frequency operation, FEM modelling aspects, laboratory tests of a transformer prototype.

1. Introduction

Magnetic inductors and transformers are one of the fundamental components in switch-mode power supplies (SMPS). They are used as high frequency filters, EMC chokes, energy storages, galvanic insulations, etc. Designing of inductive elements proves to be a complex idea with different nuances, regarding mainly industrial applications. From a mass-production point of view, the most important aspect is the stability of fundamental and parasitic parameters (inductances, resistances, leakage inductances, stray capacitances). Conventional inductors, especially those manually assembled, have a wide tolerance of the mentioned parameters. In SMPS, radio-frequency devices or resonant converters, however, the tolerance of inductor parameters is much smaller, which influences new and sophisticated constructions of the developed inductors and transformers.

One example of a developed and available construction is presented and discussed in this paper. This is a planar transformer, dedicated for a DC/DC Converter with a Resonant Inverter. In this sort of a power electronic converter the leakage inductance must be strictly fitted to the designed output parameters. That is why the transformer must really be designed and manufactured with a high precision. The leakage inductance can be changed precisely by adjusting some physical parameters including dimensions of the conducting tracks, the thickness of the insulation layers, the air gap length and turns arrangements inside the core. In the described construction all windings of a transformer are made as tracks on a multilayer PCB (printed circuit board) and have a spiral shape of coils. Therefore, in each produced coil the windings are placed exactly in the same position in relation to each other and to the core segments.

On one hand the implementation of a planar coil allows to control parasitic parameters that are of crucial importance in industrial applications like resonant inverters, SMPS or radio-frequency devices. On the other hand, however, the analytical designing of planar coils causes a lot of problems, mainly while determining the inductance values. A specific geometry of a planar coil and a relative position of windings are very difficult to describe by analytical formulas. One of the most fundamental empirical description of calculating the inductance of planar spiral inductors was published by Wheeler [1]. The error between the measured and calculated inductances is around 25%. Higher accuracy (error around 3%) is achieved, however, by implementing expanded Wheeler's equations given by Mohan [2].

Although the above mentioned analytical formulas are very helpful in some rough estimations of a coil inductance, they are limited to the strictly defined applications (e.g. air-coils, one layer of planar windings, close distance between layers, etc.). Much more effective, in turn, proves to be the implementation of numerical methods (e.g. FEM methods) for calculation of a different geometry of planar coils and the determination of physical parameters with good accuracy. This approach is widely presented in literature, e.g. in papers by Zhao [3], Ouyang [4] and Ma [5].

The geometry of the analysed planar transformer and the configuration of the magnetic core is very complicated. This is the reason for a numerical method implementation (FEM - COMSOL software) while determining main parameters of the analysed transformer. A verification process of computational results took place based on laboratory measurements of a transformer prototype.

2. A multilayer planar transformer

The geometry of the analysed multilayer planar transformer with fundamental dimensions is presented in Figure 1. Additionally, the main manufactured elements (a coil made of PCB winding and ferrite magnetic core) are collected.

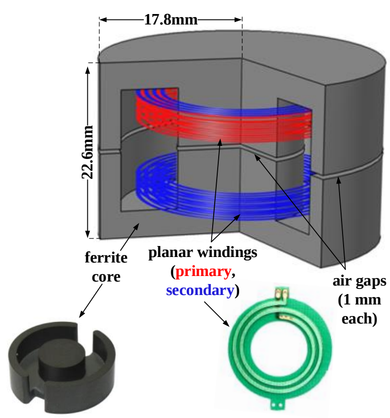


Figure 1. Construction of the analysed planar transformer.

The magnetic core of the transformer is made of a ferrite material while its windings are printed in cooper PCB boards with a spiral shape of a layout. Each PCB board consists of 2 or 4 turns and that is why boards are connected in series so as to achieve an adequate number of turns. The fundamental parameters of the analysed transformer are collected in Table 1.

Table 1: Fundamental parameters of the analysed transformer

Item	Value
pri./sec. voltage U_1/U_2	750 V/600 V
pri./sec. current I_1/I_2	1.33 A/1.67 A
output power S_{OUT}	1.00 kVA
operation frequency f_n	500 kHz
turns @ pri./sec. N_1/N_2	14/20
maximum flux density of a magnetic core B_{MAX}	0.5T
pri./sec. inductance L_1/L_2	48.3 µH /93.0 µH
coupling coefficient k	0.87

3. The application of COMSOL Multiphysics

3.1 Mathematical description

Numerical simulations of the multilayer planar transformer were prepared in a frequency domain using the AC/DC Module and the Magnetic Fields Interface. This interface allows to calculate the electromagnetic field distribution based on two equations:

$$\begin{cases}(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)\mathbf{A} + \nabla\times\mathbf{H} = \mathbf{J_e} \\ \mathbf{B} = \nabla\times\mathbf{A}\end{cases} \quad (1),$$

where: ω – the angular frequency of a magnetic field, σ – the electrical conductivity of modelled materials, ε_0, ε_r – vacuum and relative permittivity of modelled materials, **A** – a magnetic vector potential, ∇ – a nabla operator, **H** – magnetic field intensity, **B** – magnetic flux density, **Je** – externally generated current density. This system of equations is implemented to each finite element of the transformer model. Solving the given equations allows to obtain the magnetic flux distribution in a simulated model.

The outer boundaries of the model domain were described by a magnetic boundary condition:

$$\mathbf{n}\times\mathbf{A} = \mathbf{0} \quad (2),$$

where: **n** – a normal vector, **A** – a magnetic vector potential. This equation sets the tangential component of the magnetic potential **A** to zero.

Additionally, transformer windings were coupled with an electrical circuit and described by a system of two equations:

$$\begin{cases} I_{\mathrm{COIL}} = \int \mathbf{J} \cdot \mathbf{e}_{\mathrm{COIL}} \\ \mathbf{J_e} = \sigma \frac{V_{\mathrm{COIL}}}{2\pi r} \mathbf{e}_{\mathrm{COIL}} \end{cases} \quad (3),$$

where: I_{COIL} – a current amplitude of the transformer coil current, $\mathbf{J}$ – current density of windings, $\mathbf{e}_{\mathrm{COIL}}$ – a coil direction vector (a direction of current in a coil area), $\mathbf{J_e}$ – current density in windings, σ – an electrical conductivity of materials, $\mathbf{V}_{\mathrm{COIL}}$ – a voltage drop induced in a coil, $2\pi r$ – the length of the current path in a conducting material.

3.2. The analysis sequence

The analysis of the planar transformer was based on a bottom-up approach, presented in Figure 2.

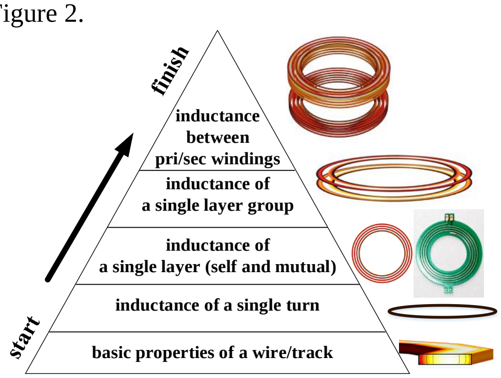


Figure 2. The bottom-up approach of the planar transformer analysis

The starting point of the analysis has included fundamental information and basic properties of a wire (to determine the track width and height so that the ac resistance to dc resistance ratio was minimum at the frequency of interest). Next steps focused on the determination of the inductance parameters for different configurations of the windings. In order to do that, firstly, a spiral shape of each layer winding with 2 or 4 turns was modelled respectively as a 2 or 4 concentric, circular shape, separated windings. For such a winding, the inductance of a single turn was determined. Next, the inductance (self and mutual) for each layer regarded as a separate from other layers and not affected by them was calculated. Then, the inductance of all of one winding (primary and secondary) layers was estimated. Finally, the inductance between primary and secondary winding was determined. The presented bottom-up approach proved to be very helpful in complex analyses.

3.3 Models' description

In order to simplify the analysis and to reduce the required disk space and the computation time all COMSOL models were prepared as a 2D axial symmetry. It was possible due to the fact that the prototype of the planar transformer was axially symmetric as it is composed of a pot core and round planar coils. A 2D model is less computation-heavy than a 3D one. This is very important in the considered designing procedure since it requires many iterations of the simulation process to fully describe the properties of the analysed device.

All developed models were based on the equations provided by the AC/DC module and the Magnetic Field interface. To analyse the transformer as a whole also the Electrical Circuit interface was applied. The Single Turn Coil Domain (STCD) feature was used to model each turn of a planar transformer. All of the analyses were made in the frequency domain (with the adjusted frequency 500 kHz).

All models were solved by the Stationary, Direct solver. A single model of a complete transformer requires 3 seconds, 899 MB of physical memory and 1013 MB of virtual memory to be solved.

The study step called a Parametric Sweep helps to handle a fairly large set of simulations that change the coils arrangements inside the core.

The model geometry was entirely made using COMSOL graphical tools. Therefore, the dimensions could be parameterized and then modified in a parametric sweep analysis in order to investigate the dependencies in a transformer. The 2D model geometry is shown in Figure 3. This cut view loops around the axis of the symmetry resulting in a 3D geometry of the real device.

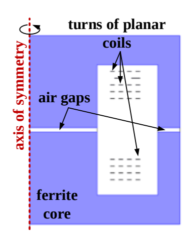


Figure 3. Geometry of the 2D axis symmetry planar transformer.

The model utilizes materials from the COMSOL Material Library. The assumed material parameters of the analysis are collected in Table 2

Table 2: Material parameters of the COMSOL models

Material	Relative permeability	Electrical conductivity
Air	1	1 S/m
Cooper	1	$5.998 \cdot 10^7$ S/m
Ferrite core	1650	1 S/m

Material properties of copper were assigned to windings whereas properties of air were assigned to regions inside and outside the pot core (separate layers of laminate were not modelled in this approach). The core has constant permeability, which reflects the properties of the ferrite core used in the constructed prototype. Nonlinear changes of the permeability were not included as the transformer is intended to operate in the linear region of the B-H characteristic of the core.

3.4 Meshing of the FEM Model

The appropriate settings for mesh are crucial for a correct analysis because a single simulation model should include various physical effects, like the magnetic coupling effect between coils, the fringing flux in the air gap, the skin effect in a single wire and the proximity effect between tracks. Therefore, two types of mesh were used: a free quad and a free triangular. The quadrilateral mesh elements were used for copper tracks as their height is very low (35μm) but they are wide (0.5 mm or 1 mm). For such elongated domains the implementation of quad elements instead of triangular ones allows to reduce a number of discretized areas and achieve the desired accuracy of calculation (implementation of approximately isotropic triangular elements results in the increase of the total number of meshed elements; rectangular meshing allows to reduce elements without reducing the accuracy). A full model of a planar transformer with a core is composed of 33 000 elements of quality higher than 0.19. Figure 4 shows the mesh of the model. It has a varying density and is finer in areas of importance such as expected zones of the fast varying magnetic flux density.

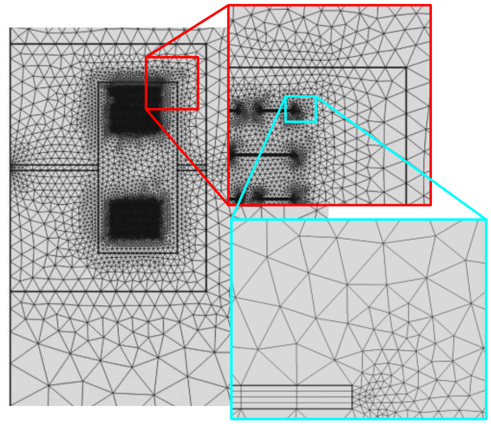


Figure 4. Mesh of the whole model domain. Two types of elements were used in the model: quads for PCB tracks and triangular ones for the core and air domains.

3.5 Implementation of the Electrical Circuit interface

The output results of a simulated multilayer planar transformer were impedances, determined in 4 characteristic configurations of the windings:

- the impedance of a primary winding in an open-circuit configuration of a secondary winding (signed as L_{SO});
- the impedance of a primary winding in a short-circuit configuration of a secondary winding (signed as L_{SS});
- the impedance of a secondary winding in an open-circuit configuration of a primary winding (signed as L_{PO});
- the impedance of a secondary winding in a short-circuit configuration of a primary winding (signed as L_{PS}).

The aforementioned configurations of the transformer windings connections are presented in Figure 5.

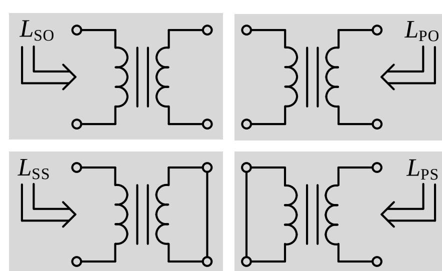


Figure 5. Windings' configurations for the impedance measurement that allows to determine the transformer's equivalent circuit parameters.

The four listed measurements enable to identify the equivalent circuit parameters of the transformer like: main inductances, winding resistances, leakage inductances, core losses, etc. [6]. The comparison of the 4 mentioned impedances between computational results and laboratory tests of a prototype can give a view on a quality of the developed COMSOL model.

To determine the aforementioned impedances, the Electrical Circuit interface was used, which, in turn, allowed to combine the electromagnetic FEM model with the external electric circuit. Each single turn of the analysed transformer is modelled as the STCD and connected in an electrical circuit, which is equivalent to winding connections in the transformer prototype. The structure of the electrical circuit used in analyses is presented in Figure 6.

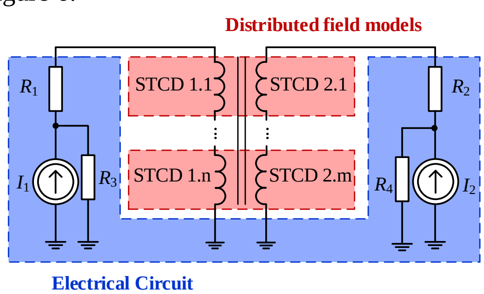


Figure 6. An equivalent circuit of a planar transformer including distributed field models of coils.

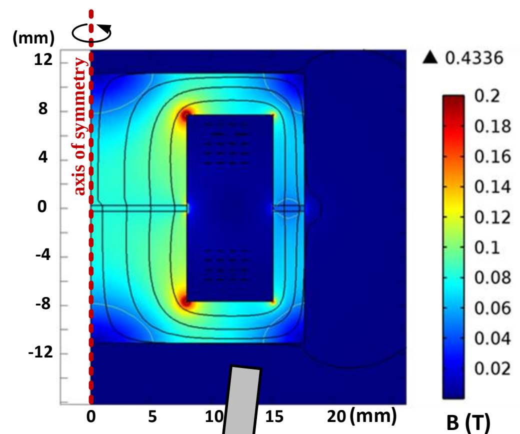
The use of the Electrical Circuit interface allows to determine current and voltage values on each coil and to determine the requested impedance. Additionally, the Electrical Circuit interface allows easy modifications of the circuit topology (operation in an open-circuit or a short-circuit mode), which is very effective in complex calculations.

4. Results of electromagnetic analyses

From the design point of view, the most important results of electromagnetic analyses are as follows: the amplitude of the magnetic core flux density (the magnetic core should not be saturated during a normal operation because of the increasing power losses); the magnetic flux lines distribution (magnetic flux lines should be closed in the magnetic core or in the controlled air space because of the potential increase of the fringing flux); the current density of windings (because of the high frequency operation and phenomena of skin effect and proximity effect).

Results of the FEM analysis are presented in Figure 7a (the magnetic flux distribution with flux lines) and Figure 7b (3D revolution of the 2D axial symmetry model – a distribution of the magnetic flux and current density in windings). The magnetic flux is distributed in the magnetic core and its density is not higher than the required B_{MAX} which means that the magnetic core is not saturated and operates properly. Flux lines are closed in the magnetic core material and in the controlled air space of the air-gap, which, in turn, means the fringing flux is on an acceptable level. Transformer windings operates at dedicated current densities, which proves an acceptable level of skin and proximity effects

a)



b)

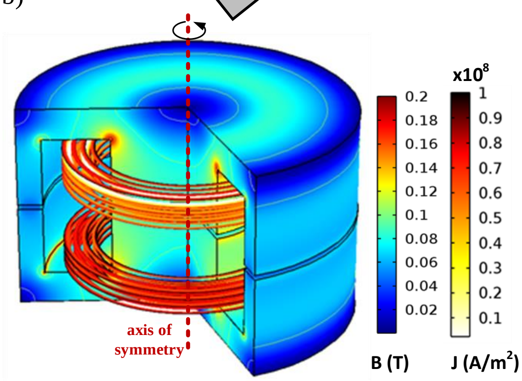


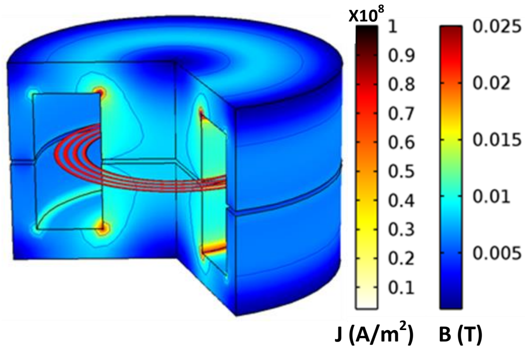
Figure 7. Results of electromagnetic simulations:

a) 2D model with the magnetic flux distribution and flux lines;

b) 3D revolution of the 2D model with the magnetic flux distribution and current densities in transformer windings.

The complexity of analysed geometry resulted in several steps of sub-analyses with different positions of transformer windings. The exemplary steps are presented in Figure 8.

a)



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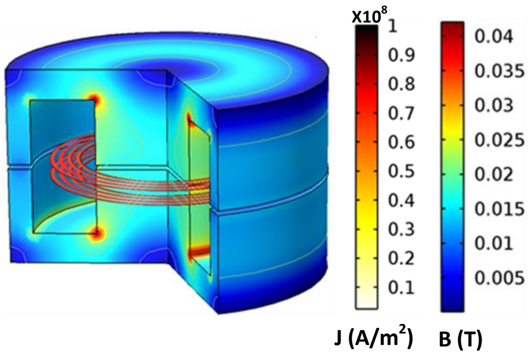

c)

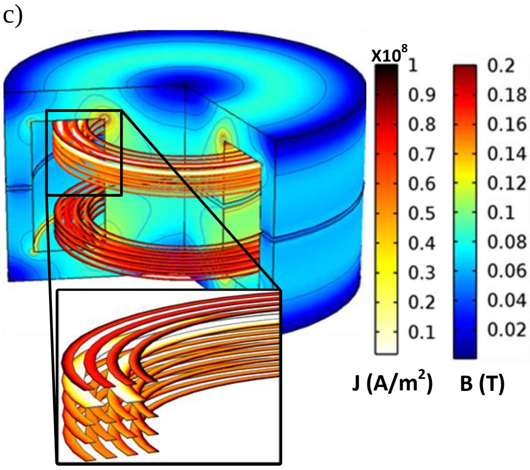

Figure 8. Magnetic flux and current densities for different steps of the transformer geometry analysis:

a) a model with one primary winding layer;
b) a model with two primary winding layers;
c) a model with completed layers of primary and secondary windings.

The presented results of the modified position of transformer windings were used to design the recommended geometry with expected main and leakage inductance values. Moreover, analyses were helpful to determine the coupling coefficient between primary and secondary windings. Additionally, results allowed to evaluate the influence of skin and proximity effects on transformer properties. The step-by-step analysis was recommended to enable proper understanding of physical phenomena in the studied geometry of the transformer.

5. Prototype

The prototype of the designed planar transformer was constructed in order to verify the modelling method. The magnetic core used in the prototype was a ferrite P-core 3622, made of N49 material (MnZn) with maximum flux density B_{MAX} = 490 mT [7]. The ferrite core was selected due to its stability of the permeability in a high frequency region.

Primary and secondary windings were made as tracks on a multilayer PCB and formed as spiral coils (each PCB consists of 2 or 4 turns). Corresponding layers of primary and secondary windings were connected in-series to achieve the required number of turns (primary – 14 turns, secondary – 20 turns). In order to get the requested inductance and leakage inductance, the printed circuit boards with planar coils did not occupy the whole volume inside the pot core. Additionally, to fulfill the voltage clearance requirements, PCBs were stacked alternately with insulating spacers. Main parts of the prototype and the assembled transformer are presented in Figure 9.

Figure 9. Prototype of the multilayer planar transformer

6. Experimental results

The prototype of the constructed planar transformer was measured by the Agilent 4294A Precision Impedance Analyzer [8] that enables precise measurements of the impedances (the magnitude and the phase) in a wide range of the current frequency (40 Hz –110 MHz). As for the analysed planar transformer, four characteristic impedances were measured (impedances of four characteristic configurations of the transformer windings – LSO, LSS, LPO, LPS; the same as in the FEM model – see chapter 3.5).

The comparison of FEM analyses and prototype measurements is collected in Table 3. The obtained results have an acceptable accuracy and confirm the correctness of the FEM model. The existing difference between the FEM calculation and the laboratory measurements' results mainly from the inaccuracy of the prototyping. Added to that, the assumed simplifications of a model bring an error too: the real 3D object was modelled by a 2D axial symmetry neglecting some core shape details (terminal slots) and the winding was represented as a set of concentric circles while, in fact, it is a spiral in a real device.

Table 3: Inductances of a planar transformer: measured and calculated

Item	Measurement	Simulation	Diff %
L_{SO}	44.02 μH	48.42 μH	10.0
L_{SS}	11.63 μH	13.20 μH	13.5
L_{PO}	83.66 μH	90.02 μH	7.6
L_{PS}	21.93 μH	24.55 μH	11.9

7. Conclusions

The presented analyses of the multilayer planar transformer allow to draw the following conclusions:

- The COMSOL software is helpful for electromagnetic calculations of complex and sophisticated geometries,
- The FEM analyses allow to determine a magnetic core point of operation and protection against the magnetic saturation,
- The FEM calculation of a current density (with skin and proximity effects) allows an optimal design of the cross-section of the transformer windings,
- Changes of the transformer windings configurations impact the magnetic field distribution in the magnetic core – the COMSOL software allows to control the design and optimisation process,
- The comparison of the FEM model results and laboratory measurements shows the reliability of the COMSOL calculations (difference at level ~10% is acceptable at preliminary design, it can be decreased by more precise prototyping and increasing the finite elements' number).

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