COMSOL
CONFERENCE
2025 AMSTERDAM

Numerical Analysis of an Integrated LLC Transformer with Multi Air Gaps and Litz Wire Windings

Jana Morick[1], Roman Kunde[2], Mikhail Tolstykh[3], Lars Fromme[4]
1. Faculty of Engineering and Mathematics, Hochschule Bielefeld – University of Applied Sciences and Arts (HSBI), Bielefeld, Germany.
2. PHOENIX CONTACT Power Supplies GmbH, Paderborn, Germany.
3. Bielefeld Institute for Applied Materials Research (BIfAM), HSBI, Bielefeld, Germany.
4. Institute for Technical Energy Systems (ITES), HSBI, Bielefeld, Germany.

Abstract
In this work, a novel approach based on numerical simulations is presented for analyzing the structure of a high-frequency integrated inductor–inductor–capacitor (LLC) resonant transformer. The objective is to create a digital twin of the LLC transformer that closely resembles an actual device. To validate the simulation models, the equivalent circuit parameters of the assessed LLC transformer are compared with specific measurements of the real device.

Keywords: LLC transformer, Meeker litz wire approximation, equivalent circuit parameters, multi air gaps.

Introduction
In contemporary development processes, optimizing simulation models has become increasingly critical for reducing development time and costs. The simulated model facilitates the extraction of equivalent circuit parameters for the LLC transformer based on its geometric specifications. Conversely, this knowledge can be employed to determine the geometric dimensions of an LLC transformer prior to the fabrication of a physical prototype.
A key aspect of the approach is the consideration of multiple air gaps in the middle leg of the transformer core. The magnetizing inductance, which is a critical design parameter for LLC transformers, can be precisely adjusted through the number and height of air gaps. The simulation model enables the parametric variation of these dimensions, allowing both the avoidance of core saturation and the reduction of magnetic flux fringing. Based on the simulated inductance factor, the required air gap configuration can be determined in advance, prior to physical prototyping, based on the target inductance for future designs.
Traditional methods for simulating the equivalent circuit parameters of LLC transformers often encounter challenges in accurately modeling high-frequency litz wires within the transformer windings, which is essential to account for high-frequency losses due to skin and proximity effects. Our approach utilizes the newly introduced capabilities of the software COMSOL Multiphysics to simulate losses in litz wires. The implementation is based on the Meeker approach for hexagonally packed litz wires [1], incorporating an additional factor to account twisted litz wires.

DC/DC Converters with an LLC Transformer
Figure 1 demonstrates the circuit design of the DC/DC converter with an LLC transformer which is utilized in this work. The topology representation includes a differentiation between an integrated (light blue) and a not integrated (dark blue) LLC transformer. Integrated LLC transformers utilize the transformer leakage inductance as the resonance inductance L_r.

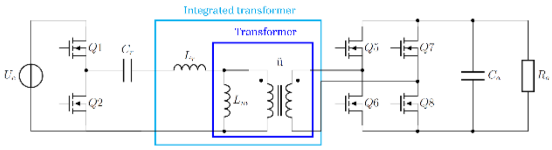

Figure 1. DC/DC converter topology with a LLC transformer.

The DC voltage U_e is transformed into a rectangular voltage due to the half-bridge MOSFET circuit of *Q1* and *Q2*. This rectangular voltage excites the resonance circuit of the LLC transformer and results in a sinusoidal voltage and current. By adapting the switching frequency dependent to the resonance frequency, zero voltage switching or zero current switching can be provided.
The next part of the DC/DC converter is the actual transformer device which adapts the voltage level.

The sinusoidal voltage is rectified with a MOSFET full-bridge circuit so that a DC voltage is present at the resistor R_a due to the filtering of the capacitor C_a.

Parameters of the Real Device

Important parameters of the transformer are the exciting current, the output current and the resonance frequency. The utilized device is shown in figure 2, it is part of a current source that converts the mains source into a 24 V DC voltage and allows a current flow of 20 A at the device output. The input current of the transformer is defined with 2.3 A.

Both coils are made of copper with the number of turns $N_p = 58$ in the primary and $N_s = 3$ in the secondary coil. In the real device litz wires are utilized in the windings to reduce the losses, in this case the number of primary and secondary litz wire strands are $n_p = 120$ and $n_s = 360$, respectively.

The integrated LLC transformer in this device utilizes the DC/DC transformation of the mains voltage with a resonance frequency of nearly $f_{res} = 100\ \mathrm{kHz}$.

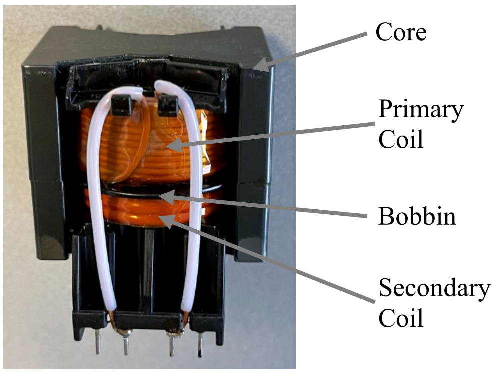

Figure 2. Existing LLC transformer.

The functionality of the transformer is primarily determined by the material composition of its core, which is typically made of ferrite due to its eddy current loss reducing properties. Here the core consists of a N97 Ferrite with a relative permittivity of $\varepsilon_r = 270$ and an electric conductivity of $\sigma = 0.125\ \mathrm{S/m}$. The magnetic properties of the core material are defined by the complex relative permeability of $\overline{\mu}_r = 2365 + j\,25.01$ at the resonance frequency [2].

Due to manufacturing reasons air gap plates are made of non-conductive materials. Here, the remaining parts of the real device are made of plastic composites as PET (bobbin) and FR4 (air gap plates).

Measurement of the Equivalent Circuit Parameters

An open and short circuit test is performed to measure the resistance and inductance values of the LLC transformer.

The simulation of the device is based on the same measurement methods of open and short circuit tests where the excitation of the secondary transformer coil is defined accordingly.

To simplify the analysis of a transformer an equivalent circuit as presented in figure 3 is used. The elements of the simplified circuit are determined by different output configurations. The magnetizing inductance L_m and the iron resistance R_{Fe} of a transformer are experimentally found using open terminals at the secondary transformer coil (open-circuit test). The leakage inductance L_s and the winding resistance R_w are calculated using a short-circuit at the secondary transformer coil (short-circuit test).

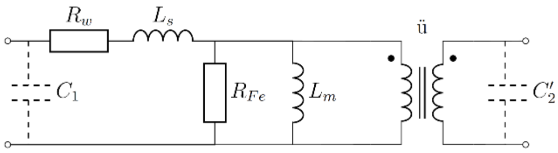

Figure 3. Equivalent circuit parameters of a transformer.

The equivalent circuit parameters of the existing LLC transformer are measured by an impedance analyser with the auto-balancing bridge method. The open- and short-circuit measurements result in different impedances where the real part is the resistance value and the imaginary part the reactance. The measured values for the resonant frequency are shown in table 1.

Model Definition

The main geometry used in the simulation models is imported from a file. This CAD geometry, originally generated during the manufacturing process of the actual device, is shown in figure 4.

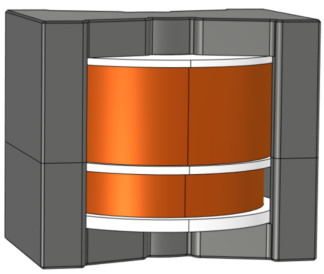

Figure 4. CAD geometry containing the core, the bobbin, and the primary and secondary coil domains.

The air gaps are located in the center leg of the core (see figure 5). The number and height of these gaps are parameters which can be varied in the geometry definition.

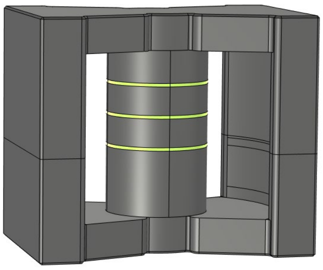

Figure 5. Three air gaps in the middle leg of the transformer core. In this case the height of each gap is 0.5 mm.

An air domain around the main geometry is added to the model as well as spherical infinite element domains to emulate an infinite open space surrounding the transformer.
The *Magnetic fields* interface is utilized to define the physics and a frequency-domain analysis at the resonance frequency is performed. The magnetic losses in the core are introduced by specifying a complex permeability for the core material.
The transformer windings are defined using the *Coil* node. The bundle of electrically thin wires separated by an insulating material is not resolved geometrically, thus a homogenized conductor model is used. The *Conductor model* for solid copper wires corresponds to the *Homogenized multiturn* while twisted stranded wires are determined with the new *Homogenized litz coil* feature. The difference of these two *Conductor models* is described in more detail in the following subsections.
The inductances and resistances in the transformer can be evaluated using different secondary coil excitations in the *Magnetic fields* interface. An open circuit test is created by setting the current of the secondary coil in the *Coil* Definition to zero, while a short circuit test is created by setting the voltage of the secondary coil in the *Coil* Definition to zero.

Comparison of Different Conductor Models

Transformer windings, as previously discussed, can be modelled as an effective medium without resolving the bundle of thin wires geometrically. COMSOL Multiphysics version 6.3 introduces new conductor models in the *Coil* feature including high-frequency losses. Skin and proximity effects are included in the model in a lumped sense, using an effective loss model [3]. Besides the *Homogenized multiturn* model also the new *Homogenized litz coil* feature is available in version 6.3. This new conductor model is a variant of the multiturn model where the effects of helical twisting and multiple strands per turn are accounted for.
To verify if the new litz wires approximation improves the simulation model significantly, the numerical results of two different model approaches, i.e. the resulting equivalent circuit parameters, are compared to each other.
In one model approach, the *Homogenized multiturn* model is used for the coil domains. In this case, the coils are modelled as a bundle of electrically thin solid wires separated by an insulating material. The solid wire cross-section area is defined as $A_{wire} = n \cdot A_{strand}$, where n indicates the number of individual strands in a single conductor wire and A_{strand} describes the cross-sectional area of a single strand. This model approach does not include high-frequency losses in the conductors.
In a second model approach the new *Homogenized litz coil* feature is used to represent the bundle of thin litz wires separated by an insulating material in the coils. This second approach takes into account that each turn consists of many thin wire strands, individually insulated and twisted together. In addition, this approach includes the new harmonic loss option to compute the coil's intrinsic AC loss in the frequency domain.

Litz Wire Approximation

The new *Homogenized litz coil* conductor model enables specification of strand count and DC resistance per unit length, compensating for resistance added by twisting patterns. The *Litz wire DC resistance per unit length* ρ_{DC} is defined as:

$$\rho_{DC} = 1.06 \cdot \frac{1}{\sigma \, n \, A_{strand}} \qquad (1)$$

where σ is the electric conductivity of the conductor material, n is the number of individual strands and A_{strand} describes the cross-sectional area of a single stranded wire. To consider the helical twisting of the stranded wire, an increase of 6% is estimated.
An additional important feature of the *Homogenized litz coil* conductor model is its incorporation of harmonic losses in the high frequency range. In real LLC transformers litz wires are utilized in the windings to reduce the losses. Thus, the simulation model should be suitable to account for high-frequency losses due to skin and proximity effects in a proper way.
The new *Homogenized litz coil* feature in the software COMSOL Multiphysics is based on Meeker's approach considering skin and proximity effects for hexagonally packed litz wires. In this approximation approach the complex magnetic permeability μ_{eff} and electric conductivity σ_{eff} are calculated depending on the parameter f which

describes the fill factor of the entire conductor cross-section. In addition, four functions c_1, c_2, c_3 and c_4 dependent on this fill factor are introduced. Meeker outlines the determination of these functions based on different values of the fill factor [1].
To simplify the calculation of the effective material parameters the non-dimensional frequency Ω is introduced:

$$\Omega = \omega\, \sigma\, \mu_0\, \frac{A_{strand}}{2\pi} \qquad (2)$$

The effective relative permeability then reads:

$$\mu_{r,\mathrm{eff}} = 1 + c_2 \cdot \left(\frac{\tanh \sqrt{j\, c_1\, \Omega}}{\sqrt{j\, c_1\, \Omega}} - 1 \right) \qquad (3)$$

and the effective conductivity is given by:

$$\sigma_{\mathrm{eff}} = \left(\frac{j\, c_4\, \Omega}{\sigma} + \frac{\sqrt{j\, c_3\, \Omega}}{\sigma\, \tanh \sqrt{j\, c_3\, \Omega}} - \frac{1}{2}\, j\, \omega\, \mu_0\, \mu_{r,\mathrm{eff}}\, \frac{A_{max,wire}}{\sqrt{3}}\, f \right)^{-1} \qquad (4)$$

In this formula $A_{max,wire}$ is the maximum wire area, i.e. the cross-section of the complete coil divided by the number of turns N and by the number of strands n.

Results

In table 1 the resulting equivalent circuit parameters from the numerical simulations using different approximations for the coils are shown. In addition, the corresponding measured values of the real LLC transformer are displayed.

***Table 1**: Equivalent circuit parameters of different simulation models and the corresponding measured values.*

	L_m /µH	R_{Fe} /mΩ	L_s /µH	R_w /mΩ
measurement	580	373	162	1340
Hom. multiturn	626	307	179	787
Hom. litz coil	626	390	179	993

The comparison of the different simulation results with the measured values shows that the magnetizing inductance L_m and the leakage inductance L_s are identical for both approximations and the values are consistent with the measurements. In the technical data sheet of the real device the value of L_m is specified as 600 µm $\pm$ 5%. However, for the iron resistance R_{Fe} and the winding resistance R_w the numerical results differ from each other. Obviously, the *Homogenized multiturn* model approach (without harmonic losses) undervalues the resistances. Notably, the resistance values of the simulation with the *Homogenized litz coil* approximation exhibit a significant improvement. As a conclusion, the discretization of litz wires as well as high-frequency effective losses must be considered for more accurate simulation results.
With the verification that *Homogenized litz coil* simulation model is more accurate, the magnetic field distributions for different air gap configurations can be analyzed.
Figure 5 shows the distribution of the magnetic flux density in the cut plane trough the transformer with 3 air gaps, each measuring 0.5 mm in height giving a total air gap height of 1.5 mm.

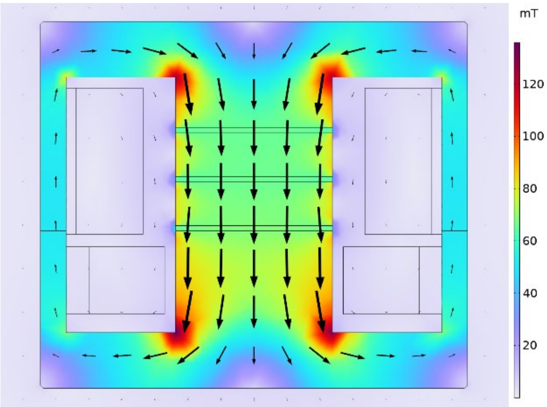

Figure 5. Magnetic flux density inside the transformer core with 3 air gaps.

In general, more air gaps lead to a smaller field diffraction into the transformer's bobbin and core.
The so-called inductance factor A_L is a value that specifies a magnetic core's inherent inductance, representing the self-inductance per unit square of the number of turns when a coil is wound on that core. The difference in the inductance factor for different air gap configurations is shown in table 2.
The value h_{tot} defines the total air gap height, which is split dependent on the air gap number to reduce air gap diffraction.

***Table 2**: Inductance factor for different air gap configurations.*

A_L/nH	h_{tot} = 0.3 mm	h_{tot} = 0.5 mm
1 air gap	769	211
3 air gaps	726	181
5 air gaps	721	178

The inductance factor values for different numbers of air gaps illustrate that the most significant optimization of the inductance factor occurs between one and three air gaps. The difference between three and five air gaps is smaller, leading to the conclusion that the effectiveness of air-gap separation decreases as the number of air gaps increases.

Conclusions

In this project, a digital twin of an integrated LLC transformer that closely mirrors a real device was developed and analyzed.

The enhanced capabilities of COMSOL Multiphysics for simulating high-frequency litz wire conductors within the transformer windings, which is crucial for capturing losses due to skin and proximity effects at high frequencies, proved valuable.

The numerical model enables the extraction of equivalent circuit parameters for the LLC transformer based on its geometric specifications. It also permits parametric variation of the number and height of air gaps in the middle leg of the transformer core, thereby avoiding core saturation and reducing magnetic flux fringing. Based on the simulated inductance factor, the required air gap configuration can be determined in advance, prior to physical prototyping, to meet the target inductance for future designs.

References

[1] D. C. Meeker, “An improved continuum skin and proximity effect model for hexagonally packed litz wires,” *Journal of Computational and Applied Mathematics,* vol. 236, no. 18, pp. 4635-4644, 2012.

[2] TDK Electronics AG, *SIFERRIT material N97 - Ferrites and accessories,* 2025.

[3] COMSOL, *AC/DC Module User's Guide*, 2024.