FEM modelling and experimental validation of proximity loss

ABSTRACT
Skin depth and proximity effects in transformer windings are important phenomena influencing the design even at power frequencies (50-60 Hz). They become critically important at elevated frequencies, especially for high-frequency transformers. This article presents results of computer simulations and experimental validation on physical prototypes. The investigated frequency range was from 1 Hz to 10 kHz.

KEYWORDS
copper loss, proximity loss, skin effect

Computer simulations and experimental verification from 1 Hz to 10 kHz

1. Introduction

The topic of proximity loss and skin effect in transformer windings was discussed in the two-part paper published in the previous issues of Transformer Magazine [1, 2]. However, the previous papers focused solely on results obtained from computer simulations through 2D Finite-Element Method (FEM) modelling.

FEM modelling is used extensively in many branches of design and optimisation of electromagnetic devices, rotating machines and transformers.
In this paper the same FEM modelling technique is used. However, the modelled structures were simplified so that they could also be built as physical prototypes. A specially designed and built measurement apparatus was used for the experimental measurements.

In this way a direct comparison between the simulated and the measured results could be achieved. These results, both absolute and relative are presented below.

2. FEM modelling

FEM modelling is used extensively in many branches of design and optimisation of electromagnetic devices, rotating machines and transformers [3]. The simulations can be conducted as two-dimensional (2D) or three-dimensional (3D).

2D FEM is carried out with the assumption that the modelled structure can be represented as a 2D geometry. This means that the modelling will be carried out for a single cross-section view, with the assumption that such cross-section is representative for the rest of the volume. There are two main approaches: 2D planar and 2D axisymmetric.

In the 2D planar approach, the structure is assumed indefinitely long and uniform. The representation takes form of a cross-sectional view (Fig. 1a). However, in the axisymmetric approach (Fig. 1b), the object is assumed to exhibit perfect rotational symmetry and only right-hand side of the cross-sectional view is modelled. Due to the mathematical calculations, the results are correctly taking into account the fact that the structure is three-dimensional, despite the fact that only 2D representation is used [4].

For 3D FEM the whole structure is represented (Fig. 1c). However, the 3D calculations are severely more computationally demanding. Both the computer memory and execution time are several orders of magnitude greater than for 2D representation. It might be even impossible to represent the full structure in 3D. For instance, despite great progress in computer technology, laminated cores still cannot be modelled in 3D and this remains a great challenge even for 2D FEM [5]. Therefore, it was decided to use 2D FEM in order to perform the calculations for this study.

The magnetic cores used for simulations were ETD49 [6] and ETD34 [7]. An example of ETD49 is shown in Fig. 2. The core has two identical halves. The central core “leg” or limb has a circular cross-section, therefore the windings also have a cylindrical shape.

Despite great progress in computer technology, laminated cores still cannot be modelled in 3D and this remains a great challenge even for 2D FEM

---

Skin depth and proximity effects in transformer windings are important phenomena influencing the design even at power frequencies (50-60 Hz)
layers, 1 layer and 0.5 layer, as shown in Fig. 4, which meant that only small part of the core window was occupied by the winding.

Performance of each configuration was measured as the total loss of the whole transformer, as shown in Fig. 5. The primary winding was driven and the secondary winding was short-circuited. Therefore, at higher frequencies the transformer operated as a current transformer with very small flux density $B$ in the core. The short circuit was made by soldering the two terminals of the secondary winding together (visible in Fig. 3).

3. Experimental procedure

For the prototypes plastic bobbins with multiple sections were used (Fig. 3). The barriers between sections helped keeping the wires in the intended positions, which turned out to be important for correct simulations.

It was decided that all the experiments will be carried out with a fixed length of wire. Namely, each winding was re-made from the same piece of wire, which ensured that the same overall resistance was present in the windings. The windings were made in three configurations: 2 layers, 1 layer and 0.5 layer, as shown in Fig. 4, which meant that only small part of the core window was occupied by the winding.

Performance of each configuration was measured as the total loss of the whole transformer, as shown in Fig. 5. The primary winding was driven and the secondary winding was short-circuited. Therefore, at higher frequencies the transformer operated as a current transformer with very small flux density $B$ in the core. The short circuit was made by soldering the two terminals of the secondary winding together (visible in Fig. 3).

**Performance of each configuration was measured as the total loss of the whole transformer**
Fig. 3b). Additionally, after finishing all the tests, both primary and secondary copper wire was unwound from the transformer, straightened out, and soldered into one long hairpin-shaped wire (Fig. 5).

Good grade of magnetically soft ferrite 3C90 was chosen. The estimated $B$ in the core was at the level of $\mu T$, which is known to be a region in which the magnetisation is reversible (the so-called Rayleigh region) [8, 9]. Thus the core operated a negligible practical loss (the highest estimated value was around $1 \mu W$).

The power loss was measured by means of purpose-built precise wattmeter based on the data acquisition device NI PCI-6120 with a 16-bit resolution [9]. The measurements were performed up to 10 kHz, because this was the highest operating frequency for the wattmeter. Detailed description of the verification procedure for the wattmeter is outside of the scope of this paper. However, the accuracy was verified with non-inductive and inductive loads before the main experiments and the achieved accuracy is higher than 2 % throughout the frequency range, up to 10 kHz.

4. Results

Experimental results for as-measured power loss for ETD49 are shown in Fig. 6. The data for ETD34 was very similar and is not shown for the purpose of brevity, but some results are shown below.

All curves measured on transformers display reduced values of loss at 1 Hz. This results from an insufficient current transformer mode at such low frequencies, so the current induced in the secondary winding was too small to generate appropriate losses and the overall loss was reduced proportionally. Hence, at 1 Hz the measured loss was related only to the loss in the primary winding. For ETD49 the primary winding had resistance of 2.89 mΩ, so the ideal loss should be 28.9 $\mu W$. For ETD34 the primary winding had resistance of 4.66 mΩ, so the ideal loss should be 46.6 $\mu W$. As can be seen in Fig. 6, the value measured at 1 Hz is very close to the expected value.

The values plateau above 50 Hz, in both the measurements and FEM. This is because the proper current mode operation was set up in the transformer, and the current in the secondary winding became equal to that in the primary winding. As a result, the total losses became directly proportional to the total resistance of both windings, namely 5.28 mΩ (52.8 $\mu W$) for ETD49 and 10.6 mΩ (106 $\mu W$) for ETD34. At frequencies above 1 kHz the proximity effect increases the losses considerably.
FEM simulations show that the losses are indeed slightly lower for 4 wires (and more) than for only 2 wires
The configuration with 2 wires is represented in Fig. 5 (bottom right). There are just 2 straight parallel wires short-circuited at one end. The configurations with 4 wires (and more than 4) are equivalent to a 0.5 layer structures from Fig. 4.

FEM simulations show that the losses are indeed slightly lower for 4 wires (and more) than for just 2 wires. This effect can be explained by the curves shown in Fig. 9, because for the 2 wires the peak current density is visibly higher, and since the losses are proportional to the square of the current density, the contribution towards the total loss is greater.

In this experiment, the configuration with effective 0.5 layer prevents the proximity effect from developing above the skin effect, which itself cannot be avoided.

Qualitatively, the values for ETD34 are similar to ETD49. However, thinner wire was used (1.4 mm) and the positioning of the wires in FEM was perhaps not as well represented as the real winding. Also, the measured values differ by around ±2 % at 10 kHz. However, for this experiment, the measurements were performed over a few days, so the equipment stability or even copper temperature coefficient (0.4 %/K) could be responsible for such changes.

The FEM results are overestimated for the 2-layer structure, which again could be attributed to imperfect representation of the actual windings. As shown above (Fig. 7), spacing of the wires can significantly influence the proximity effect, so a small discrepancy can have a large effect, especially for small distances.

For ETD34, the measured and FEM curves for 1 layer are much closer because the positioning of wires in the real windings was better defined due to the sections of the bobbin (see also the title photo). For 0.5 layer and the straight wires, the skin effect is barely noticeable.

5. Summary

FEM simulations were compared with measurements on physical prototypes. Qualitatively, the performance is comparable and the proximity effect is

---

**Spacing of the wires can significantly influence the proximity effect, so a small discrepancy can have a large effect, especially for small distances**
As expected, the skin effect is always present, even though the proximity loss can be reduced to a negligible level for certain configurations of the windings.

clearly demonstrated. Moreover, after including the losses in the connecting wires the agreement is very good even quantitatively, as demonstrated on losses expressed in μW.

The remaining inconsistencies for 2 layers can be contributed to the discrepancy between the positioning of real wires and their representation in the FEM model. With better representation, due to better control through the presence of bobbin sections, the agreement was very good for 1 layer and 0.5 layer configurations.

It is evident that, as expected, the skin effect is always present, even though the proximity loss can be reduced to a negligible level for certain configurations of the windings.

The same FEM modelling technique was used for the study presented by the author in the previous papers published in Transformers Magazine [1, 2], and the conclusions made there were valid, which is confirmed by the experimental verification presented herein.

Bibliography


Author

Stan Zurek completed a PhD in electrical engineering in 2005 and continued research in magnetic materials at Wolfson Centre for Magnetics, Cardiff University, UK. He joined Megger in 2008 and is Manager of Magnetic Development. He is the author and co-author of over 65 scientific publications related to magnetics and magnetic materials. Dr. Stan Zurek is a Senior Member of IEEE Magnetics Society.