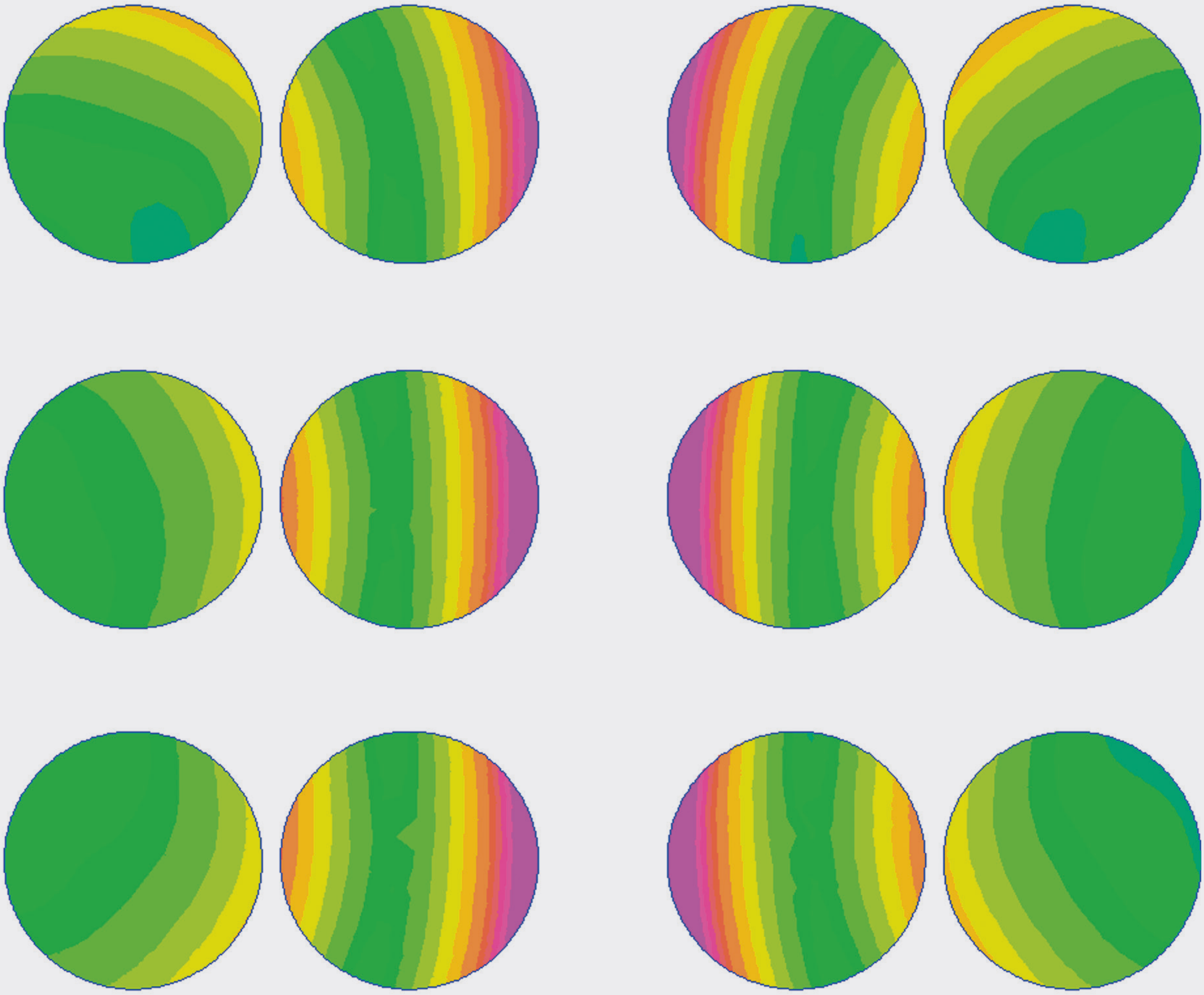

FEM modelling and experimental validation of proximity loss

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.

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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.

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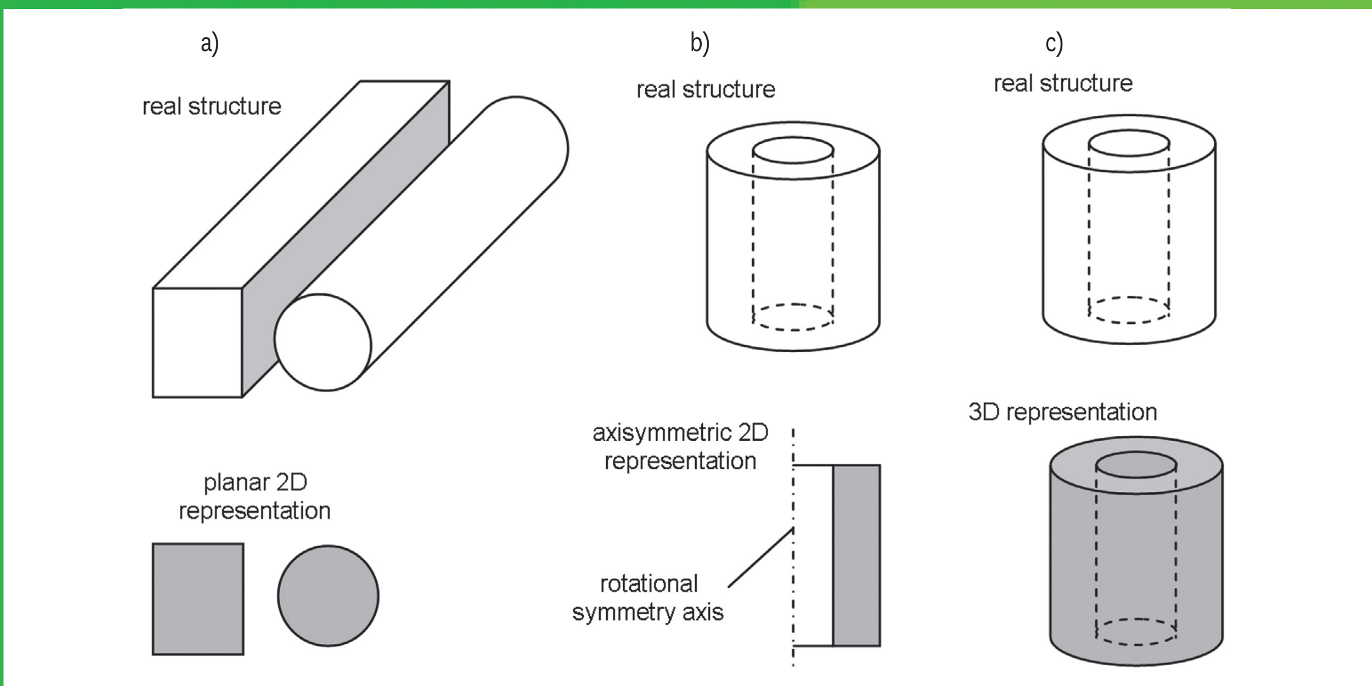

Figure 1. Representations in planar 2D FEM (a), axisymmetric 2D FEM (b), and 3D FEM (c)

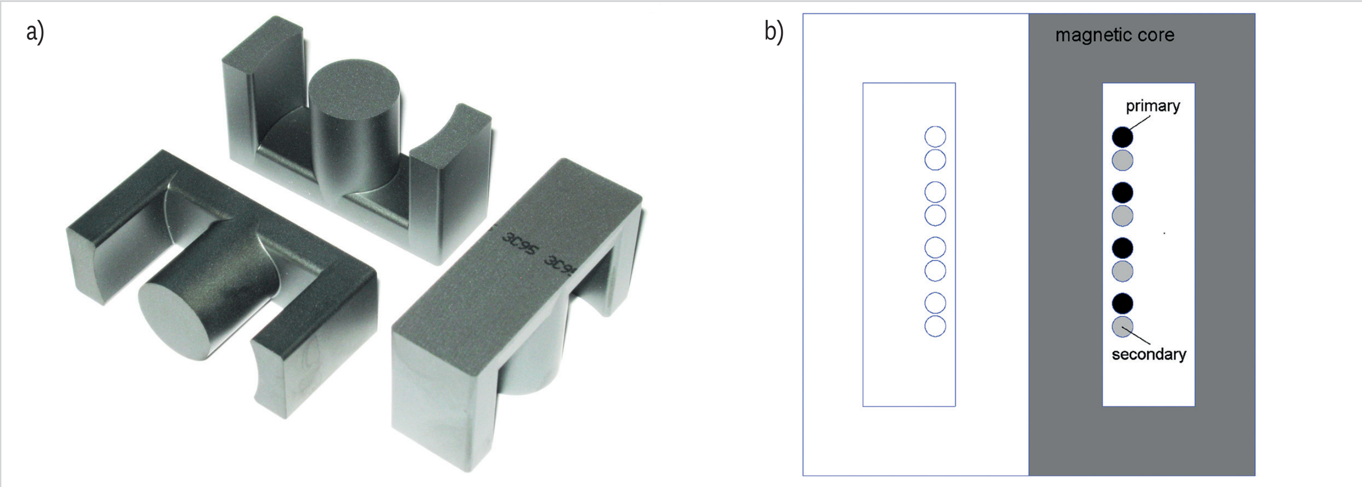

Figure 2. Core halves of ETD49 (a), and 2D axisymmetric representation in FEM (b), with mirror image shown for completeness, but only the right-hand-side components were modelled

For this reason, it is possible to model such structure by using the 2D axisymmetric approach (Fig. 1b). The central limb and the windings are represented well, with all 3D effects taken into account, because they resemble ideally cylindrical shapes.

The outer limbs are not represented precisely, because in the axisymmetric model they become a cylindrical "sheath". However, this has very little effect on the results (as shown below), because the core losses are irrelevant for this analysis.

The other part which is not represented in such model is the wires connecting the transformer to the power supply. This has more influence on the calculated absolute results, as discussed below. The simulations were run from 1 Hz to 10 kHz with sinusoidal excitation current of the same amplitude as the experimental measurements (100 mA rms).

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

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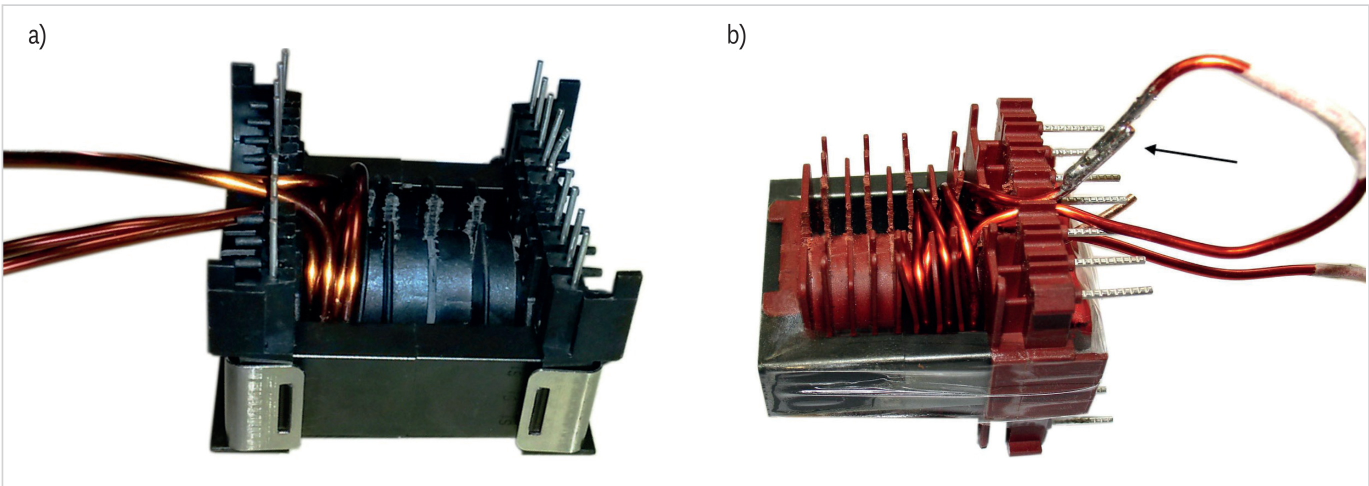

Figure 3. Prototypes: a) ETD49 wound with 2.24 mm wire, b) ETD34 wound with 1.4 mm wire; the arrow shows the short circuit in the secondary winding

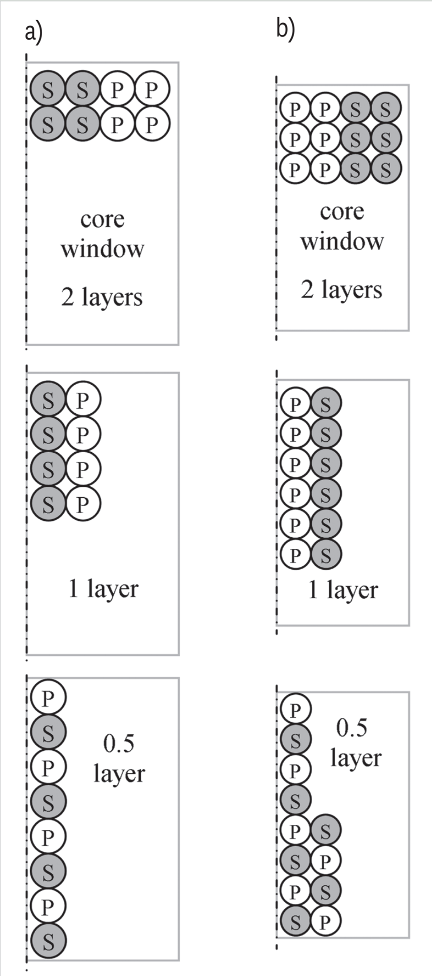

Figure 4. Winding configurations: a) for ETD49 with primary winding outside, b) for ETD34 with primary winding inside; drawings not to scale (P – primary, S – secondary)

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).

In both cases (the measurement and FEM) the elevated losses due to proximity effect at higher frequencies are clearly visible

Good grade of magnetically soft ferrite 3C90 was chosen. The estimated B in the core was at the level of µT, 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 µW).

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 µW. For ETD34 the primary winding had resistance of 4.66 mΩ, so the ideal loss should be 46.6 µW. 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 µW) for ETD49 and 10.6 mΩ (106 µW) for ETD34. At frequencies above 1 kHz the proximity effect increases the losses considerably.

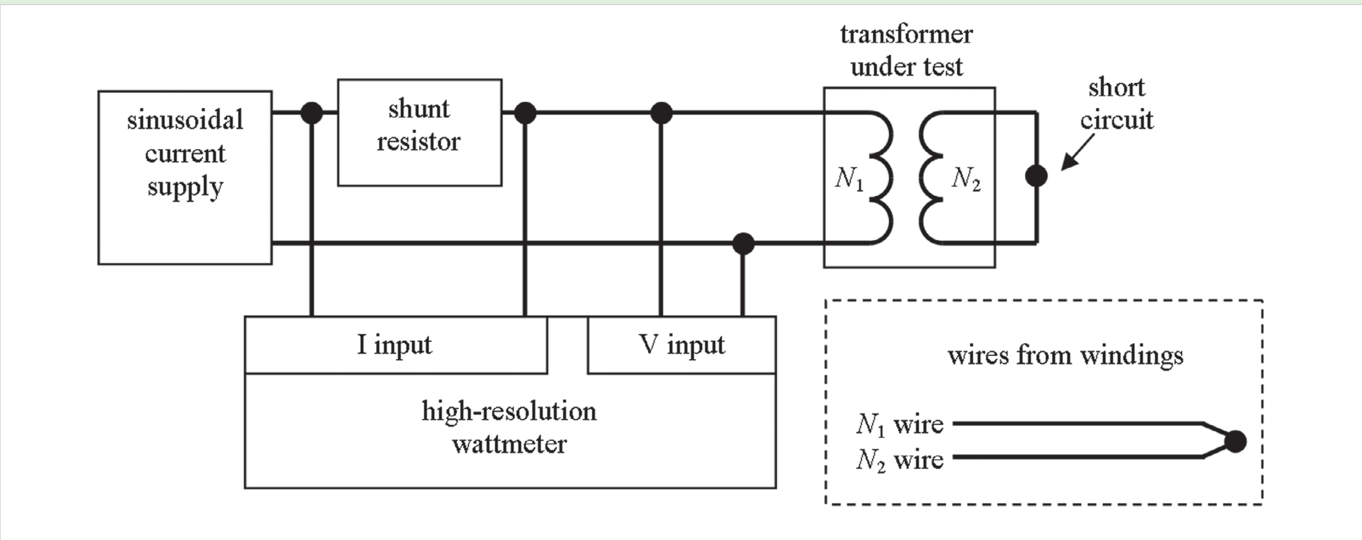

Figure 5. Block diagram of the experimental setup

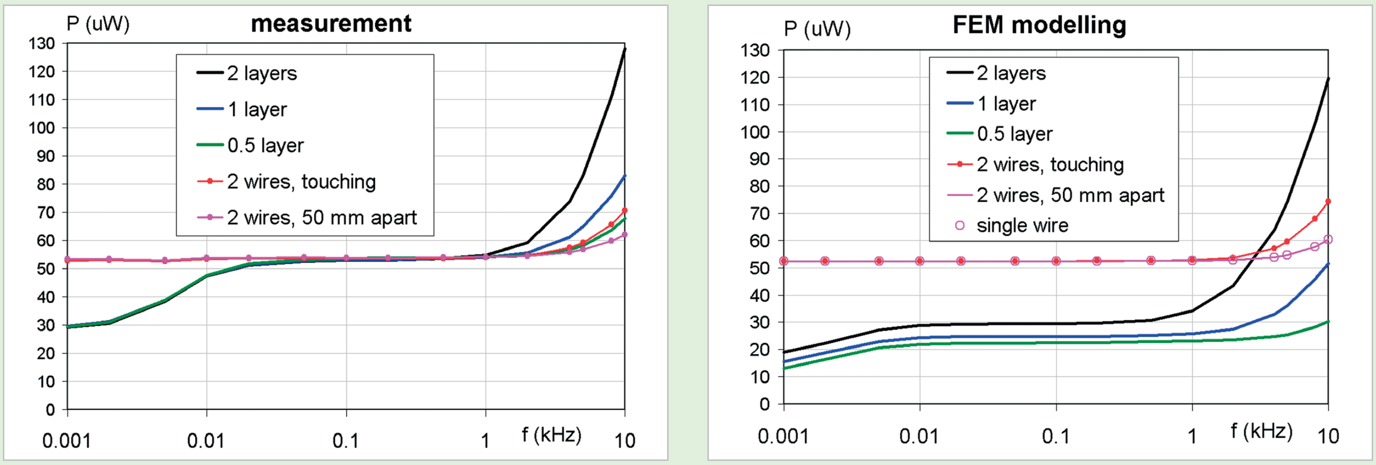

Figure 6. Comparison of absolute loss in μW for ETD49

However, for FEM curves the absolute losses are different from the measured values. This is a direct consequence of the fact that the FEM simulations did not take into account the resistance of the length of the wires outside of the transformer windings (i.e. the connections), and these were significant as compared to the resistance of the windings (see Fig. 3). Also, the additional length resulting from the fact that in reality the windings had to be "spiral" (because of the pitch of the wires) was not included in the simulations. Additionally, with each configuration from Fig. 4 the resistance of the modelled winding was changing, because, for instance, for "2 layers" the turns were longest due to the increased radius of winding. Therefore, the base resistance was highest for this configuration, as were the base losses (in the plateau), but still lower than the measurement due to the lack of loss in the connections.

In both cases (the measurement and FEM) the elevated losses due to proximity effect at high are clearly visible.

Nevertheless, both the measurement and simulations returned very close losses, in absolute terms, for measurement on straight wires (see also Fig. 5). For this FEM simulation, the planar 2D FEM was used (Fig. 1a) because it represented the modelled configuration very well (two long parallel wires, or a single long straight wire). The FEM results (Fig. 7) for a single wire exhibit elevated loss, due only to the skin effect – because there is no second wire to contribute to the proximity loss. On the other hand, in the worst case, the wires were touching in the experiment and this produced visible proximity loss. Similar results were obtained by spacing the wires by 0.5 mm in FEM (Fig. 7).

FEM simulations show that the losses are indeed slightly lower for 4 wires (and more) than for only 2 wires

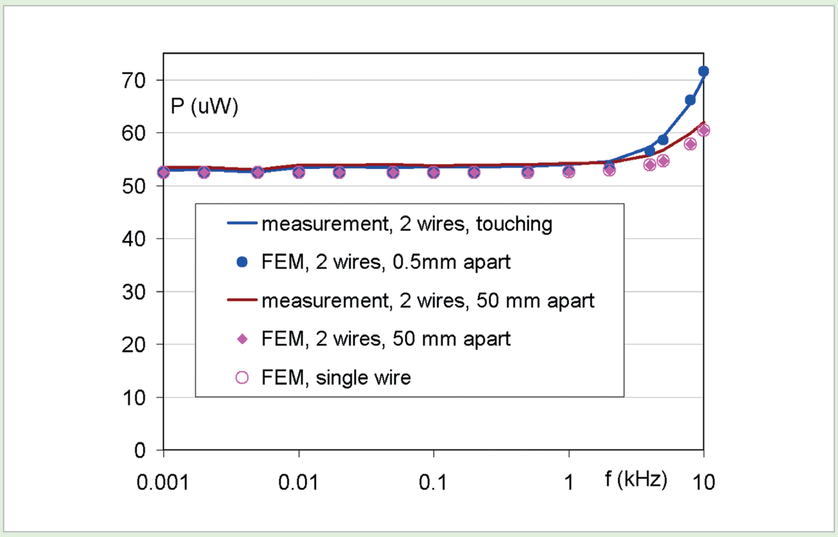

Figure 7. Comparison of absolute loss in μW for straight wires

Therefore, the absolute values for FEM calculations (Fig. 6) can be adjusted by adding the missing loss component for the connecting wires outside of the transformer. The loss dissipated in these connections will be equal to at least the loss in the comparable length of a single wire, with some increase at high frequency due to skin effect. Such correction was applied to the FEM values for both the ETD49 and ETD34 configurations and the results are shown in Fig. 8.

The proximity effect is clearly visible. For ETD49 at 10 kHz the loss for 2 layers is increased from 62.0 μW (just skin effect in separated wires) to 128 μW, which is more than double (+106 %). Changing to 1 layer reduced the loss to 83 μW (+34 %). Interestingly, the 0.5 layer configuration gave losses very close to the separated wires 67.8 μW, and this was a value slightly but noticeably lower (-4 %) than those measured for the bare wires touching 70.5 μW. This is probably the effect of several interleaved wires within one layer as this slightly modifies the proximity effect.

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

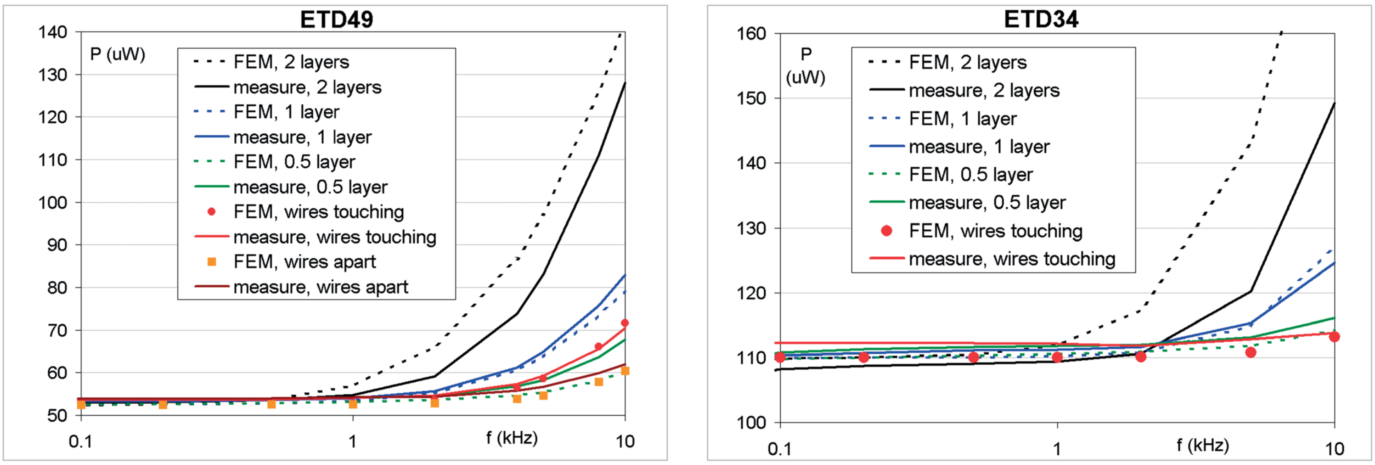

Figure 8. Comparison of measured and FEM estimated loss for ETD49 and ETD34

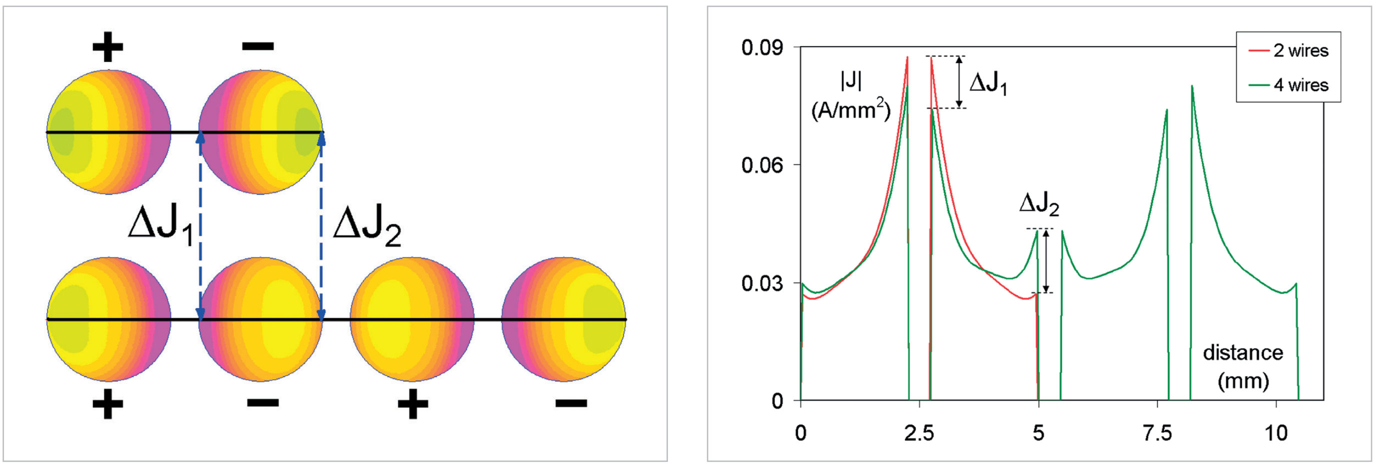

Figure 9. Proximity effect is slightly higher for 2 wires than for 4 wires (|J| – current density along the black lines); configuration with just 4 wires is shown for clarity

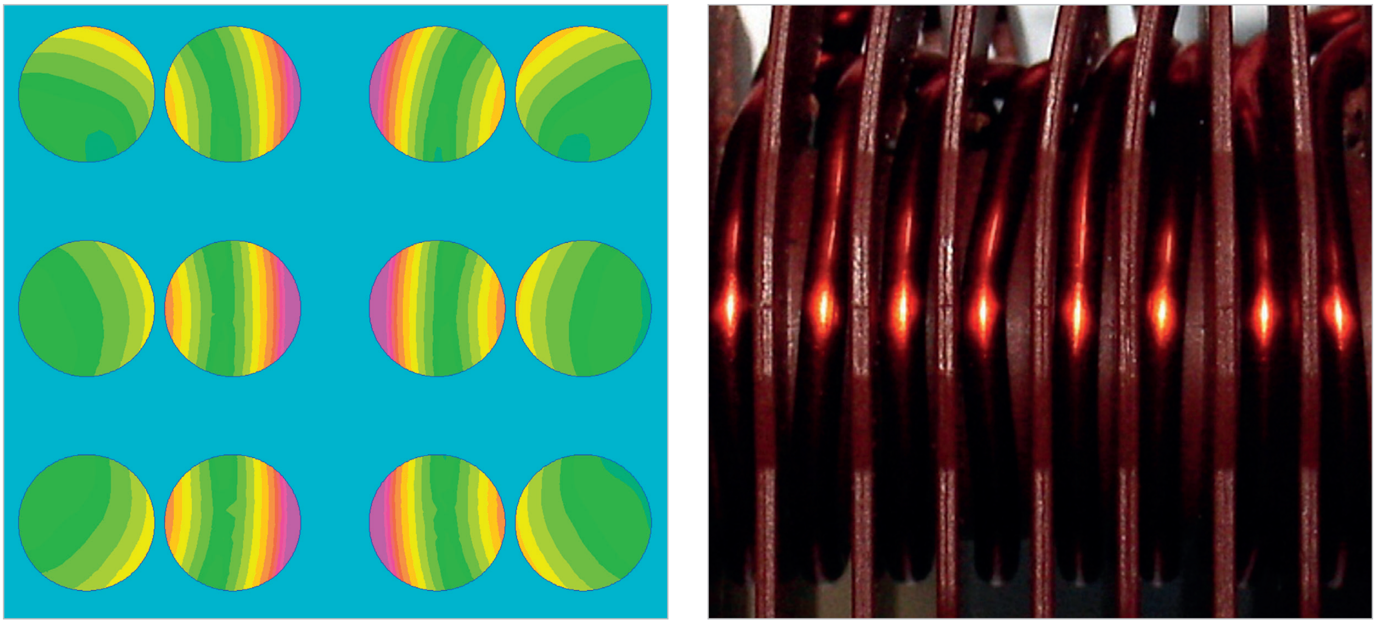

Figure 10. An example of simulated distribution of current density in ETD49 2-layer winding (see also Fig. 9) and a close-up of ETD34 prototype with 0.5 layer windings (see also Fig. 4).

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.

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