Improved AC-Resistance of Multiple Foil Windings by Varying Foil Thickness of Successive Layers

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Abstract-**A novel optimization strategy for planar inductor design, based on a per-layer approach for calculation of the optimal foil thickness is presented in this paper. Implementation of this strategy results in reduced ac- and dc-resistance of the winding. Inductor windings optimized for sinusoidal excitation were constructed and the resistance measured. Results are shown for air core inductors and the performance of the same windings in gapped magnetic cores is also reported. An optimisation technique for non-sinusoidal excitation is also proposed. Air gap proximity losses can be reduced by notching the winding in the region of the air gap. This technique combined with the newly proposed layer optimisation strategy is also investigated for a trapezoidal current waveform.**

I. INTRODUCTION

The main sources of thermal losses in magnetic component structures are core- and conduction losses, which limit the maximum attainable power density of converters [7]. Conduction losses are a direct result of increased ac-resistance at high frequencies subsequent to proximity and skin effects in the conductive medium. Work done up to the present moment is based on finding an optimum foil thickness with which the entire winding is constructed [1],[2],[6]. An alternative method is proposed in section II where each layer thickness is optimised for sinusoidal current excitation. An existing strategy for non-sinusoidal excitation is adapted in section III. Losses in gapped core inductors are caused by eddy currents being induced in conductors that are in close proximity of the air gap and can be reduced by shaping the winding in this region to avoid the fringing flux [5]. This concept is investigated in section IV.

II. PROPOSED ALTERNATIVE – SINUSOIDAL CURRENT

This work illustrates a method of reducing ac-resistance and dc-resistance by choosing optimal values of foil thickness for each layer in planar inductor windings. The manufacturing process is ideally suited to accommodate this technique since individual turns are prepared separately and then interconnected.

The optimization technique is based on the equation describing the ac-resistance of each layer in a winding section (1) based on its position (m) in the magnetic field and (3) and (4) can be used to calculate the optimal foil thickness (h_m) for these layers. (Δ = Foil thickness/Skin-depth = h/δ) The new method proposed is based on differentiating equation (1) for each layer of foil in a winding section. A general simplified equation (2) in terms of m can be written and solved to find the minimum and maximum points:

$$R_{acm} = R_{dcm}\frac{\Delta}{2}\left[\frac{\sinh\Delta + \sin\Delta}{\cosh\Delta - \cos\Delta} + (2m-1)^2\frac{\sinh\Delta - \sin\Delta}{\cosh\Delta + \cos\Delta}\right] \qquad (1)$$

$$m(m-1)[\cosh^2\Delta + \cos^2\Delta] - [2m(m-1)-1]\cosh\Delta\cos\Delta = 0 \qquad (2)$$

The solutions were all obtained using MATLAB. In order to prevent having to solve the equations for each layer a curve fitting technique (Nelder-Mead simplex algorithm) was employed using MATLAB, yielding the following general equation for calculating the coefficient C(m) and the optimal foil thickness for each layer using (3) and (4):

$$C(m) = 3.0785e^{-1.1056m} + 0.5737e^{-0.0523m} \qquad (3)$$

$$h_{opt}(m) = C(m)*\delta \qquad (4)$$

Fig. 1 shows a cross section of such a proposed planar inductor winding and the 1D-predictions calculated using the one-dimensional solutions proposed by Dowell [1] are shown in Fig. 2. The dc-resistance of the new structure reduces by 18% and the ac-resistance is 11.5% lower than that of the reference winding at 100kHz. The simulation values in this case were chosen based on availability of copper foils used to construct the actual windings.

A. *Air core inductors*

A planar air-core inductor optimized for 100kHz sinusoidal excitation and constructed according to the new strategy was compared to a similar inductor where the optimal foil thickness (0.133mm) for the entire winding was calculated and a standard 0.125mm foil size was used for construction of all the layers. Fig. 1 shows the foil sizes used for the new winding and Fig. 3 shows a photograph of the inductor. The resulting ac-resistance as a function of frequency was measured with an LCR-meter and is shown in Fig. 4. FEM 2-D simulations were also done at discrete frequencies to verify the experimental results. Reduction in the dc-resistance amounts to 18% and the ac-resistance at the design frequency of 100kHz is approximately 12.5%. This result was verified through calorimetric experiments.

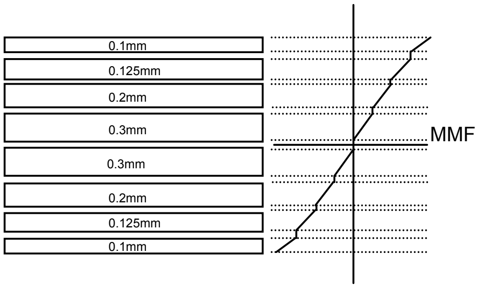

Fig. 1. Proposed 8-layer planar winding with associated mmf-diagram

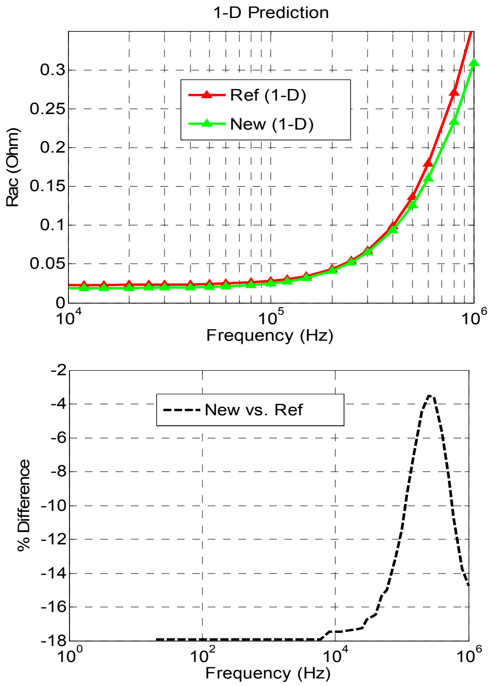

Fig.2: Predicted difference in ac-resistance of reference and new structure

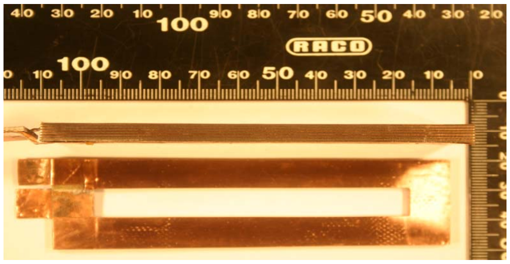

Fig. 3: Photograph of planar winding

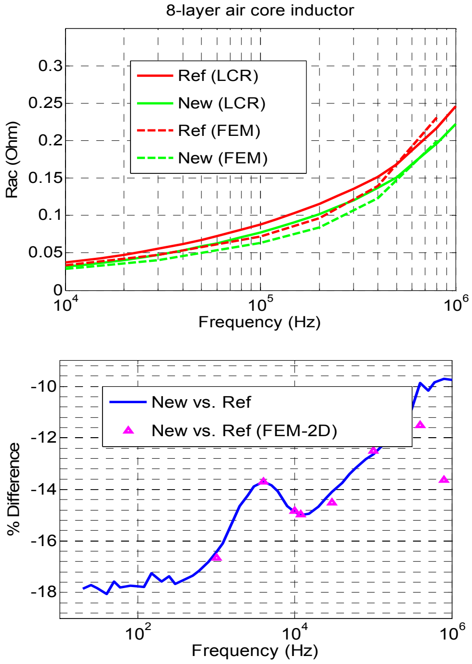

Fig. 4: Results for planar air core inductors

B. Gapped ferrite cores

The same windings were now inserted in gapped ferrite cores. Fig. 5 shows a photograph of the arrangement from the rear end. Spacers are used to align the centre turns with the air gap. The results for these inductors are shown in Fig. 6 and an up to 20% reduction in losses at the design frequency (100kHz) is predicted and verified with LCR-measurement and calorimetric experiments. Comparative measurements were obtained for two different cores and compare well with FEM 2-D simulation results.

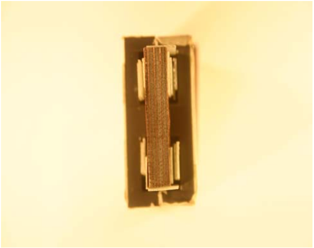

Fig. 5: Photograph of inductor assembly

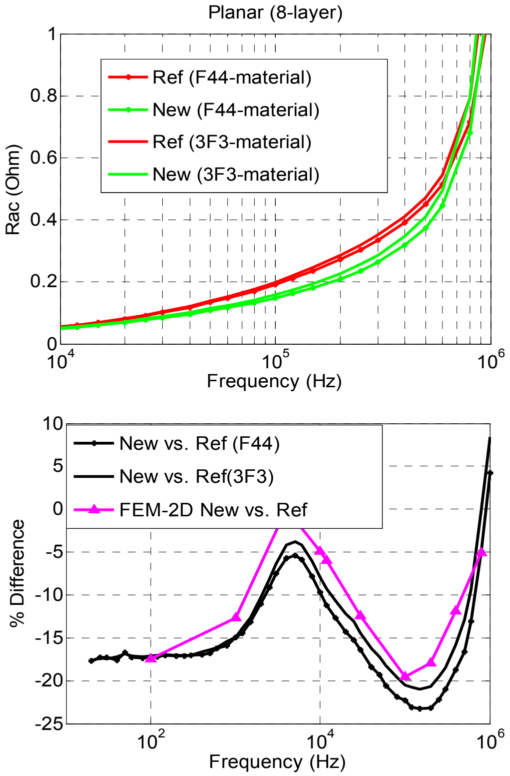

Fig. 6: Results for gapped ferrite core inductors

III. OPTIMISATION FOR NON-SINUSOIDAL CURRENT

An existing method proposed in [4] was adapted to optimise each layer individually for non-sinusoidal excitation. This method is based on the original Dowell equations for the total resistance of a p-layer winding section approximated by using series expansions for the trigonometric and hyperbolic functions in the total-resistance equation and only the rms-values of the current and its derivative are used instead of the Fourier coefficients.

The following equation is then derived for the optimal foil thickness (h) normalised to the skin depth (δ).

$$\Delta_{opt} = \frac{h}{\delta} = \frac{1}{\sqrt[4]{\psi}}\sqrt{\frac{\omega I_{rms}}{I'_{rms}}} \qquad (5)$$

where: $$\psi = \frac{5p^2 - 1}{15} \qquad (6)$$

I_{rms} is the rms-value of the resulting current, I'_{rms} the rms-value of the first derivative of the current, p is the total number of layers in a winding section and ω is the fundamental frequency.

This work uses the same basic equation as proposed in [4]. Equation (6) is adapted by performing a series expansion on equation (1), which describes the resistance of each layer in the winding section and yields (7).

$$\psi_m = \frac{60m^2 - 60m + 16}{60} \qquad (7)$$

Equations (5) and (7) can now be used to calculate the optimal foil thickness for each of the layers in the winding section.

Substituting I_{rms} and I'_{rms} for a 100kHz sinusoidal current waveform yields similar results for a 4-layer winding section to those obtained through the direct method using (3) and (4). Recall that availability of foils largely dictates the sizes used in the prototypes.

For waveforms containing a considerable dc-component it is suggested that the new calculated foil thickness only be used up to the point where the suggested value is lower than the reference foil thickness and the reference thickness used further on. This philosophy will prevent excessive increase in dc-resistance of specific turns causing localised power dissipation.

The effect of this technique on the loss-improvement was investigated for several different continuous and discontinuous current waveforms. Improvements of up to 26% were obtained in cases where windings were optimised for discontinuous triangular current waveforms. The additional amount of copper (36%) used in the new winding raised the question about the justifiability of the new technique in terms of cost. A winding shaping technique was considered next to minimise losses due to air –gap proximity and to investigate the effects when using different thickness layers.

IV. WINDINGS SHAPED IN THE REGION OF AIR GAP

The fringing effect in gapped core inductors cause excessive losses in conductors situated in close proximity to the gap. The winding can be shaped in this region and conductors arranged parallel to the flux patterns in order to minimise induced losses [5]. Fig. 7 illustrates the concept of notching the winding in the region of the air gap.

Circular notching was considered in [5] but proposed for solenoidal foil windings only. In this paper the technique is applied to planar foil windings. If the foil windings in structures are shaped in this manner the dc-resistance also increases and therefore a compromising optimum design has to be found considering both the dc- and the ac-loss components. The width of the center foils will be reduced in order to avoid the high flux density regions around the air gap. Since the newly proposed scheme results in thicker foils being used in the center of the winding it was decided to investigate the matter further.

Again different waveforms were considered and numerous simulations performed in order to find the application that best utilises the advantages offered when using varying foil sizes in the winding section.

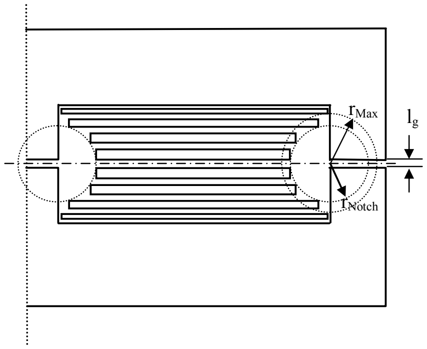

Fig. 7. Winding shaped in the region of air gap

Trapezoidal current waveforms like the one shown in fig. 8 have a dc-component and very high harmonic content.

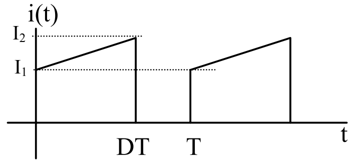

Fig. 8. Trapezoidal current waveform

An example of a specific simulation will now be discussed. Both the reference and the new winding were optimised for a frequency of 100kHz, a duty cycle of D=0.5, I_1=2.9A and I_2=3.7A. These values were specifically chosen to yield available thickness values in copper foil. The air gaps in the EE-core center and outer legs are 0.5mm and the insulation thickness between windings is 0.4mm. The reference winding comprises of 8 turns of 0.5mm copper foil and the new winding section starts with a 1mm copper plate in the middle, followed by a 0.625mm and two 0.5mm foils arranged similar to the layers shown in fig. 1.

The simulation current used is 1A peak and the simulation is performed at 10Hz to obtain the dc-resistance and harmonic frequencies up to 1MHz. The electromagnetic loss for each layer is calculated every time for the sinusoidal excitation at the particular frequency and the total losses calculated using the Fourier coefficients of the chosen current waveform. At first the windings are not notched and the loss values obtained are used as a reference set. The windings are now notched incrementally in the simulation and all results are compared to the reference set. The notching process is normally done intuitively in incremental steps until the minimum loss point is obtained. Solutions that converge much quicker are currently being developed.

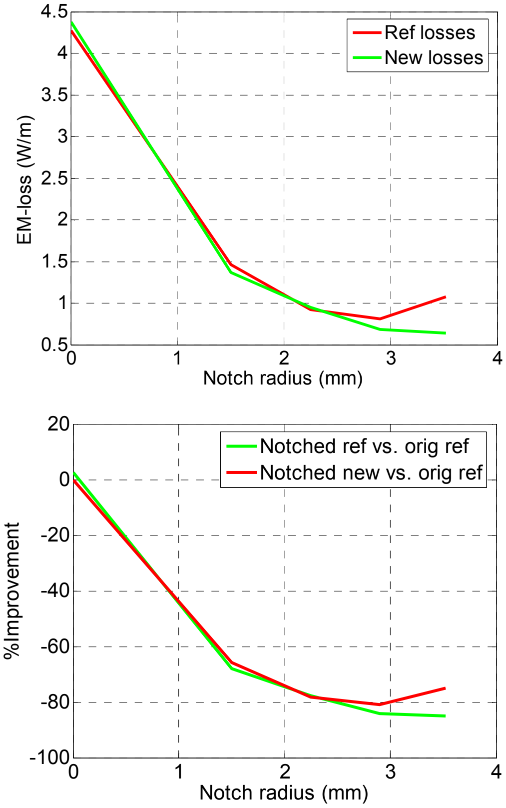

Fig. 9: EM-loss comparison

In case of this particular example both the reference winding and the new winding optimal notch radius turned out to be the maximum possible value (r_{Max}) before altering the width of the outer most turns. The notch radius was equal to 2.9mm for the reference winding and 3.52mm for the new winding. Consider the graphs in fig. 9 for the results. The fact that the new winding can be notched further than the reference winding results in effectively only 10.8% more copper being used compared to the notched reference winding. The new winding notched to the optimum point however displays a 21.4% improvement when compared to the reference winding notched to its optimum point. Compared to a reference winding which is not notched the notched reference winding has a loss reduction of 81% and the new winding 85%. For the physical windings parallel foils had to be used in order to obtain the design thickness. It was decided to insulate these parallel layers in the region of the air gap because the lamination effect should further reduce the losses. Simulations were again performed using the laminated layers and the loss prediction for the new winding indeed showed an improvement of 29% (vs. 21.4%) with respect to the notched reference. Windings were constructed and the resistance measured at different frequencies using an LCR-meter. The loss calculation through the Fourier coefficients shows an improvement of 24% when comparing the two notched windings and the overall improvement compared to a reference winding which is not notched is 78% (vs. 81% simulated) for a notched reference and 81% (vs. 86.5% simulated with laminated turns) for a notched winding comprising layers of different thickness. A concern at this point is the alignment of the various layers in the stack resulting in a notch shape, which is not circular and the manufacturing technique is being altered to obtain a better result.

The trapezoidal current waveform is typical of a continuous-mode fly-back converter topology. Generating this current waveform to characterise the behaviour of the inductors designed is the next step towards performing the calorimetric experiments for verification of these results.

V. CONCLUSIONS

The proposed scheme of optimising the foil thickness of individual layers proves to reduce both ac- and dc-resistance. An existing optimisation technique used for non-sinusoidal current profiles was successfully adapted to suit this new method. The improvement in losses was investigated for various waveforms combined with the notching technique described and best results were obtained for trapezoidal waveforms where it is expected that the additional amount of copper used could be justified by the percentage improvement in losses obtained in the process. The manufacturing process has to be altered to achieve better alignment and the results have to be confirmed with higher levels of excitation.

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