Transformer Winding Design Using Finite Element Modeling

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Abstract— **In this paper design and fabrication of a ferrite core based high frequency power transformers was considered. The primary aim of the work was to study and minimize winding losses in the transformers for power converter applications. The second aim of the work was to study improved winding methods for disc-type planar high frequency power transformers with copper foil windings. Methodology for an optimal choice of the foil thickness and foil arrangement was proposed.**

I. Introduction

Power transformers are usually considered the bulkiest and the most expensive components in the switched mode power supplies. They are critical for power converter performance, such as dynamic response, efficiency and electromagnetic interference. Ready made power transformers are seldom available so that they must be described and designed during the converter design process. High frequency (>>50Hz, typically 1kHz - 1MHz) power transformer design, including loss analysis, has attained considerable attention in literature. For example, core losses have been modelled using Steinmetz equation [1], additional harmonic analysis and form factor correction [2], while winding losses have been modelled using DC-resistance, analytical expressions for the winding AC resistance (Rac/Rdc) [3] or Finite Element Method (FEM) derived winding AC resistance [4]. The accuracy of the proposed design method needs yet to be judged by experimental verification of the data.

Solid wire winding is commonly used winding, but in high frequency power conversion, due to skin effect and proximity effect, eddy current losses become critical. Winding losses can be reduced using *litz wire* winding [5], but this increases material and manufacturing costs. Interleaving between primary and secondary windings can help, but this also makes manufacturing process more complicated. Eddy currents can be minimized and high frequency winding losses can be reduced using *foil conductors* [6].

Foil (plate) conductors have potential for higher copper fill factor compared to litz wire. Foil windings are usually combined with low profile (planar) ferrite cores. The popular way of foil windings implementation is by use of multilayer printed circuit board (PCB) traces. Unfortunately, the copper fill factor of a standard FR4 glass epoxy plate based PCB is quite low (typ. 0.2 - 0.3). This is particularly true due to the low standard copper foil thicknesses (35µm and 70µm). For intermediate frequencies it is not necessary to use very thin foils. Stacked copper stampings with thicker copper plates can be used for producing a high fill factor copper planar winding [7].

The optimum foil (plate) conductor thickness selection is considered in this paper. Finite element modelling approach is used to calculate winding losses at the frequencies of interest. For specified thicknesses and arrangements, the frequency limit is established for which the winding losses are doubled, compared to the DC and the low frequency losses.

II. Model Description

3D finite element analysis was used to take into account both the conductor losses inside the core window and the external winding losses. Due to a PC hardware and software capabilities nowadays, the structures with a small number of turns, like the ones considered here, can be analyzed in minutes.

In order to compare losses for several winding arrangements, all calculations were done on windings placed on standard EE64/10/50 type ferrite cores, manufactured by Ferroxcube (Fig.1). The core is suitable for medium power and medium frequency applications. Similar analysis is applicable for any other core.

The core losses were not analyzed in this paper. Linear ferrite material was assumed with a constant relative permeability μ_r=1000.

The first step in the finite element analysis was to verify that the current distribution in the primary and secondary windings, assuming linear magnetic material for the core, is independent of the secondary load. Taking this into account, the analyses of the winding loss dependence on the copper sheets thickness could be simplified - the transformer secondary could be short circuited.

In order to analyze the effect of different loading conditions, a one turn primary and a one turn secondary

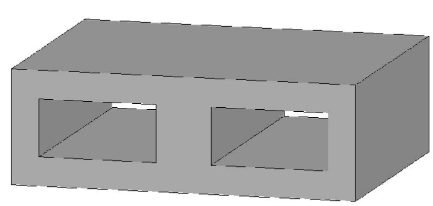

Fig. 1. Low profile (planar) ferrite core EE 64/10/50 manufactured by Ferroxcube Co.

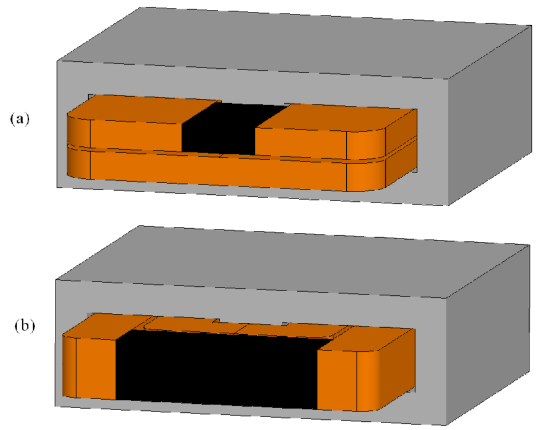

Fig. 2. Two arrangements considered: a) horizontal division of the core window, b) vertical division of the core window.

was implemented on the core. The copper turns occupied almost the entire window in order to obtain a large copper fill factor (Fig. 2). Two arrangements were analyzed: the first, with a horizontal division of the core window, and the second with a vertical division of the window. Winding cross sections for the primary and the secondary were the same and equal to $90mm^2$, for both winding arrangements. The black boxes in Fig. 2 represent the load made of a high resistance material, connected to the secondary. The primary was excited by a sinusoidal current source implemented in the perpendicular cross section of the primary. The average RMS primary current density was set to $5A/mm^2$ in all analyses.

Winding losses were calculated using finite element analysis at several frequencies (100Hz, 1kHz, 10kHz) and for several load resistances. The same was repeated both for the horizontal and the vertical arrangement. The dependence of the loss on the specific resistance of the load material is shown in Figs. 3 and 4. The winding losses are almost independent of the load resistance in both arrangements. Only at very low frequencies and very large load resistances, the secondary winding loss decreased and the large part of the primary current was used for the core magnetization. Due to this phenomenon the secondary current fell significantly. Consequently, so did the losses calculated for the short circuited secondary windings. The appropriate losses will be presented in Section III as the losses of the loaded transformer windings.

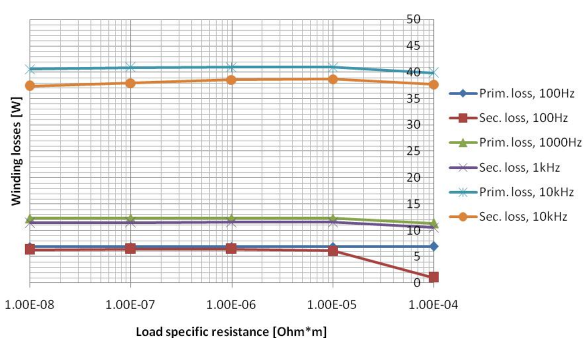

Fig. 3. Horizontal arrangement winding losses versus specific resistance of the load material at some frequencies.

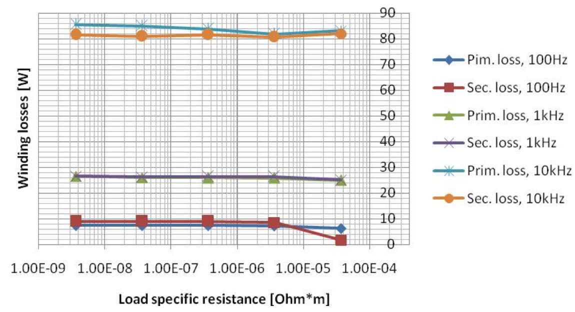

Fig. 4. Vertical arrangement winding losses versus specific resistance of the load material at some frequencies.

III. Simulation Results

The objective of the numerical simulations was to find the appropriate winding arrangement and the plate conductor thickness for a specified excitation frequency. To achieve that, we considered different arrangements and calculated winding losses for several frequencies, starting from the low frequency of 100Hz. The frequency at which the winding losses doubled, compared to the losses at the low frequency, can be considered the limit for the particular arrangement.

For higher excitation frequencies smaller copper plate thickness could be defined by appropriate partition of the winding area. The loss calculations need to be repeated for the new arrangements. By iterative procedure the optimal plate thickness could be found for the frequency of interest.

A. One turn primary - one turn secondary transformer

To illustrate the described procedure, the losses were calculated for the one turn primary - one turn secondary arrangements (horizontal and vertical) given in Section II, but with the secondary short circuited (Fig. 5).

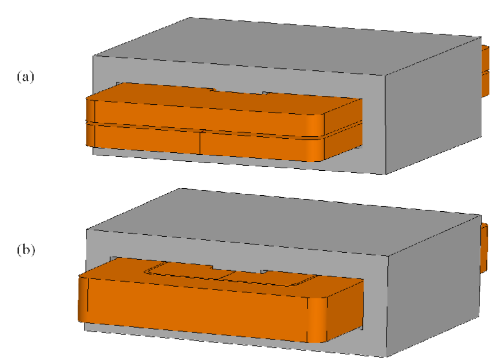

Fig. 5. One turn primary - one turn secondary arrangements from Fig. 2, but with the secondary shorted: a) horizontal division of the core window, b) vertical division of the core window.

The frequency dependence of the primary losses is presented in Figs. 6. and 7. The upper frequency limit for the vertical arrangement was found to be around 300Hz. The horizontal arrangement gave better results. Maximal usable frequency was found to be 1300Hz. These values are quite low due to the large winding thicknesses.

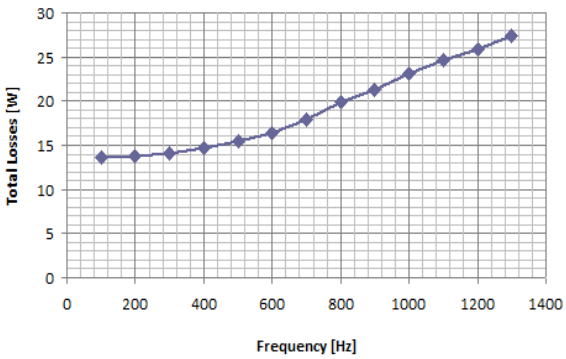

Fig. 6. Frequency dependence of the total winding losses for the one turn primary - one turn secondary horizontal arrangement.

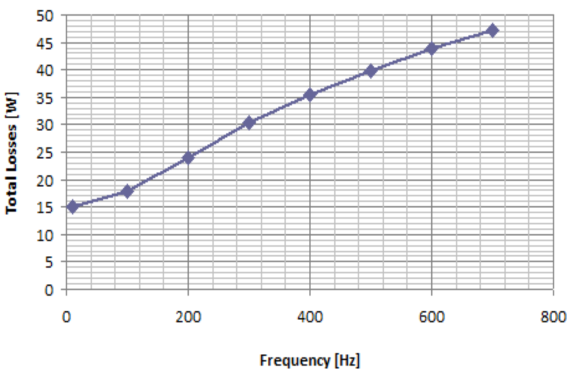

Fig. 7. Frequency dependence of the total winding losses for the one turn primary - one turn secondary vertical arrangement.

B. *Two turns primary - two turns secondary transformer*

The procedure was repeated for the two turns primary - two turns secondary arrangements shown in Fig. 8. The total number of the possible winding arrangements was higher accordingly and we could address interleaving of the windings. Three substantially different schemes were possible: one without interleaving (P1-P2-S1-S2), and two with interleaving (P1-S1-P2-S2, P1-S1-S2-P2).

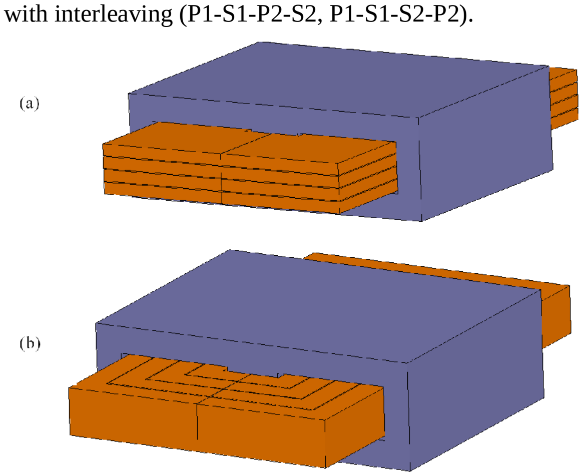

Fig. 8. Two-turn arrangements considered: a) horizontal division of the core window, b) vertical division of the core window.

Frequency dependence of the total winding losses for the horizontal arrangement is shown in Fig. 9. The winding losses are same for all arrangements at the low frequencies. As the frequency goes up, the losses in the non-interleaved (P1P2S1S2) arrangement increase rapidly. The interleaved arrangement P1S1P2S2 gave much better results. Accordingly, this winding could be reasonably used up to 9kHz.

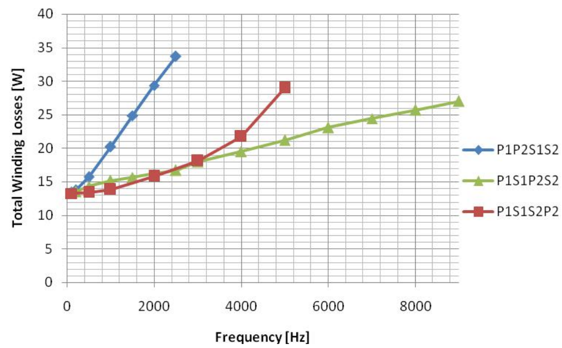

Fig. 9. Frequency dependence of total winding losses for the two turn primary - two turn secondary *horizontal* arrangement.

Frequency dependence of the total winding losses for the vertical arrangement is shown in Fig. 10. The winding losses are same for all arrangements considered at the low frequencies. As the frequency increased, the losses in the non-interleaved (P1P2S1S2) arrangement increased very quickly. The interleaved arrangement P1S1P2S2 gave the best results. Consequently, this winding could be reasonably used up to 3kHz.

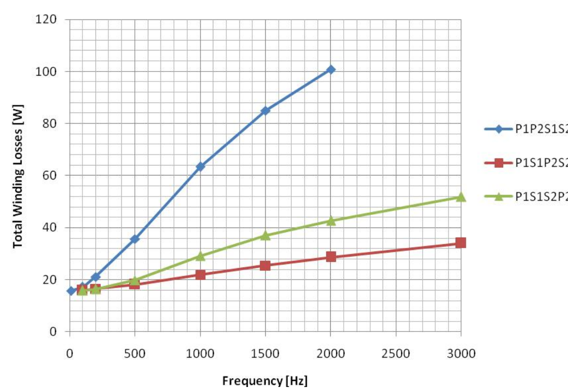

Fig. 10. Frequency dependence of the total winding losses for the two turns primary - two turns secondary *vertical* arrangement.

IV. Summary and Discussion

A methodology based on finite element analysis is presented for planar transformer winding sheet thickness and arrangement selection. As the first step, the current distribution was tested at the representative frequencies and for several loading conditions. The current distribution was found almost independent on the transformer loading. This justified the adopted procedure to explore any winding arrangement with a short circuited secondary winding.

Comparison between the different winding sheet thicknesses and arrangements was possible based on the total ohmic losses. The finite element analysis results were in a good agreement with the results available in literature [7], where the reduced conductor thickness and interleaving of the primary and the secondary windings decreased the overall winding losses.

The frequency limits obtained are quite low but by division of the core window to more sections and by use of smaller plate thicknesses, the usual frequency range of converter transformers could be achieved. Low number of turns and unusual plate thicknesses are considered to simplify the finite element analysis procedure.

Future work should explore the losses of the ferrite core, both for a linear and nonlinear model.

Acknowledgment

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