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2D finite-element determination of tank wall losses in pad-mounted transformers

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Abstract

This paper presents a two-dimensional (2D) finite-element (FE) analysis of losses generated in the tank wall surrounding the high-current bushings of pad-mounted transformers. Although the problem is truly three-dimensional (3D), it is shown that a 2D approach gives results that closely agree with 3D simulations and experimental results. Thus, it is possible to avoid the very demanding computational resources required for 3D modeling or the cost of experiments. Nine cases are analyzed to study the impact of inserting small plates of different geometry (located near the high-current terminals) on the reduction of tank losses. Significant reductions in stray losses on the tank wall are obtained with low-cost plate inserts. 2D and 3D time-harmonic FE models are used to determine the losses in the tank wall. Two load loss tests were carried out on experimental transformers to validate the simulations.

Keywords: Stray transformer losses; Tank wall losses; Low-voltage conductor; Pad-mounted transformer; Stainless-steel plate; Finite element method

1. Introduction

Tank wall losses due to high eddy currents near the low-voltage bushings in distribution transformers have received relatively little attention. A few papers have been published on the subject [1–6]. Recently we have reviewed those contributions and proposed the use of small inserts in the tank as an economical alternative to reduce this kind of losses [7]. In that work, the experimental study was complemented with three-dimensional finite-element (3D FE) analyses to estimate the loss reduction due to the inserts. The calculated value of losses using 3D FE analyses is in very close agreement with the experimental results. However, the computational resources demanded by 3D FE models are enormous, requiring hours of computational time. On the other hand, 2D models require modest computer resources, as the model requires many elements only in regions where the magnetic field changes rapidly and in zones where the penetration of eddy currents is small. In this paper we show that even though the field distribution is not planar, 2D analyses can be used to estimate the loss reduction due to the inserts in the tank.

The electromagnetic field distribution in the region near the low-voltage bushings is truly of a 3D nature. The eddy currents in the tank wall are not only in the same direction (axial) as the currents in the conductors, but there is also an important transversal (radial) component. This is because the tank wall is only a few millimeters thick and thus the eddy currents close themselves following a radial path preferably. This phenomenon has been clearly observed in numerical simulations [7]. When comparing the absolute eddy losses calculated with 2D and 3D FE analyses, the former are several orders of magnitude smaller than the latter. However, the loss reduction due to the small inserts proposed in [7] can be properly estimated using cost-effective 2D FE analyses. The validity of this statement is based on the comparison of 2D and 3D results, showing that 2D FE models can

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be used to estimate the loss reduction due to plate inserts placed near the low-voltage conductors of the transformer. It is important to notice that the 3D model has been validated using test results [7].

Thus, this paper shows the application of a 2D FE approach to estimate the stray losses on tank walls in distribution transformers. Since the 2D approach is computationally efficient and easily implemented, it has been possible to analyze several cases of metallic inserts of different geometry and material. The numerical approach taken in this work assumes that the stray magnetic field is nearly planar with linear behavior. We also assume that the transformer currents are perfectly sinusoidal, so that the electromagnetic equations can be solved in the frequency domain.

2. 2D electromagnetic background

We briefly review the essentials of 2D electromagnetic modeling, including the equations, excitations and boundary conditions used to set up the eddy current problem. When current densities are perpendicular to the plane, the magnetic vector potential can be described by [8]:

$$-\nabla^2 A_z + \mu\sigma \frac{\partial A_z}{\partial t} = \mu J_{sz} \qquad (1)$$

where μ is the permeability and σ is the electric conductivity. A_z is the axially directed magnetic vector potential and J_{sz} is the dc source current density within the conductors. It is important to note that this dc current density is the current distribution that would exist, if eddy currents were absent. The total current density in a conductor depends on this value and the induced eddy currents. Several conducting regions may exist in a problem. The materials for an FE model can be: non-conducting, stranded conductors, and massive conductors. The governing equations for each case are as follows:

(a) Non-conducting regions (such as air): these regions are governed by the Laplace equation:

$$\nabla^2 A_z = 0 \qquad (2)$$

(b) Stranded conductors (such as machine windings): these regions are governed by the Poisson equation:

$$-\nabla^2 A_z = \mu J_{sz} \qquad (3)$$

It is assumed that conductors have a very small diameter, so that eddy currents are negligible. The distribution of J_{sz} is known a priori.

(c) Massive conductors: Eq. (1) holds for this kind of regions. However, additional constrains may be required depending upon the type of problem. For problems where the total current of the conductor is known, but its distribution is unknown, it is necessary to include the following constraint:

$$\int_S \sigma \left(E_a - \frac{\partial A_z}{\partial t} \right) dS = I_{tot} \qquad (4)$$

and J_{sz} in Eq. (1) is given by:

$$J_{sz} = \sigma E_a \qquad (5)$$

where E_a is the voltage gradient applied to the massive conductor. Here, E_a is unknown whereas I_{tot} is known. This is the 2D formulation used for massive conductors analyzed in this work.

The transformer walls are modeled by assuming that eddy currents can return at infinity. This is equivalent to saying that the far and near ends of the massive conductor are short-circuited at infinity. The total eddy current I_{eddy} is simply calculated as [8]:

$$-\int_S \sigma \frac{\partial A_z}{\partial t} dS = I_{eddy} \qquad (6)$$

It is important to emphasize that for sinusoidal steady-state conditions the problem can be easily formulated by substituting $j\omega$ for $\partial/\partial t$ and treating each electromagnetic variable in the previous equations as a phasor [9].

3. 2D and 3D simulations

A 3D FE model of the transformer analyzed in this work was set up and validated in [7]. The results of the FE model with and without a T non-magnetic insert are given in Table 1 (third and fourth rows, see [7] for more details). The results of the experimentally validated 3D model will be used as reference values in this work. Fig. 1 depicts the outline of the tank wall, which shows the T plate used for reduction of losses. The circles represent the low and high-voltage phase conductors. The rated currents in the low and high-voltage conductors for the transformer are, respectively:

$$\begin{aligned} I_{X1} &= 590.49\,\text{A} \\ I_{H1} &= 5.65\,\text{A} \end{aligned} \qquad (7)$$

The plate is 6.35 mm thick. The material conductivities are as follows: 1.03×10^7 S/m for the ASTM A36 steel, 1.1×10^6 S/m for the stainless steel and 5.7×10^7 S/m for the copper. Two types of 2D FE simulations were performed in this work: (a) simulations with plate and (b) without plate. Fig. 2 shows the FE mesh used during the simulations, where the magnetic vector potential was set to zero in the outer

Table 1
Tank losses with and without stainless steel T plate

Simulation	Tank wall losses (W)	T plate losses (W)	Total losses (W)
With stainless steel T plate (2D)	6.8E−3	0.286	0.293
Without stainless steel T plate (2D)	13.43	–	13.43
With stainless steel T plate (3D)	7.97	0.14	8.11
Without stainless steel T plate (3D)	170.71	–	170.71

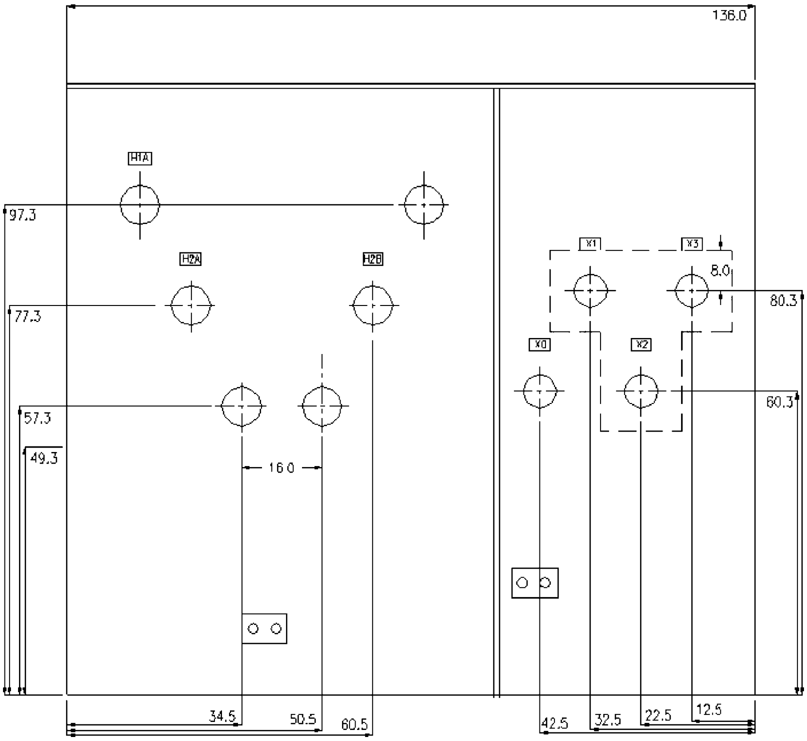

Fig. 1. Plate outline (letter X for low-voltage side and letter H for high-voltage side).

rectangle as a prescribed/Dirichlet boundary condition. A commercial FE software (MEGA V6.1 [10]) was used to perform the simulations shown in this paper. It is also important to mention that several meshes (with fewer elements) were used to calculate the losses. The purpose was to find the best mesh that could accurately model the small skin depth in the conductors. It was found that coarser meshes lead to erroneous results, whereas the mesh of Fig. 2 gives results consistent with experiments. Finer meshes did not give noticeable different results.

Constant relative permeabilities of 100 and 1 are assumed for the ASTM A36 and stainless steel, respectively, whereas a frequency of 60 Hz was set up during the simulations. The results of the calculations are shown in Table 1 (first and second rows). Figs. 3 and 4 show the magnetic vector potential distribution for tank walls ‘with’ and ‘without’ stainless

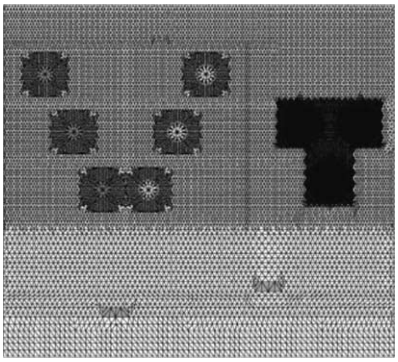

Fig. 2. 2D FE mesh: 73,396 elements and 36,884 nodes.

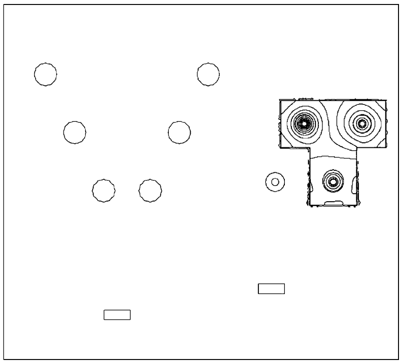

Fig. 3. Contours with stainless T plate; $\mu_r = 100$ on the tank wall and $\mu_r = 1$ on the stainless steel T plate.

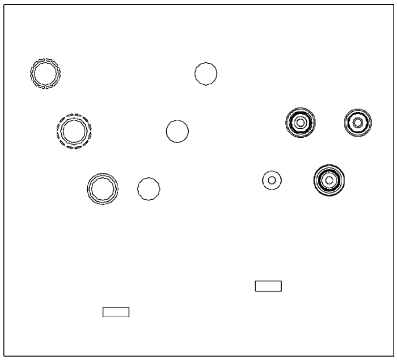

Fig. 4. Contours without stainless steel T plate; $\mu_r = 100$ on the tank wall.

Table 2
Percent reduction in load loss with stainless steel plate

	%
3D model	97.81
2D model	95.25

steel T plate. It can be clearly seen from Table 1 that the 2D FE model gives results that depart from the 3D approach by several orders of magnitude. The reason is that the magnetic field is not planar and appreciable eddy currents, circulating in the *x* and *y* directions, are completely neglected.

It could be concluded at this point that 2D formulations must be avoided in this sort of applications. However, note that the percent loss reduction (97.8%, see also Table 2) obtained from the 3D approach matches well the percentage value (95.25%) given by the 2D FE technique. This interesting result could lead to the conclusion that 2D FE models, for this particular problem, are still useful for predicting the percentage reduction of losses with different insert geometries.

A different geometry (see Fig. 5) with different excitations was used to verify this statement. Experimental results also exist for this geometry, leading to the validation of 3D FE simulations [11]. Fig. 5 shows the geometry and the eddy current distribution for a 3D FE analysis for the case that considers rectangular inserts near the conductors, whereas Fig. 6 shows the eddy current distribution for a 2D FE approach (see Section 2). Table 3 gives the plate losses for both the 3D and 2D cases and the 'with' and 'without' insert situations. It can be seen again from the results that the 2D case underestimates the losses by several orders of magnitude. However, the percent loss reduction (73.63%) obtained from the 3D approach matches well the percentage value (67.47%) given by the 2D FE technique. This indicates that a 2D FE approach is able to predict the percentage loss reduction due to the placement of inserts near the transformer low-voltage conductors with reasonable accuracy. Hence, easy-to-implement 2D FE techniques can be used in this type of specific problem, despite the fact that the eddy currents induced in the tank wall are not confined to just one direction. As a result, several plate insert configurations can be readily analyzed without resorting to demanding (and usually to very difficult to implement) 3D FE models. The next section shows the results of applying the 2D FE approach described here to study the reduction of losses produced by diverse plate insert configurations.

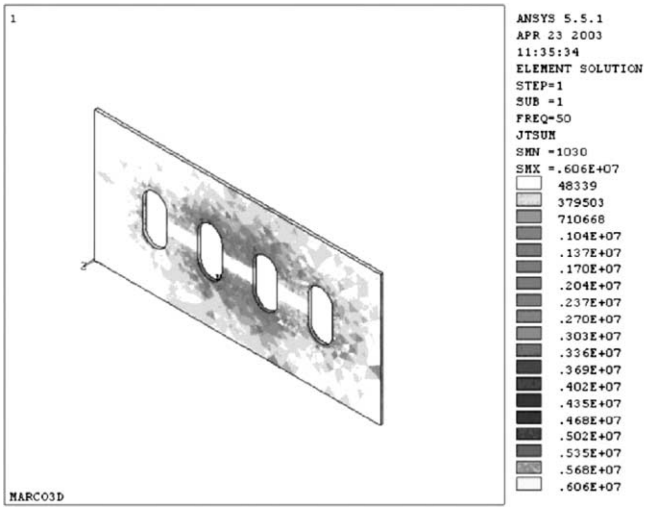

Fig. 5. Geometry of a different plate and 3D eddy current density distribution.

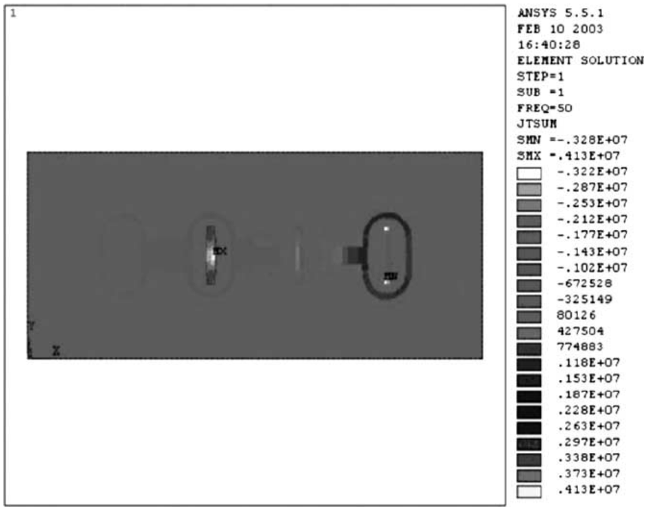

Fig. 6. Eddy current density distribution for 2D case.

Table 3
Tank losses with and without stainless steel insert for the model of Figs. 5 and 6

Simulation	Tank wall losses (W)	Insert losses (W)	Total losses (W)
With stainless steel insert (2D)	7.5	3.33	10.85
Without stainless steel insert (2D)	33.36	–	33.36
With stainless steel insert (3D)	136.28	8.09E−2	136.36
Without stainless steel insert (3D)	517.22		517.22

4. Reduction of tank wall losses with plate inserts

The main objective of these simulations is to show that a substantial reduction of load losses can be achieved with smaller plate inserts of different geometry and material. The following nine cases are analyzed. Case 1: Tank wall with stainless steel T plate; Case 2: Tank wall without stainless steel T plate; Case 3: Tank wall with three small squared plates in each phase; Case 4: Tank wall with three small triangular plates in each phase; Case 5: Tank wall with only one triangular plate; Case 6: Tank wall with triangular frame

Table 4
Total wall losses using $\mu_r = 100$ and $\mu_r = 1$ for carbon steel and stainless steel, respectively

Case	Tank wall losses (W)	Plate losses (W)	Total wall losses (W)
1	5.87	34.45	40.32
2	242.95	–	242.95
3	28.17	57.25	85.42
4	26.55	48.18	74.73
5	216.79	1.12	217.91
6	227.46	1.031	228.49
7	49.9	1.9×10^{-14}	49.9
8	6.37	37.03	43.40
9	261.38	–	261.38

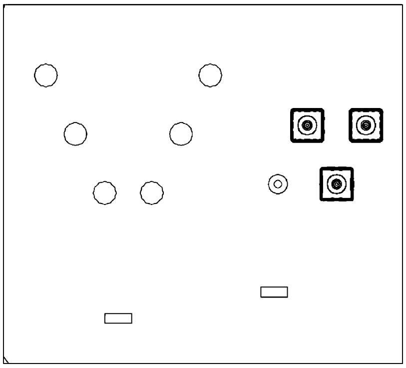

Fig. 7. Tank wall with three small squared plates in each phase (Case 3).

plate; Case 7: Tank wall with bakelite T plate; Case 8: Tank wall with stainless steel T plate taking into account current unbalance; Case 9: Tank wall without stainless steel T plate taking into account current unbalance. Table 4 shows the results of the FE simulations for the nine cases, where total tank wall losses are presented. The calculations were performed by setting the neutral current to zero. Figs. 7–11 show the calculated magnetic flux distribution for Cases 3–7.

It can be seen that the reduction of losses for all cases is not as large as in the case of the T plate case, but a trade-off may be necessary in some situations. For instance, it could be important to reduce losses, but it is also necessary to keep manufacturing costs low at the same time. As a result, the T configuration analyzed in this work reduces the losses more than any other arrangement, but the cost of the transformer unit is also higher. The importance of reducing losses can be very important for some situations, such as in distribution of bulk electrical power, but a low price of transformer units can be more meaningful for small industrial applications.

Finally, the reduction of losses with plate inserts is further illustrated with experimental results to also show the tendency of losses with respect to transformer rating. Table 5 shows the calculation of tank losses of two transformers: 150 and 300 kVA. The difference of losses between the cases with and without stainless steel T plate is 90 and 360.2 W, respectively. This shows that the insertion of plates becomes more necessary as the transformer rating increases.

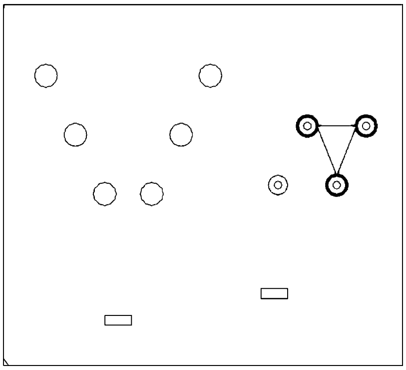

Fig. 9. Tank wall with only one triangular plate (Case 5).

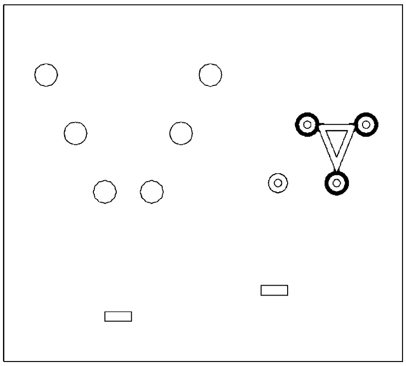

Fig. 10. Tank wall with triangular frame plate (Case 6).

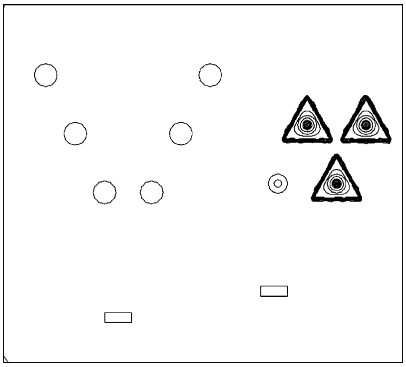

Fig. 8. Tank wall with three small triangular plates in each phase (Case 4).

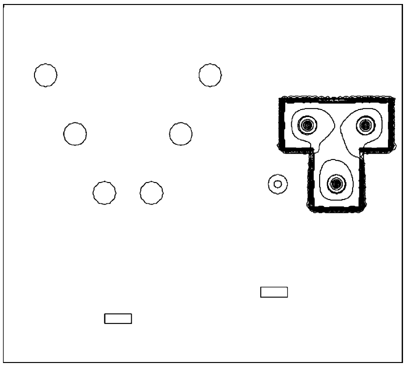

Fig. 11. Tank wall with bakelite T plate (Case 7).

Table 5
Tank losses of 150 and 300 kVA transformers

Case	Tank wall losses (W)	Stainless steel plate losses (W)	Total losses (W)
300 kVA transformer with T plate	10.4	61.3	71.7
300 kVA transformer, no T plate	431.9	–	431.9
150 kVA transformer with T plate	2.6	15.3	17.9
150 kVA transformer, no T plate	107.9	–	107.9

5. Present worth analysis

In this section we present the cost–benefit analysis of using stainless steel plates in a 225 kVA transformer. Assuming an annual loss factor of 0.35 the average power loss savings (APLS) are [12]:

$$\begin{aligned}\text{APLS} &= (\text{Power loss saving at peak load} \\ &\quad \times \text{annual loss factor}) \\ \text{APLS} &= (202.63\,\text{W})(0.35) = 70.9\,\text{W}\end{aligned} \tag{8}$$

And the total annual energy loss savings (TAELS) are:

$$\begin{aligned}\text{TAELS} &= (\text{APLS})(8760\,\text{h per year})(\text{US}\,\$\,0.06739) \\ \text{TAELS} &= (70.9\,\text{W})(8760\,\text{h per year}) \\ &\quad (\text{US}\,\$\,0.06739/\text{kWh}) \\ \text{TAELS} &= \text{US}\,\$\,41.87\end{aligned} \tag{9}$$

The question that needs to be answered is: how much money would be worth today the savings in the tank wall losses over the 30-year life of the transformer? The savings of including a stainless-steel plate in the low-voltage side of a 225-kVA transformer are US $ 41.87 per year (see Fig. 12).

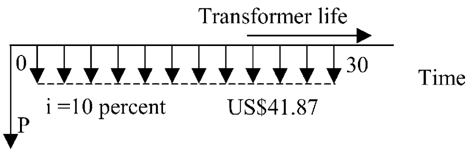

Fig. 12. Uniform series payment present worth example cash flow diagram.

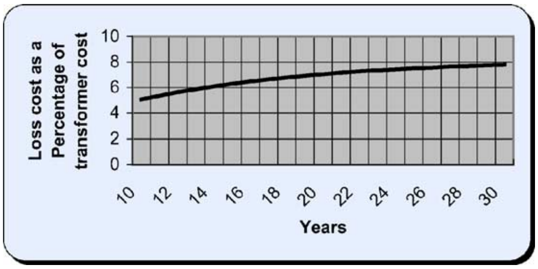

Fig. 13. Loss cost as a percentage of transformer material cost versus time (years).

As a result, the solution is:

$$\begin{aligned}P &= \frac{(1+0.1)^{30}-1}{0.1\,(1+0.1)^{30}}(\text{US}\,\$\,41.87) = (9.43)(\text{US}\,\$\,41.87) \\ &= \text{US}\,\$\,394.7\end{aligned} \tag{10}$$

The loss cost US $ 394.7 represents 7.8% of the transformer material cost (see Fig. 13) and in less than 2 years the extra cost of stainless-steel T plate is recovered.

6. Conclusions

This paper has dealt with the question of using 2D FE models for predicting losses in tank walls of pad-mounted transformers. It is found that 2D models under-predict by several orders of magnitude the losses, whereas 3D approaches are very accurate. However, the computer resources that are required by 3D techniques are extremely demanding. A clever design of the 3D mesh is required since thousands of elements are generated, leading to computational times that can be extremely long. While a 2D finite element model can be solved in a matter of seconds, 3D models may require hours of computing time. As a result, the assessment of different configurations may result in making the use of 3D models unrealistic. Hence, 2D FE techniques are valuable for solving this sort of problem. It was found that the 2D approach is able to predict the percentage reduction of losses with good accuracy. This allows the rapid design of low cost inserts using moderate computer recourses. Hence, for a particular class of problem, if a correlation between 2D and 3D results can be determined (by doing 2D and 3D analyses for one or two cases), for subsequent variations of the problem, simpler and less time consuming 2D analysis can be intelligently and conveniently used.

The paper also presented a study of eddy-current losses for different insert geometries. It has been found that the insertion of ‘T’ shaped plates is one of the best options to substantially reduce tank wall losses in these transformers. The use of bakelite and smaller stainless steel plates in the low-voltage side is also a cost-effective way to reduce stray losses and local overheating.

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