

Improved Insert Geometry for Reducing Tank-Wall Losses in Pad-Mounted Transformers

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Abstract—This paper presents a numerical analysis of losses generated in the tank-wall surrounding the high-current bushings of pad-mounted transformers using a three-dimensional (3-D) finite-element approach. Two cases are analyzed to study the impact of inserting small plates of different geometry (located near the high-current phases) on the reduction of tank losses. Significant reductions in stray losses occurring in the tank wall are obtained with plate inserts of low-cost. With the “T” configuration proposed in this paper, we reduce the tank-wall losses by a factor of 1/21 at rated current when compared with the case of tank wall without the stainless-steel plate. A 3-D time-harmonic finite-element model is used to determine the losses in the tank wall. Two load loss tests were carried out on experimental transformers to validate the simulations and effectiveness of the low-cost inserts.

Index Terms—Finite-element method, low-voltage conductor, pad-mounted transformer, stainless-steel plate, stray losses, tank-wall losses.

I. INTRODUCTION

MEANS FOR preventing local overheating in the windings and other elements of transformers have been studied. However, the subject of tank-wall losses near the low-voltage bushings in distribution transformers has received little attention. In 1954, Poritsky and Jerrard [1] discussed the eddy-current losses in a semi-infinite solid slab subjected to an alternating current by solving Maxwell’s equations both in air and in a solid conductor. In the case of transformer tanks, the steel plate acts essentially as a semi-infinite solid slab because its thickness is greater than the penetration depth at power frequencies. Saturation was neglected by assuming constant permeability. Maxwell’s equations were solved by Fourier-integral superposition. In 1957, Deuring [2] presented empirical equations to calculate losses in steel plates. He found that, for unshielded magnetic steel-plate materials, the induced tank losses in large power transformers vary with current to a power smaller than two. Curves of watts per foot for shielded and unshielded plates were given.

Manuscript received April 15, 2003.

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Digital Object Identifier 10.1109/TPWRD.2004.824431

In 1981, Saito *et al.* [3] presented an experimental analysis of eddy-currents in the structure that surrounds the high-current bushings of transformers. He used a model with a conducting current of about 20 kA. The experimental setup consisted of three buses, a bushing pocket, a bushing base plate (made of stainless steel), a bus cover flange, bus covers and isolated-phase bus enclosures. The magnetic flux density on the tank cover and bus cover flange was less than 0.001 T, and therefore there was no possibility that leakage flux caused local overheating. In 1988, Furman *et al.* [4] dealt with eddy current losses and local heating in transformer tank parts by using high-current taps. Their experiments were performed on a full-scale model representing the tank cover of the transformer rated over 1000 MVA. The authors presented several methods to reduce the transformer tank losses, some of them are: 1) increase of distance between the high-current conductor and the cover surface; 2) direct connection of winding leads to the corresponding bushings to avoid sections parallel to the tank cover; 3) close arrangement of different phase taps; 4) use of nonmagnetic conducting materials; 5) splitting of a high-current conductor into parallel conductors; and 6) choice of an optimal position of the tap and the hole in the tank cover. In 1990, Renyuan *et al.* [5] presented an integral method to determine eddy current losses produced by heavy currents in transformer leads. This method accommodates the open region and artificial boundaries are not needed. In another paper [6], they applied a boundary element method in terms of the magnetic vector potential and the electric scalar potential, finding that the most serious overheating was in the low-voltage wall between the holes. The maximum magnetic flux density considered was 22 mT. In this paper, it was assumed that the exciting current was sinusoidal.

In 1994, Junyou *et al.* [7] applied the boundary element method to the problem of overheating due to heavy current carrying conductors in a 360 MVA, 500 kV transformer. According to their results, nonmagnetic materials with aluminum screen are favorable to prevent overheating of the cover. In 1997, Turowski and Pelikant [8] carried out an analysis of high current bushings passing through steel cover plates based on analytical solutions of Maxwell’s equations. The method of calculating eddy current losses in steel walls is based on Poynting’s theorem. The authors obtained a formula to establish the maximum permissible bushing current in the flat cover with and without nonmagnetic inserts. Four cases were simulated: 1) a flat cover with three-phase bushing without gaps between holes; 2) similar to 1), but with nonmagnetic metal inserts; 3) as in 1), but with metal turrets; and 4) similar to 2), but with metal turrets. In 1999, Kim and Hahn [9] presented an

improved design of cover plates to reduce eddy-current losses due to heavy currents passing through the steel cover plates of a transformer. The authors applied the indirect boundary integral equation method to the problem of heavy currents in transformer leads and compared the calculations with experimental results. The improved transformer cover plate consisted of two slits between the holes of the current leads. The eddy current losses in the plates were reduced by 25%.

After reviewing all the literature regarding losses on the low-voltage side of transformers, authors observed that work needs to be done for improvement of geometry of tank wall surrounding the high-current bushings of distribution transformers. Studies reported in the literature for analyzing losses in high current terminations are predominantly for power transformers and studies reported for distribution transformers are very scarce or almost nonexistent.

This paper shows the application of a 3-D finite-element approach to estimate the stray losses on tank walls of distribution transformers. The numerical approach taken in this work assumes that the stray magnetic field has linear behavior. Although this assumption may seem oversimplified, the comparison of simulation and experimental results shows that the finite-element model is accurate enough.

The finite-element approach used in this work also assumes that transformer currents are perfectly sinusoidal, thus the electromagnetic equation can be solved in the frequency domain. One of the main objectives of this paper is to assess the impact of nonmagnetic metallic plate inserts on the reduction of tank losses. It is found that even small inserts bring substantial reductions of stray losses without adding considerable cost to the transformer.

Two cases are analyzed to study the impact of inserting small plates of different geometry (located near the high-current phases) on the reduction of tank losses: 1) tank wall with stainless-steel T plate and 2) tank wall without stainless steel.

The use of bakelite and smaller stainless-steel plates in the low-voltage side are also a cost-effective ways to reduce stray losses and local overheating. We will be studying these options in the near future.

II. ELECTROMAGNETIC BACKGROUND

The calculation of losses in the tank wall of a pad-mounted transformer is performed using a 3-D finite-element model. A brief discussion of the equations, excitations and boundary conditions that were used to solve the problem are given here. The 3-D boundary value problem is formulated using the \mathbf{A} , $\mathbf{A} - V$ potential formulation [10]. The magnetic vector potential \mathbf{A} is used for any kind of material region (such as air, source current regions and nonconducting permeable regions), while the electric scalar potential V is only used for eddy current regions. It is not difficult to show that the following equations define the 3-D eddy current problem [10], [11]

$$\nabla \times \nu \nabla \times \mathbf{A} + \sigma \frac{\partial \mathbf{A}}{\partial t} + \sigma \nabla V = \mathbf{0} \quad (1)$$



Fig. 1. Test transformer under load test.

for eddy current regions, whereas

$$\nabla \times \nu \nabla \times \mathbf{A} = \mathbf{J}_s \quad (2)$$

applies for other regions. Here, ν is the reluctivity and σ is the electric conductivity. \mathbf{J}_s denotes a source current density, which is known. The boundary conditions can be formulated as [10], [11]

$$\nu \nabla \times \mathbf{A} \times \mathbf{n} = \mathbf{0} \quad (3)$$

and

$$\mathbf{A} \times \mathbf{n} = \mathbf{0} \quad (4)$$

where the tangential component of the magnetic field intensity and the normal component of the magnetic flux density are zero for (3) and (4), respectively. Equations (1)–(4) define the magnetic field uniquely [10], [11]. Nevertheless, the magnetic vector potential is not fully determined, but it can be fixed within a finite-element context using edge elements (see [11] for more details). For sinusoidal steady-state operating conditions, the problem is formulated by substituting $j\omega$ for $\partial/\partial t$ and treating each electromagnetic variable in the previous equations as a phasor. This approach has for instance been demonstrated in [12].

III. EXPERIMENTAL RESULTS

The pad-mounted transformer is the most commonly used type of distribution transformer serving loads of distribution networks with an underground cable network. Pad-mounted transformers can be manufactured as: 1) single-phase or three phase—in this paper, we use the three-phase transformer shown in Fig. 1, or 2) loop or radial—loop units have two conductors per phase in the high-voltage side (see left side of Fig. 2), while radial units only have one primary cable per phase.

The power absorbed during short-circuit test consists of the I^2R losses in the windings, eddy current losses in the copper and stray losses in structural conducting parts. The iron losses are negligible because the applied voltage is quite low. If a three-

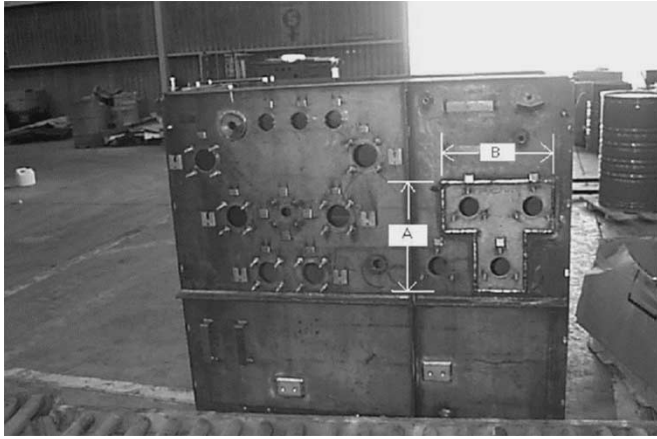


Fig. 2. Test transformer with the stainless-steel T plate on low-voltage side.

phase transformer is considered, the load losses are given by [13], [14]

$$P_{\text{load}} = 3P_{I^2R} + P_{EC} + P_{\text{stray}} \quad (5)$$

where

- P_{load} load losses (W);
- P_{I^2R} I^2R losses (W);
- P_{EC} winding eddy-current losses (W)
- P_{stray} stray losses (W).

The stray losses arise from eddy currents induced in metallic parts of the transformer, for instance in clamps and in tank walls. Accurate understanding of stray losses and their reduction mechanisms are necessary for improving the design of large-capacity transformers [15].

Experimental tests have been performed to validate the numerical calculation performed in this paper. The load loss test is performed by short-circuiting the secondary winding (see Fig. 1) and applying a reduced voltage to the primary, i.e., the voltage necessary to cause rated load current to flow. All connections associated with this test are cleaned and smeared with contact grease before being firmly bolted. In this case, the transformer does not have stainless-steel plate on the low-voltage side. Fig. 2 shows the same transformer with stainless-steel T plate on low-voltage side. The plate is made of AISI 304 stainless-steel material. The dimensions of the stainless-steel plate are $A = B = 36$ cm and the plate thickness is 6.35 mm (1/4 in).

The experiment consisted in performing a load loss test on two tank configurations: 1) transformer tank without stainless-steel T plate and 2) transformer tank with stainless-steel T plate.

In order to have a better comparison of results, the same tank and the same active element were used in both cases. In other words, transformer of case 1) was tested first and afterwards the stainless-steel T plate was welded on the low-voltage side and the test was repeated. In both cases, the transformers were not filled with oil to avoid drying process and reduce the time of the experiment. Additionally, performing the tests in this way allows us to exclude from the measurements, via subtraction, the losses due to all other structural and active components. We simply look at the loss difference of two otherwise identical tests.

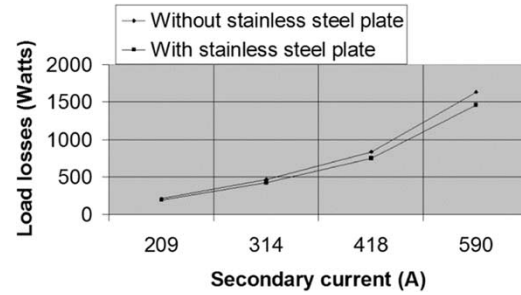


Fig. 3. Load losses versus secondary current for a 225 kVA, 23000, 220Y/127 V transformer with and without stainless steel.

TABLE I
PERCENTAGE DECREASE OF LOAD LOSSES
BY USE OF STAINLESS STEEL PLATE

Secondary current (A)	Load Losses W (without plate)	Load Losses W (with plate)	% decrease in load losses
209	209.58	189.7	9.49
314	465.6	418.5	10.12
418	834.4	746.6	10.52
590	1634	1458.2	10.76

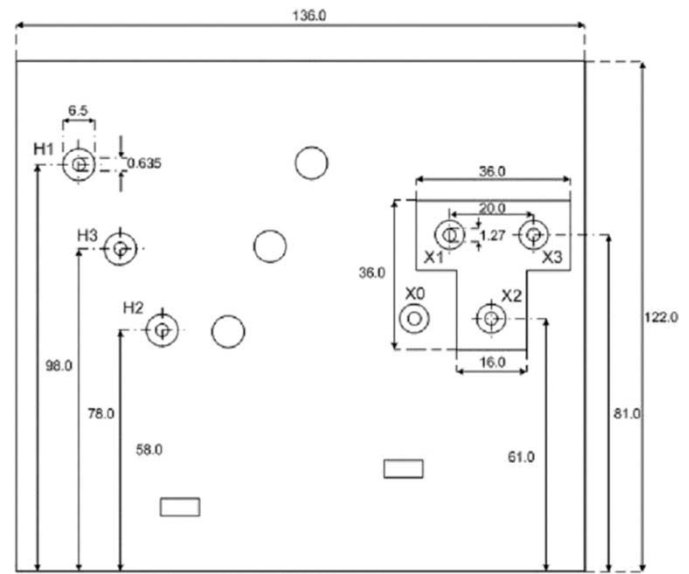


Fig. 4. Plate outline. Dimensions in centimeters.

Fig. 3 shows the variation of load losses versus measured primary current for a pad-mounted transformer of 225 kVA rating (see the Appendix). At lower current, losses in both cases (with and without stainless-steel plate) are almost equal.

From Table I, we see that the maximum reduction of load losses is when the transformer secondary excitation is rated current.

IV. SIMULATIONS

Fig. 4 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 currents in the low and high voltage conductors for Dy5 transformers are [16], [17]

$$\begin{aligned} I_{X1} &= 590.49 \text{ A} \\ I_{H1} &= 5.65 \text{ A} \end{aligned} \quad (6)$$

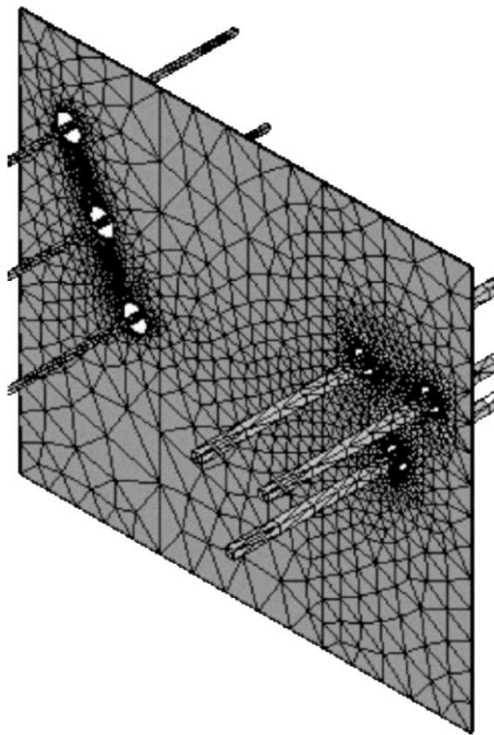


Fig. 5. 3-D Mesh: 90 179 elements and 121 791 nodes.

TABLE II
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	0.14	7.9686	8.11
Without stainless steel T plate	170.71	-	170.71

The plate is 6.35-mm thick. The material conductivities are: 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 for the copper. Two types of simulations were performed: simulations with the plate and without the plate. Fig. 5 shows the finite-element mesh used during the simulations.

A commercial finite-element software (ANSYS 5.5.1 [18]) 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 coarse meshes lead to erroneous results, whereas the mesh of Fig. 5 gives consistent results with experiments. Finer meshes did not give noticeable improvements in results.

Constant relative permeabilities of 400 and 1 are assumed for the ASTM A36 and stainless steel, respectively. The results of the calculations are shown in Table II. Figs. 6 and 7 show the magnetic flux density distribution for tank walls with and without stainless-steel T plate. Similarly, Figs. 8 and 9 show the induced current density for the “without” and “with” T plate, respectively.

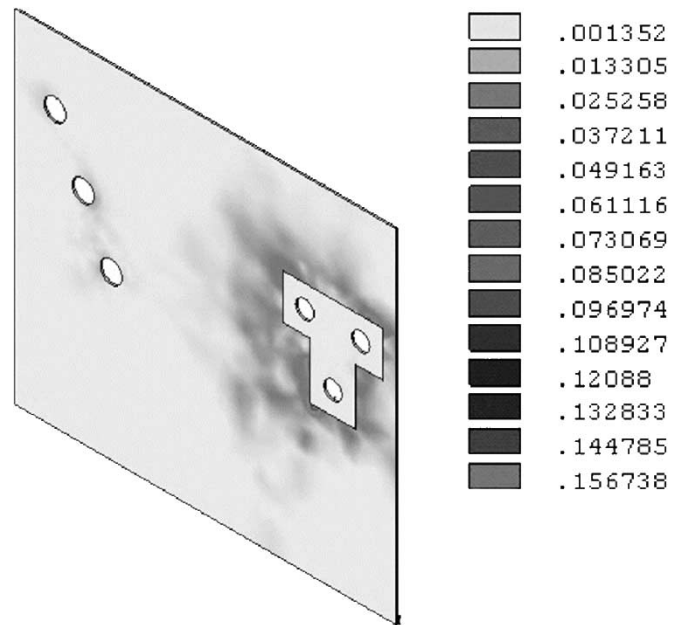


Fig. 6. Magnetic flux density [T] distribution with the T stainless-steel plate, $\mu_r = 400$ on the tank wall and $\mu_r = 1$ on the stainless-steel T plate.

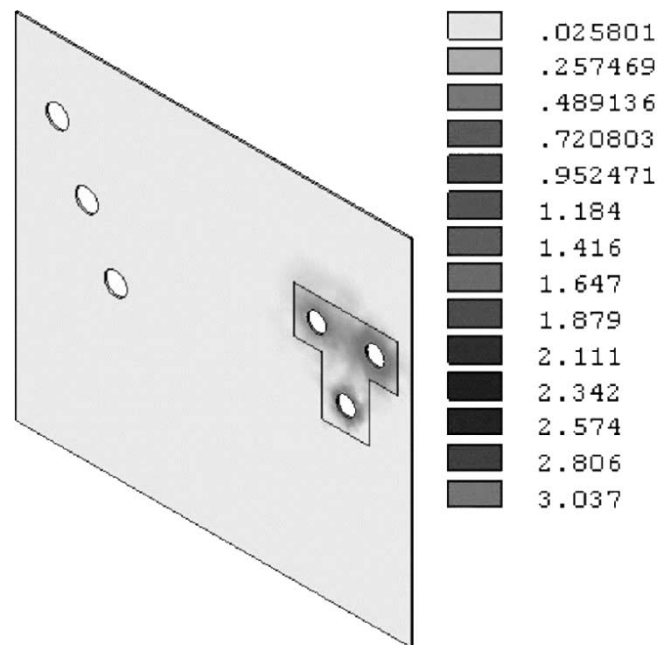


Fig. 7. Flux magnetic density [T] distribution without T stainless-steel plate, $\mu_r = 400$ on the tank wall.

The measured and calculated values of the difference between two load losses corresponding to cases of pad-mounted transformer with and without stainless-steel plate are presented in Table III.

The relative error between the calculated and measured reduction in load losses is about 7.5% which is quite acceptable.

Some transformer manufacturers use a stainless-steel plate with a triangular form as shown in Fig. 10. In this case, the plate covers a smaller area surrounding the low-voltage conductors. Thus, the tank losses are higher in comparison with the case of stainless-steel T plate.

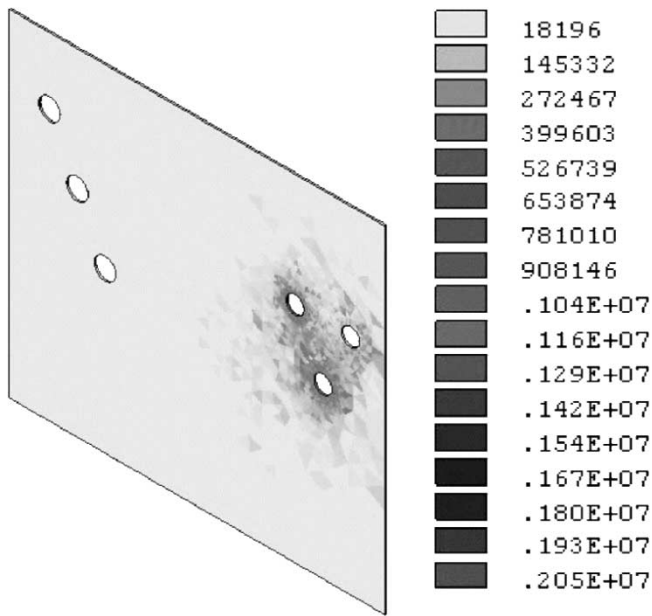


Fig. 8. Current density [A/m²] distribution without T stainless-steel plate.

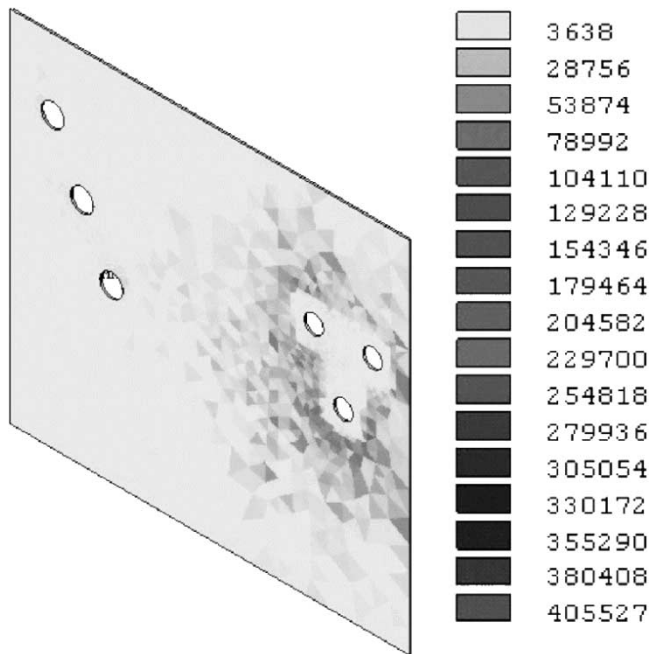


Fig. 9. Current density [A/m²] distribution with T stainless-steel plate.

TABLE III
REDUCTION IN LOAD LOSS WITH STAINLESS STEEL PLATE

Measured losses (W)	Calculated losses (W)
175.8	162.6

V. 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 [19]

$$\begin{aligned}
 \text{APLS} &= (\text{Power loss saving at peak load}) \\
 &\quad \times (\text{Annual loss factor}) \\
 \text{APLS} &= (162.6 \text{ W})(0.35) = 56.9 \text{ W} \quad (7)
 \end{aligned}$$



Fig. 10. Transformer with triangular stainless-steel plate on low-voltage side.

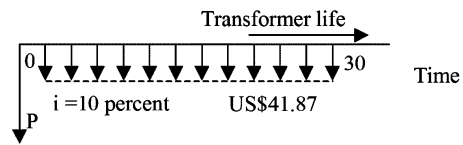


Fig. 11. Uniform series payment present-worth example cash flow diagram.

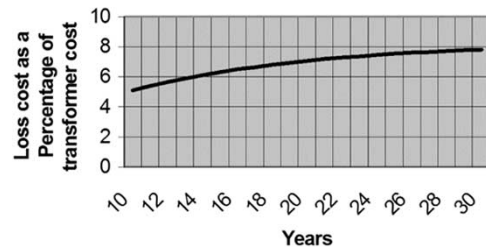


Fig. 12. Loss cost as a percentage of transformer material cost versus time (years).

and the total annual energy loss savings (TAELS) are

$$\begin{aligned}
 \text{TAELS} &= (\text{APLS})(8760 \text{ h/year})(\$0.06739) \\
 \text{TAELS} &= (56.9 \text{ W})(8760 \text{ h/year})(\$0.06739/\text{kWh}) \\
 \text{TAELS} &= \text{US\$}33.6. \quad (8)
 \end{aligned}$$

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. 11).

The solution is

$$\begin{aligned}
 P &= \frac{(1 + 0.1)^{30} - 1}{0.1(1 + 0.1)^{30}} (\text{US\$}33.6) = (9.43)(\text{US\$}33.6) \\
 &= \text{US\$}316.85
 \end{aligned}$$

The loss cost US\$316.85 represents 7.8% of the transformer material cost (see Fig. 12) and in less than two years the extra cost of stainless-steel T plate is recovered.

VI. CONCLUSIONS

This paper has presented a study of eddy-current losses surrounding the low-voltage bushings of pad-mounted transformers. It has been found that the insertion of “T”-shaped

TABLE IV
TRANSFORMER DETAILS

Primary voltage (V)	23000
Secondary voltage (V)	220Y/127
Primary connection	Delta
Secondary connection	Star
Total weight (kg)	1768.0
Frequency (Hz)	60
Impedance at 85 °C (%)	2.24
Efficiency (%)	99.01

plates is one of the best options to substantially reduce tank-wall losses in these transformers.

With the “T” configuration proposed in this paper, we are able to reduce the tank-wall losses by a factor of 1/21 when compared with the nonshielded case.

A 3-D finite-elements time-harmonic solver has been used to determine the losses in the metallic parts of interest. The results have been validated with tests on experimental transformers.

An error of 7.5% is obtained in estimation of stray losses in tank when compared with actual measurements. This difference may be explained by the fact that material properties were assumed linear. On the other hand, a two-dimensional approach is computationally economic and easily implemented, avoiding the complications posed by a 3-D finite-element approach, but it does not give accurate results.

APPENDIX A

More details of the transformer used in this paper are indicated in Table IV.

REFERENCES

- [1] H. Poritsky and R. P. Jerrard, “Eddy-current losses in a semi-infinite solid due to a nearby alternating current,” *AIEE Trans.*, pt. I, vol. 73, pp. 97–106, May 1954.
- [2] W. G. Deuring, “Induced losses in steel plates in the presence of an alternating current,” *AIEE Trans.*, pt. III, vol. 75, pp. 166–173, June 1957.
- [3] S. Saito, K. Inagaki, T. Sato, Y. Inui, K. Okuyama, and H. Otani, “Eddy currents in structure surrounding large currents bushing of a large capacity transformer,” *IEEE Trans. Power App. Syst.*, vol. PAS-100, pp. 4502–4509, Nov. 1981.
- [4] Y. I. Ya. I. Furman, V. L. Bereza, V. F. Ivankov, and L. P. Nizhnik, “Losses in tanks of large power transformer, caused by magnetic fields, and methods of their reduction,” in *1988 Session*, Aug./Sept., 12-07 CIGRE.
- [5] T. Renyuan, Y. Junyou, W. Zhoxiong, L. Feng, L. Churong, and X. Zihong, “Computation of eddy current losses by heavy current leads and windings in large transformers using IEM coupled with improved $R-\Psi$ method,” *IEEE Trans. Magnetics*, vol. 26, pp. 493–496, Mar. 1990.
- [6] T. Renyuan, Y. Junyou, L. Feng, and L. Yongping, “Solutions of three-dimensional multiply connected and open boundary problems by BEM in three-phase combinations transformers,” *IEEE Trans. Magnetics*, vol. 28, pp. 1340–1343, Mar. 1992.
- [7] Y. Junyou, T. Renyuan, and L. Yan, “Eddy current fields and overheating problems due to heavy currents carrying conductor,” *IEEE Trans. Magnetics*, vol. 30, pp. 3064–3067, Sept. 1994.
- [8] J. Turowski and A. Pelikant, “Eddy currents losses and hot-spot evaluation in cover plates of power transformers,” *Proc. Inst. Elect. Eng. Elect. Power Appl.*, vol. 144, pp. 435–440, Nov. 1997.
- [9] D. H. Kim and S. Y. Hahn, “Improved design of cover plates of power transformers for lower eddy current losses,” *IEEE Trans. Magnetics*, vol. 35, pp. 2529–2531, Sept. 1999.
- [10] O. Biro and K. Preis, “On the use of the magnetic vector potential in the finite element analysis of three-dimensional eddy currents,” *IEEE Trans. Magnetics*, vol. 25, pp. 3145–3159, 1989.

- [11] K. Preis, I. Bardi, O. Biro, C. Magele, G. Vrisk, and K. R. Ritcher, “Different finite element formulations of 3D magnetostatic fields,” *IEEE Trans. Magnetics*, vol. 28, pp. 1056–1059, 1992.
- [12] J. Driesen, G. Delière, and K. Hameyer, “Coupled thermo-magnetic simulation of a foil-winding transformer connected to a nonlinear load,” *IEEE Trans. Magnetics*, vol. 36, pp. 1381–1385, July 2000.
- [13] R. Feinberg, Ed., *Modern Power Transformer Practice*. London, U.K.: Macmillan, 1979.
- [14] M. W. Thomas, “Mathematical model of load loss in shell form transformers,” *IEEE Trans. Power App. Syst.*, vol. PAS-98, pp. 174–180, Jan./Feb. 1979.
- [15] S. V. Kulkarni and S. A. Khaparde, “Stray loss evaluation in power transformer—a review,” in *Proc. IEEE PES Winter Meeting 2000*, Singapore, Jan. 2000, Paper 0-7803-5938-0/00, pp. 2269–2274.
- [16] E. Ras, *Transformadores de potencia, de medida y de protección*, Segunda ed. Colombia: Alfaomega Marcombo, 1991, pp. 119–120.
- [17] *Power Transformer Handbook*, B. Hochart, Ed., Butterworths, U.K., 1987, pp. 47–49.
- [18] *ANSYS (R) Help System*, Release 5.5.1, 1996.
- [19] T. Gönen, *Electric Power Distribution System Engineering*. New York: McGraw-Hill, 1986, pp. 46–47.



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