

Impact of Low Voltage Bushings Diameter on Single-Phase Distribution Transformers Losses

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***Abstract—** This paper analyses steel tank wall losses of pole-mounted single-phase distribution transformers due to high currents crossing through the bushing holes of the low voltage terminals, and evaluates the impact of the holes diameter on load losses. The study also includes a description and comparison of analytical and empirical approaches used by other authors. The analysis was performed using simulations obtained by finite element method. The finite element model was validated reproducing results found in literature and simulations obtained for a 37.5kVA single-phase transformer model. The study was motivated by a reduction of diameter (from 4.6cm to 3.6cm) in the bushings supplied by manufacturers that represented a cost reduction. Results show no appreciable change of load losses with 1cm diameter reduction and consequently the decrease in manufacturing cost means a beneficial impact.

Index Terms—Pole-mounted distribution transformer, tank wall, load losses, efficiency, finite element method, low-voltage conductor.

I. INTRODUCTION

Load losses in transformers have a component of losses due to the presence of eddy currents in the tank in the zone surrounding the bushings [1], [2]. This effect can be ignored on the high-voltage bushings, but on the low voltage side currents are high and the effect plays an important role on load losses [3]–[7]. Among the elements that could have an impact on these losses is the closeness of low-voltage conductors to the tank wall.

In 2005 Mexican bushing manufacturers decided to reduce the diameter of low-voltage bushings used in distribution transformers and thus reduce manufacturing costs and consequently selling price to transformer manufacturers. This change could mean an increase of tank losses and therefore an evaluation of its impact was important.

In this work, a study is carried out to determine the impact of bushings diameter on the losses generated in the tank wall. The study was intended to evaluate the consequences of the reduction from 4.6cm to 3.6cm of the diameter of the bushings of pole-mounted single-phase transformers. Tank wall losses on low voltage side of other types of distribution transformers are studied by the authors in [8]–[11].

Fig. 1 shows the tank of a pole-mounted single-phase transformer where the holes for the low-voltage bushings can be observed. At the top of the transformer (transformer cover) there are two holes where the high-voltage bushings are placed.

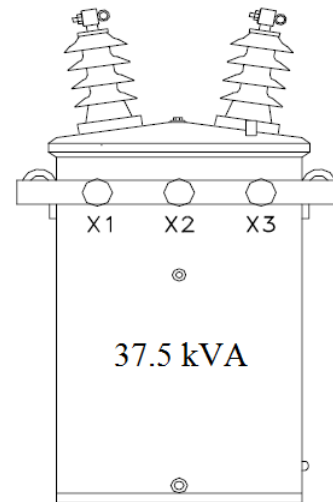


Fig. 1. Three holes for low-voltage conductors in the tank of a pole-mounted single-phase distribution transformer.

Fig. 2 shows the top view of a 37.5kVA pole-mounted single-phase distribution transformer where the distance between low-voltage bushings and the core fixture to the tank can be observed.

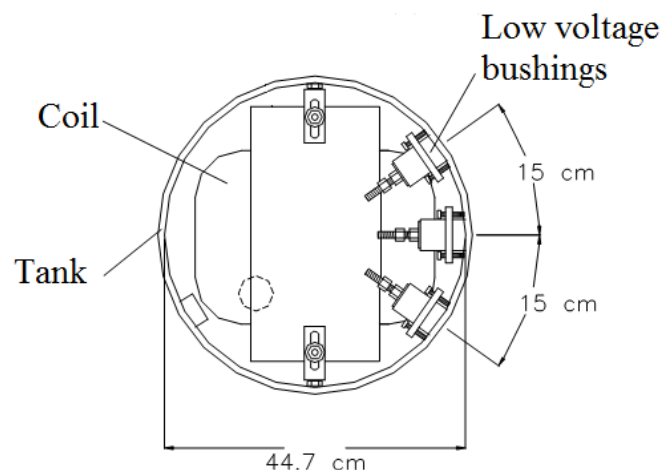


Fig. 2. Top interior view of a 37.5kVA pole-mounted single-phase distribution transformer.

Losses generated in the vicinity of transformer bushings can be the cause of hot spots that can damage the transformer oil, the gaskets, and can lead to damage that can jeopardize the maintenance staff, the peripheral equipment and could put the transformer out of service. Fig. 3 shows a low-voltage bushing used for distribution transformers with its physical dimensions. The use of gaskets is vital in the assembly of bushing to prevent oil leakage. Eddy currents induced in the transformer tank wall close to low-voltage bushings depend on several parameters, but the current magnitude, diameter hole and tank wall properties (permeability and conductivity) are the most important.

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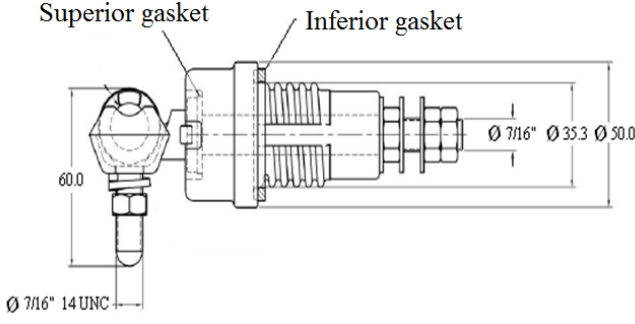


Fig. 3. Low-voltage bushing of 3.6 cm diameter for pole-mounted distribution transformers.

In this study, losses generated by currents flowing through the low-voltage conductors on transformer tank wall are calculated. The losses are obtained using closed analytical formulas and finite element method (FEM) simulations. Also results of tests to a 37.5kVA transformer are included. The following sections describe the analytical formulas, the FEM simulations, the tests performed and their comparison.

The single-phase connection for 240V of the 37.5kVA transformer is shown in Fig. 4.

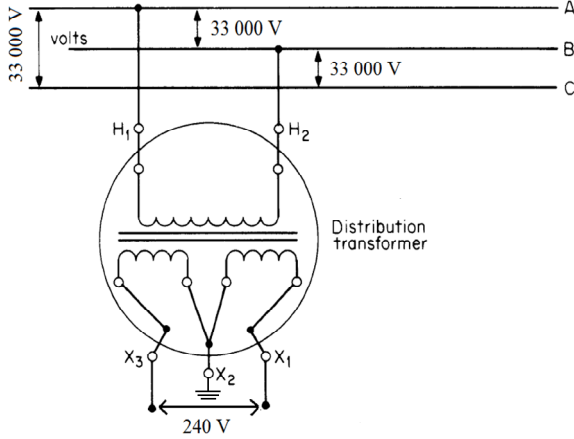


Fig. 4. 240V connection for pole-mounted distribution transformers.

II. FORMULAS TO CALCULATE LOSSES CAUSED BY A CURRENT CROSSING THROUGH A METALLIC TANK WALL

This section presents three formulas to determine losses in metal plates due to currents crossing them. Each formula has particular characteristics. For example, there are two formulas that consider the thickness of the metal plate and one that does not. Two formulas have a mathematical deduction and one is empirical. These formulas are known as Turowski [3], Karsai [4] and Del Vecchio [5] formulas.

A. Turowski's formula

Fig. 5 shows the geometry and dimensions used in [3] to determine losses on the metal surface, in this case a tank wall, due to the passage of current through a conductor. With the help of Fig. 5 the following analytic formula in terms of the magnetic field components can be obtained:

$$P = \zeta \frac{a_p}{2} \sqrt{\frac{\omega \mu_0}{2\gamma}} \iint_A \sqrt{\mu_{rs}(x, y)} |H_{ms}(x, y)|^{2x} dx dy \quad (1)$$

where ζ is a screening coefficient of field incidence on active power on the wall; $a_p \approx 1.4$ is a linearization coefficient of relative permeability μ_{rs} that changes inside the solid steel

for H_{ms} fields; $\omega = 2\pi f$; γ is the conductivity; $x=1$ for nonmagnetic metals and $x \approx 1.05$ to 1.14 for steel. A simplified analytical expression of (1) is [3]:

$$P \approx 3.15 \times 10^{-2} I^2 \sqrt{\frac{\omega \mu}{\sigma}} \left(0.74 + \ln \frac{2A}{D} \right) \quad (2)$$

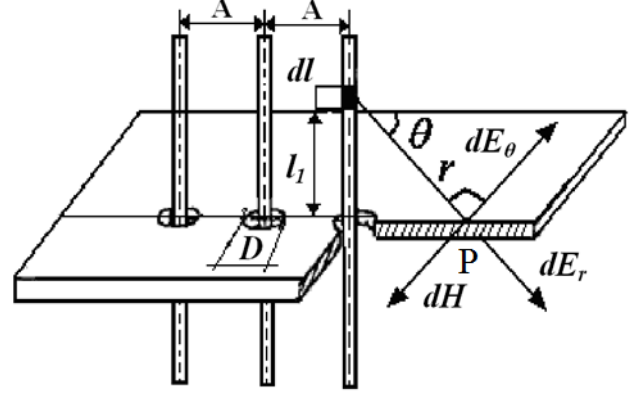


Fig. 5. Magnetic field components of a metal surface corresponding to the transformer tank. D = diameter of the bushing hole; l_1 = longitude of conductor from tank cover to the element dl ; dl = differential increment of longitude; A = distance between bushing holes; dE_r = contribution to E_r at point P from element differential; dE_θ = contribution to E_θ at point P from element differential; dH = contribution to H at point P from element differential; r vector from dl to P (copyright © 1997 Proc. IEE Electric Power Appl. [3], reprinted with permission).

The analytical formula of equation (2) is in terms of conductivity and permeability of the metallic plate that represents the tank wall. Other important parameters are the current flowing through the conductors, the diameter of the holes where the conductors go through and the distance between the holes in the metallic tank wall. The drawback of Turowski's formula, based on Poynting's theorem, is that it does not include the metallic plate thickness.

B. Karsai's formula

Karsai's formula [4] obtains the power loss for the simplified model shown in Fig. 6. This formula considers: hole diameter of bushings, current density in the conductor and is only valid for a magnetic steel of conductivity $\sigma = 7 \times 10^6 \text{ S/m}$ and magnetic flux density saturation $B_{SAT} = 1.4 \text{ T}$. These fixed values eliminate the possibility of using this formula to evaluate other materials and also has the drawback of not considering the metallic wall thickness. Karsai's formula is given in [4]:

$$P = 405 \left(0.7 - \sqrt{\frac{D}{2}} \right) I^{1.5} \quad (3)$$

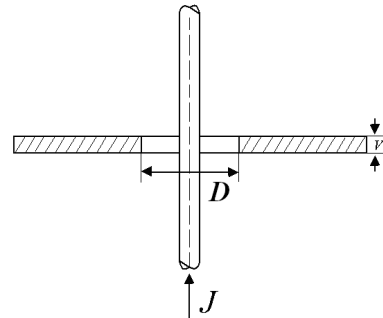


Fig. 6. Model of the conductor and steel plate used by Karsai.

C. Del Vecchio's formula

The analytical formula of Del Vecchio considers the metallic tank wall thickness and is based on the geometry shown in Fig. 7, which corresponds to a circular plate of radius r crossed by an electrical conductor in the center [5].

In [5], Del Vecchio's formula is derived from Maxwell equations in cylindrical coordinates, obtaining the following differential equation:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial H_\phi}{\partial r} \right) - r \frac{H_\phi}{r^2} + \frac{\partial^2 H_\phi}{\partial z^2} = j\omega\mu\sigma H_\phi \quad (4)$$

The tank power losses of the transformer are given by [5]:

$$Loss_{bush} = 2\pi \int_a^b \int_{-c/2}^{c/2} \frac{|J_r|^2}{\sigma} r dr dz \quad (5)$$

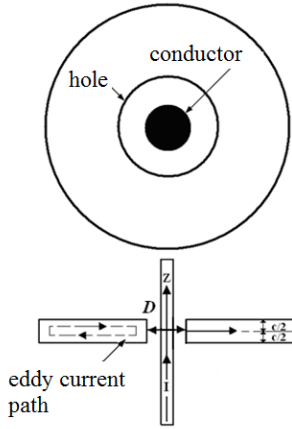


Fig. 7. Geometry used by Del Vecchio, where $D=2a$.

where a is the bushing hole radius, b is the external radius of the model plate, c the wall thickness and σ the conductivity. Solving (4) the current density J induced in the tank can be found.

Integrating (5) yields:

$$Loss_{bush} = \frac{I^2 q}{\pi\sigma} \ln\left(\frac{b}{a}\right) \left[\frac{\sinh(qc) - \sin(qc)}{\cosh(qc) + \cos(qc)} \right] \quad (6)$$

Equation (6) is the last formula used to determine the eddy current losses where q aggregates frequency, permeability and conductivity. A more simplified form of (9) when qc is small is given by [5]:

$$Loss_{bush} = \left(\frac{\pi}{6}\right) \frac{I^2 f^2 \mu^2 c^3}{\rho} \ln\left(\frac{b}{a}\right) \quad (7)$$

The results obtained using the Del Vecchio equation (6) for 4.6cm and 3.6cm bushings diameter showed a difference of 0.56W in the tank wall eddy current losses. The power loss is calculated with the following parameters: $b=0.91m$, $c=0.003m$, $\mu=500 \times 4\pi \times 10^{-7}$, $\sigma=5 \times 10^6 S/m$ and $I=220.1A$ corresponding to the peak value of the rated current of a single-phase distribution transformer of 37.5kVA for a 240V connection at $f=60Hz$.

III. CALCULATION OF TANK WALL LOSSES USING FEM

Several FEM simulations using Maxwell Ansoft 3D were performed considering a 37.5kVA, 33000-120/240V, pole-mounted, single-phase distribution transformer to determine the change in load losses when the diameter of the low-

voltage bushings is reduced from 4.6cm to 3.6cm. A simulation of a conductor crossing a steel disk for the same operating conditions reported in [6] was used for validation. A finite element analysis of the disk was carried out and then the losses were obtained in W/m^2 for the metal disk.

A. Validation of the model

Results in [6] were used to validate simulations. The calculation of eddy current loss is performed in a model, shown in Fig. 8, of carbon steel disk with inner diameter of 0.132m, outer diameter of 0.305m, thickness of 0.095m, a relative permeability $\mu_r=200$, an electrical conductivity of $4 \times 10^6 S/m$ and a conductor made of copper with $\mu_r=1$ and $\sigma=58 \times 10^6 S/m$.

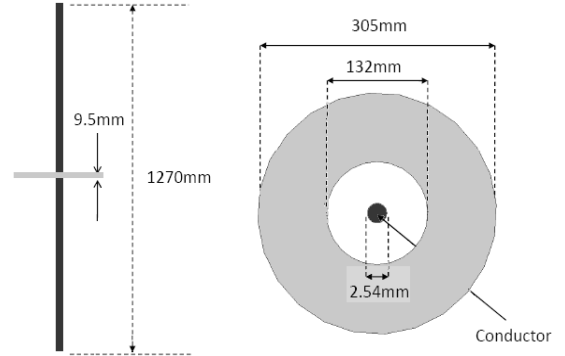


Fig. 8. Steel disk geometry to determine eddy current losses generated by current crossing it [6].

To quantify disk losses, the copper conductor and the steel disk were delimited by an external border, whose shape corresponds to a dodecahedral prism filled with air. The disk was modeled using a polygon of 24 sides or faces. In the faces of the disk an impedance boundary [6] was used to calculate power losses. When an impedance boundary is used in a volume, only the faces of the volume are meshed and the mesh in the faces is not fine. Moreover, the interior of the volume is not meshed. The use of an impedance boundary is advantageous [14]. The mesh of the model is shown in Fig. 9.

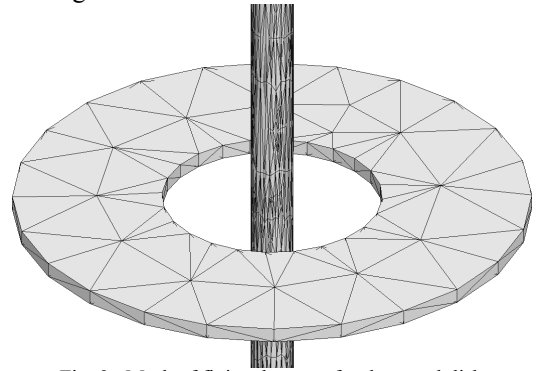


Fig. 9. Mesh of finite elements for the metal disk.

Total power losses (W) of the disk were obtained by [6]:

$$Loss = \sqrt{\frac{\omega\mu_r\mu_o}{8\sigma}} \int_{surface} \mathbf{H}_t \cdot \mathbf{H}_t^* ds \quad (8)$$

where $\mathbf{H}_t$ is the tangential magnetic field strength (A/m), $\mathbf{H}_t^*$ its conjugate, μ_r the relative permeability, μ_o vacuum permeability ($4\pi \times 10^{-7} H/m$), σ electric conductivity (S/m) and ω the angular frequency (rad/s).

Integration of (8) for the disk results in 1117.92W of total losses in the disk. This represents an error of 2% compared with the result reported in [6].

B. Flat steel plate with three 4.6cm diameter holes

The FEM is now used for a geometry similar to the zone where the low-voltage bushings are placed on the tank of a pole-mounted distribution transformer. The model is a carbon steel flat plate of 2.66mm (12 gauge) thickness, with $\mu_r = 500$ and $\sigma = 5 \times 10^6$ S/m [12]. The holes have a diameter of 4.6cm and a separation of 15cm between holes, which is the diameter and separation normally used for low-voltage bushings. Each hole was modeled by a polygon of 24 sides. Fig. 10 shows the geometry of the flat plate with three holes and their respective conductors.

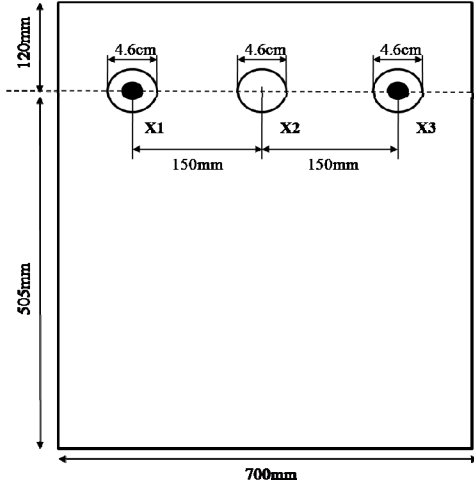


Fig. 10. Carbon steel plate with three 4.6cm diameter holes.

In the center of the bushing holes located on the sides in Fig. 10 a copper conductor of 11.938mm diameter is placed. Each conductor was modeled by dodecagon–12 sides. The conductor has a current flow of $I=220.1$ A which corresponds to the peak value of the rated current of a single-phase distribution transformer of 37.5kVA for a 240V connection (same value used in Del Vecchio's formula). Current in X2 terminal conductor is zero for a 240V connection.

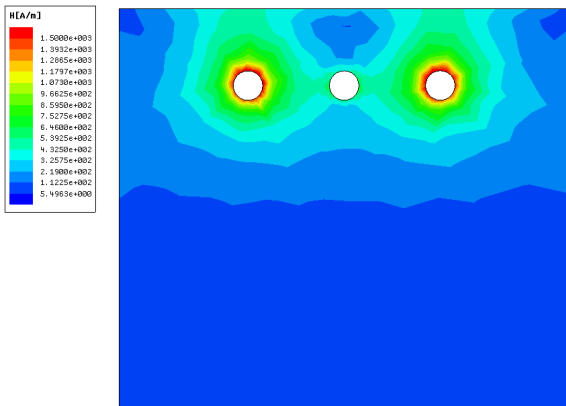


Fig. 11. Magnetic field intensity distribution in flat plate for 4.6cm diameter holes.

A second study of the same plate was also conducted, but with 3.6cm diameter holes. The obtained results are then compared with curved plate models. Fig. 11 and Fig. 12 show respectively the magnetic field intensity distribution and loss density distribution peak values in the flat plate with 4.6cm diameter holes.

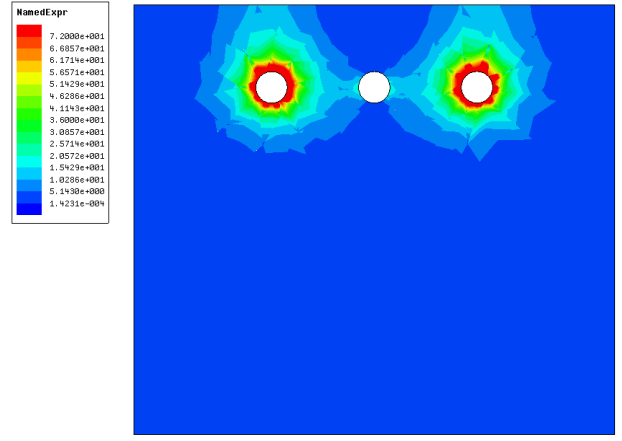


Fig. 12. Loss density distribution in flat plate for 4.6cm diameter holes.

C. Curved steel plate with three 4.6cm diameter holes

Tanks of single-phase pole-mounted distribution transformers are cylindrical; therefore the metal plate of the model was changed to a curved form to have a closer representation of the zone where the bushing holes are placed. The curved plate geometry results are compared with the flat plate results to validate the use of the flat plate geometry in future simulations. The curved metal plate with 4.6cm diameter holes is modeled with a half cylinder using a dodecagon, as flat surfaces are needed to use an impedance boundary. The arc length of the plate curvature is 700mm that corresponds to the flat plate length. The length of the conductors passing through each hole of the curved plate changed from 50cm to 100cm due to the plate curvature. Other characteristics of the plate remained constant with respect to the flat plate. The mesh of the curved steel plate is shown in Fig. 13. The model was enclosed in a rectangular boundary enclosing a volume of air, as shown in Fig. 14.

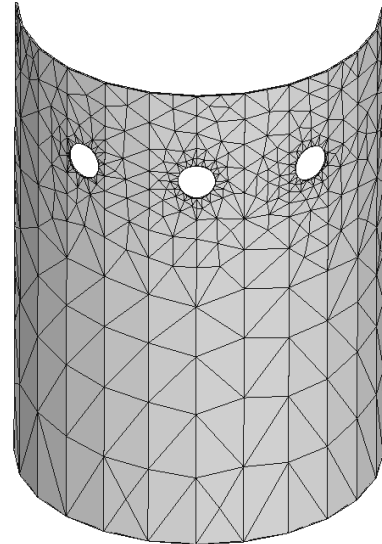


Fig. 13. 3D FE model of the curved steel plate.

3D FEM modeling of large volumes requires a mesh of very large number of elements. The impedance boundary method [13] only requires that the surface of the material be covered with finite elements. Also an impedance boundary provides a very convenient means of including the effect of a nonlinear B-H material characteristic provided the penetration depth is small compared with conductor dimensions [14].

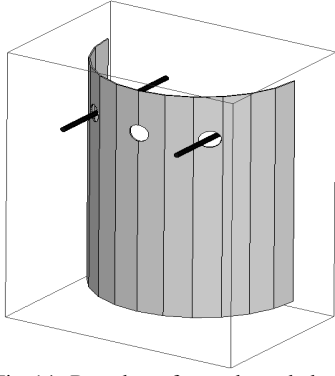


Fig. 14. Boundary of curved metal plate.

Fig 15 shows the peak values of distribution of magnetic field intensity on the curved metal plate.

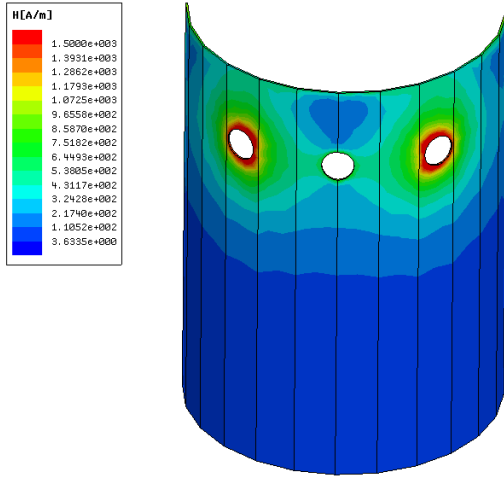


Fig. 15. Distribution of magnetic field intensity in the curved plate for 4.6 cm diameter bushing holes.

It can be observed from Fig. 11 and Fig. 15 that the distribution of magnetic field intensity for the curved plate has the same pattern as the magnetic field intensity obtained when simulation was performed with a flat plate with same holes diameter. Fig 16 shows the loss density distribution in W/m^2 on the curved plate with 4.6cm diameter bushing holes, which is very similar to the distribution shown in Fig 12 for the flat plate.

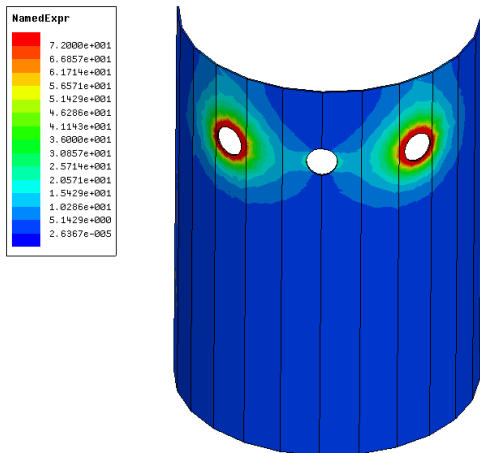


Fig. 16. Distribution of loss density in W/m^2 on the curved plate for 4.6cm diameter bushing holes.

For the case of the curved plate with 4.6cm holes total losses calculated with (8) were 4.97W. The value obtained

with the flat plate model with same diameter holes was also of 4.97W. Thus in this case eddy current losses can be obtained with the flat plate model.

D. Curved steel plate with three 3.6cm diameter holes

The mesh of the curved steel plate with three 3.6cm diameter bushing holes is of the same design as for the 4.6cm diameter. Fig 17.a shows the peak values of distribution of magnetic field intensity in the curved plate with holes of 3.6cm.

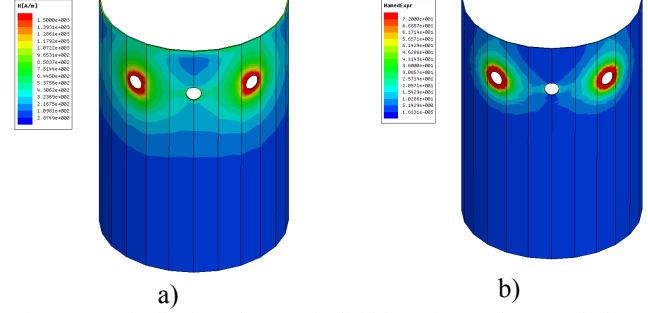


Fig. 17. a) Distribution of magnetic field intensity on the curved plate for 3.6cm diameter bushing holes, b) Distribution of loss density in W/m^2 on the curved plate for 3.6cm diameter bushing holes.

Fig 17.b shows the loss density distribution in W/m^2 on the curved plate with three 3.6cm diameter bushing holes.

Total losses for the curved plate with 3.6 cm diameter bushing holes were 5.44W using (8). This value is almost the same obtained with the flat plate with same size holes: 5.6 W. The 2.85% error means that eddy current losses can be calculated with the flat plate geometry.

E. FEM results comparison

The results of loss differences obtained for FEM simulations are shown in Table I. The results are compared in terms of the geometry used in simulations and the connection of the transformer low voltage terminals.

TABLE I
RESULTS OF FEM SIMULATIONS FOR A 37.5kVA TRANSFORMER WITH 3.6CM AND 4.6CM BUSHINGS DIAMETER

Geometry	Nominal volts of terminals	Eddy current loss difference when bushing diameter is 3.6cm versus 4.6cm (W)
Flat plate	240	0.63
Curved plate	240	0.47

The maximum difference of obtained eddy current losses in the 37.5kVA transformer is 0.63W, when simulation is performed using the plane geometry and when there is a 220.1A current flowing on low voltage terminals (Table I).

IV. CONCLUSIONS

The need to analyze the impact of changes in the bushings diameter in transformers load losses is the motivation for the reported study. The performed analysis compares eddy current losses in geometries of models of the tank zone that surrounds the low voltage bushings of pole mounted distribution transformers. The selected technique to evaluate the losses was the FEM. The models to perform the FEM simulations are mainly designed to give information on the difference of eddy current losses with bushings that have a diameter of 4.6cm and bushings with 3.6cm diameter. The comparative study shows that there is no appreciable difference between the eddy current losses obtained with 4.6cm or with 3.6cm bushings diameter. This finding

represents the possibility of a reduction of manufacturing cost of pole-mounted distribution transformers without an increase in the operation cost of 37.5kVA transformers with bushings of 3.6cm diameter.

The Del Vecchio analytical formula also shows that the difference of eddy current losses for 4.6cm and 3.6cm bushings diameter in the tank wall is very little: 1.12W.

Also eddy current losses obtained with FEM simulations for the analyzed cases show that a flat plate model can be used to determine eddy current losses, as the difference in calculated losses with flat or curved metallic plate are less than 2.85%.

Authors think that the reduction of the diameter of the holes may lead to problems with the electric rigidity of the dielectric material used to isolate the conductor from the tank only in the high-voltage bushings. In the low-voltage bushings there is no problem with it.

Authors are going to perform experimental tests and FEM simulations for other transformer ratings to give a definite conclusion on the adoption of the new bushing diameters.

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VI. BIOGRAPHIES

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Salvador Magdaleno was born in La Piedad, Michoacán, Mexico in 1983. In 2008, he obtained his B.Sc. in Electrical Engineer from the Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico. From 2003 to 2008 he has worked on research related to electromagnetic fields in toroidal transformers including the application of virtual gaps in toroidal cores. Since September 2008 he works in the Department of Technology of Power Transformers in Industrias IEM S.A de C.V as Research and Development Engineer. His areas of research include numerical calculation of electromagnetic fields using the finite element method and modeling of power transformers and reactors using the duality principle.

Eduardo Campero Littlewood was born in Mexico, D.F. in 1947. He obtained his B.Sc. in Electrical Engineering from the National Autonomous University of Mexico (UNAM-1969) and his M.Sc. in Electrical Engineering from Imperial College of Science, Technology, and Medicine, University of London, in 1977. He worked in industry from 1969 to 1975. He has been involved with research and lecturing since 1977 at Azcapotzalco Campus of Autonomous Metropolitan University of Mexico (UAM), where he is full professor since 1992. His main research interest is simulation and analysis of electrical machines.

Pavlos S. Georgilakis was born in Chania, Greece in 1967. He received the Diploma in Electrical and Computer Engineering and the Ph.D. degree from the National Technical University of Athens (NTUA), Athens, Greece in 1990 and 2000, respectively. He is currently Lecturer at the School of Electrical and Computer Engineering of NTUA. From 2004 to 2009 he was Assistant Professor at the Production Engineering and Management Department of the Technical University of Crete, Greece. From 1994 to 2003 he was with Schneider Electric AE, where he worked in transformer industry as transformer design engineer for four years, and research and development manager for three years. He is the author of the book *Spotlight on Modern Transformer Design* published by Springer in 2009. His current research interests include transformer design and power systems optimization.

R. Escarela-Perez (M'94-SM'05) was born in Mexico City, Mexico, in 1969. He received the B.Sc. degree in electrical engineering from Universidad Autonoma Metropolitana, Mexico City, in 1992 and the Ph.D. degree from Imperial College, London, U.K., in 1996. He is interested in the numerical modeling of electrical machines: transformers and synchronous generators with solid rotors. He has been involved with research and lecturing since 1996 at Azcapotzalco Campus of Autonomous Metropolitan University of Mexico (UAM).