# 3D Calculation and Modeling of Eddy Current Losses in a Large Power Transformer

A. M. Milagre, M. V. Ferreira da Luz, G. M. Cangane, A. Komar, P. A. Avelino

*Abstract* -- **Elimination of hot spots and reduction of eddy current losses in structural parts is one of the important constituents of transformer design. In this work, the eddy current losses in the clamping frame, transformer tank and electromagnetic shielding are calculated using a 3D finite element method. The clamping frame, transformer tank and electromagnetic shielding are modeled by surface impedance method. The paper analyses the effects of electromagnetic shielding and magnetic shunts on the eddy current loss reduction in the transformer tank.**

*Index Terms* – **Eddy current losses, finite element method, power transformer.**

## I. INTRODUCTION

THIS paper presents some results obtained by Research and Development (R&D) department of Siemens Ltda/TUSA Transformers, Brazil. Local losses are even more important because the loss distribution influences local temperature rise. High temperatures may accelerate aging and cause faults.

Power transformers are one of the most vital and costliest equipments of the power systems. The steady increase in the rating and size of transformers over the last few decades poses real challenge to transformer designers in today's competitive market conditions. The methods for design of active parts (core and windings) are well established. However, the design of inactive components (structural parts) is still not straightforward and requires careful treatment. The excessive losses in these components and the resulting overheating hazards could be dangerous, particularly at overloading which is not uncommon these days [1]. During the past years the problem has been treated by several authors [1]-[7], mainly analyzing transformer tank losses.

This paper deals with 3D calculation and modeling of eddy current losses in a large power transformer.

## II. 3D TIME-HARMONIC MAGNETODYNAMIC FORMULATION

To simulate a transformer at steady-state, a time-harmonic finite element method can be used. A bounded domain $\Omega$ of the two or three-dimensional Euclidean space is considered. Its boundary is denoted $\Gamma$. The equations characterising the 3D time-harmonic magnetodynamic problem in $\Omega$ are [8]:

$$\text{curl}\,\mathbf{H} = \mathbf{J}\,, \quad \text{curl}\,\mathbf{E} = -\,j\omega\,\mathbf{B}\,, \quad \text{div}\,\mathbf{B} = 0\,, \qquad \text{(1a-b-c)}$$

$$\mathbf{B} = \mu\,\mathbf{H}\,, \quad \mathbf{J} = \sigma\,\mathbf{E}\,, \qquad \text{(2a-b)}$$

where $j \equiv \sqrt{-1}$ is called the imaginary unit, $\omega$ is the angular frequency (rad/s), **H** is the magnetic field (A/m), **B** is the magnetic flux density (T), **E** is the electric field (V/m), **J** is the electric current density (A/m$^2$), including source currents $\mathbf{J}_s$ in $\Omega_s$ and eddy currents in $\Omega_c$ (both $\Omega_s$ and $\Omega_c$ are included in $\Omega$), $\mu$ is the magnetic permeability (H/m) and $\sigma$ is the electric conductivity (S/m).

The boundary conditions are defined on complementary parts $\Gamma_h$ and $\Gamma_e$, which can be non-connected, of $\Gamma$,

$$\mathbf{n}\times\mathbf{H}\big|_{\Gamma_h} = 0\,, \quad \mathbf{n}\,.\,\mathbf{B}\big|_{\Gamma_e} = 0\,, \quad \mathbf{n}\times\mathbf{E}\big|_{\Gamma_e} = 0\,, \qquad \text{(3a-b-c)}$$

where **n** is the unit normal vector exterior to $\Omega$ [8].

The Maxwell's equations in harmonic mode consider all physical quantities are sinusoidally time-varying for a given frequency. This formulation takes into account the currents induced in the conducting regions (eddy currents). It also considers the skin effects and the proximity effects in the conducting regions.

### A. *Formulation* T-$\phi$

In the **T**-$\phi$ formulation, there are two groups of unknown variables: the magnetic scalar potential $\phi$ on the nodes and the circulation of vector electrical potential **T** on the edges of the conductive elements.

Since the scalar potential is used in the non-conducting domain, the formulation in combined potentials seems quite attractive for the connection of conducting and non-conducting domains. In the conducting area the field **H** can be expressed by the combination of the vector electrical potential and the magnetic scalar potential: **T** − grad$\phi$. The weak formulation of Faraday's laws and the derivation with respect to the time of the flux conservation contained in equation [1b] implies [9]:

$$\begin{aligned}&(\sigma^{-1}\text{curl}\,\mathbf{T},\ \text{curl}\,\mathbf{T}')_{\Omega c} + j\omega\,(\mu\,\mathbf{T},\mathbf{T}')_{\Omega} + \\ &+ j\omega\,(\mu\ \text{grad}\ \phi,\mathbf{T}')_{\Omega} + <\mathbf{n}\times\mathbf{E}_s,\mathbf{T}'>_{\Gamma_c} = 0,\ \forall\mathbf{T}'\in F_T^1(\Omega),\end{aligned} \qquad \text{(4a)}$$

and

$$\begin{aligned}&j\omega\,(\mu\ \text{grad}\ \phi,\mathbf{T}')_{\Omega} + j\omega\,(\mu\ \text{grad}\ \phi,\text{grad}\ \phi')_{\Omega} + \\ &j\omega\,(\mathbf{T}_s,\text{grad}\ \phi')_{\Omega} + j\omega<\mathbf{n}\cdot\mathbf{B}_s,\phi'>_{\Gamma_e} = 0,\forall\phi'\in F_\phi^0(\Omega),\end{aligned} \qquad \text{(4b)}$$

where $\mathbf{T}_s$ is the source field due to the imposed current $\mathbf{J}_s$ (curl $\mathbf{T}_s = \mathbf{J}_s$), $\mathbf{n}\times\mathbf{E}_s$ and $\mathbf{n}\times\mathbf{B}_s$ are, respectively, constraints associated with the boundary $\Gamma_c$ and $\Gamma_e$ of domain $\Omega$ [9]. $F_T(\Omega)$ and $F_\phi(\Omega)$ are the function space defined on $\Omega$ containing the basis and test functions for **T** and $\phi$, respectively. $(.\,,.)_\Omega$ and $<.\,,.>_\Gamma$ denote a volume integral in $\Omega$ and a surface integral on $\Gamma$ of products of scalar or vector fields [8].

It should be noted that in the non-conducting domain, **H**

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is expressed by – grad $\phi$. In order to avoid the multi-valued problem of $\phi$ in the case of multi-connected conductors, it is necessary to introduce cut planes allowing potential jumps or to fill the holes by a material with low conductivity [9]. On the interface $\Gamma_c$ of domains **T**-$\phi$ and $\phi$, condition $\mathbf{n}\times\mathbf{T} = \mathbf{0}$ is imposed. This condition allows natural continuity of the tangential component of **H** between domain **T**-$\phi$ and domain $\phi$. Under this condition, it is not necessary to impose the condition of continuity since it becomes natural. Moreover, the boundary integral on $\Gamma_c$ in (4a) is zero [9].

### *B. Surface Impedance and Losses*

Some devices such as clamping frame, bus bars of transformers, windings, shielding, etc. are mainly made up of sheet or line type parts of thin air-gaps or cracks. Modeling these parts using traditional finite volume elements used in 3D software is tiresome, and even impossible. Moreover, the skin effect in ferromagnetic materials increases the difficulties of meshing eddy current problems in under sinusoidal conditions. An alternative to this difficulty of meshing the thin regions is the use special “shell elements” for the modeling of magnetic or thin conducting regions, and “surface impedance” elements for the modeling of conducting regions having a thin skin depth [9].

When the skin depth is small compared to the characteristic dimension of the conductor with a material with linear properties, the physical quantities such as the current or the magnetic field have a known exponential decay [9]. The meshing of the conducting region with traditional volume elements must consist of elements which are smaller than the size of the skin depth. This situation will lead, for some problems, to a very high number of elements. Special surface elements, using the concept of surface impedance, which describe the surface of the conducting region, allow the exponential decay to be taken into account [9]. They also allow the magnetic field to only be calculated on the surface and outside.

The concept of surface impedance comes up based on the Poynting’s Vector formulation and it is applied in finite element to the design of large power transformers. At the surface of good conductors the tangential component of the electric field **E** is approximately proportional to the tangential component of magnetic field **H** and thus,

$$\mathbf{Z} = \frac{\mathbf{E}}{\mathbf{H}} = (1 + j)\frac{1}{\sigma\delta} . \qquad (5)$$

Being **Z** the complex surface impedance and $\delta$ the skin depth in a conductor defined as

$$\delta = \sqrt{\frac{2}{\omega\,\mu\,\sigma}} . \qquad (6)$$

The surface density of Joule losses are expressed according to field **H** by [9],

$$P = \frac{1}{2}\ \mathrm{Re}(\mathbf{Z})\ |\mathbf{H}|^2 , \qquad (7)$$

where Re(**Z**) is the real part of the complex surface impedance.

## III. RESULTS

A three-phase transformer with an auxiliary reactor inside of the tank is considered as an application of this paper. The tank and the clamping frame are made of mild steel. The core and the magnetic shunts are made of silicon-steel laminations. Fig. 1 shows the tank original model. The tank wall (side A) with aluminum electromagnetic shielding, and with magnetic shunts are presented in Fig. 2 and Fig. 3, respectively.

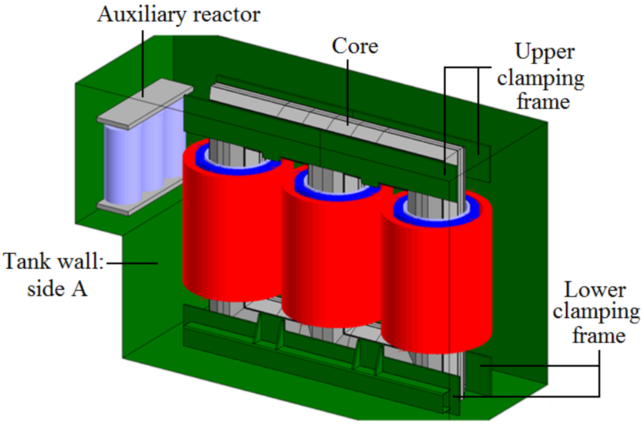

Fig. 1. Tank original model of the transformer.

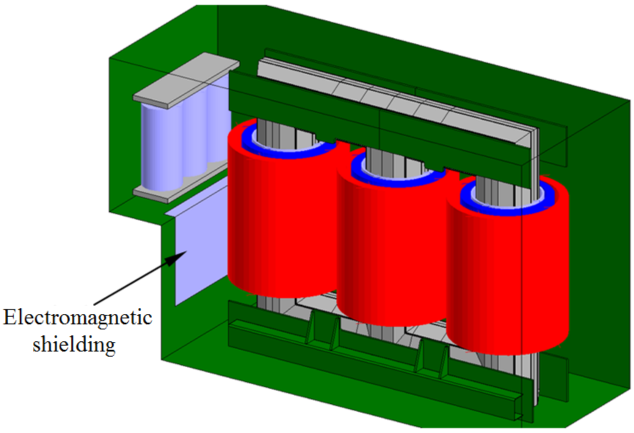

Fig. 2. Model with the tank wall (side A) protected by aluminum electromagnetic shielding.

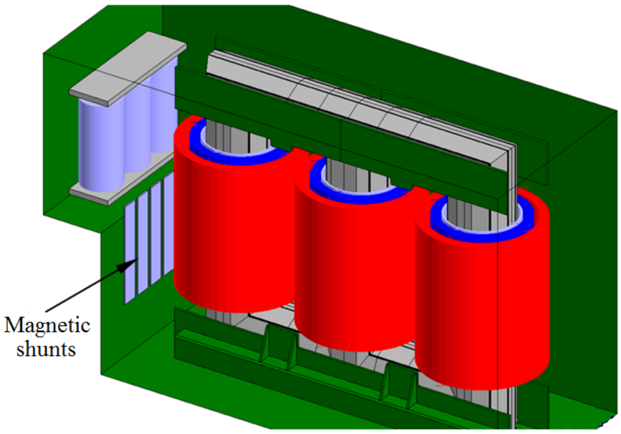

Fig. 3. Model with the tank wall (side A) protected by magnetic shunts.

Fig. 4 and Fig. 5 show the electrical circuit feeding the active part of the transformer and the electrical circuit of the tertiary winding with the auxiliary reactor, respectively. These connections are necessary to model the transformer. The circuit elements C1, C2, C3, S1, S2, S3, T1, T2 and T3 represent, respectively, the common, series and tertiary three-phase windings (coils) of the core. Reat1, Reat2 and

Reat3 represent the three-phase windings of the auxiliary reactor. Rx1 and Rx2 are the resistors. In this modeling the values used for Rx1 and Rx2 were 1mΩ to represent short-circuits. The windings (coils) S1 and S2 are fed by the current sources IH1 and IH2, respectively.

The core and reactor windings (coils) are represented as solid conductors which are characterized by a value of the skin depth comparable to or smaller than the dimensions of the conductor cross-section. The density of supplied or induced (eddy) currents is non-uniform in the cross-section of such conductors. Thus, within a solid conductor, there is a coupling between the electric and the magnetic alternating current fields; eddy currents occur in the volume of such a conductor.

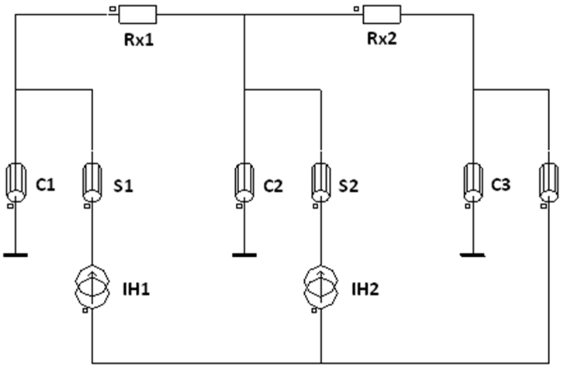

Fig. 4. Electrical circuit feeding the active part of the transformer.

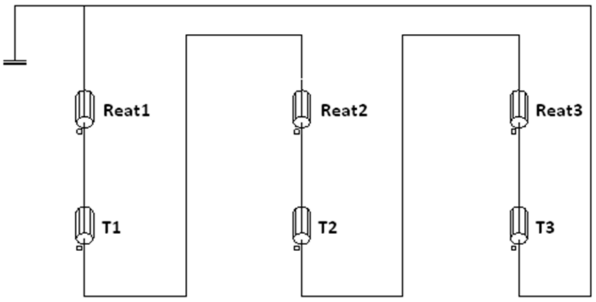

Fig. 5. Electrical circuit of the tertiary winding with the auxiliary reactor.

Fig. 6 and Fig. 7 present the 3D finite element mesh details without and with the windings.

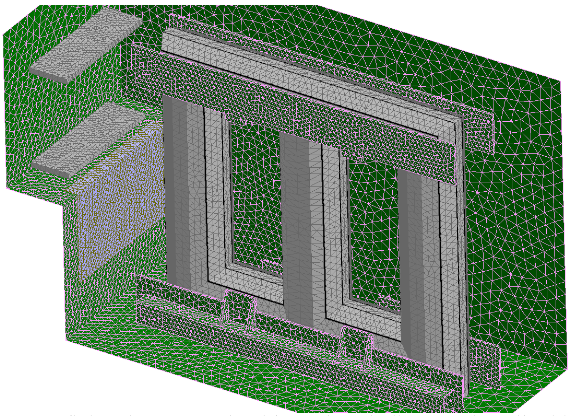

Fig. 6. 3D finite element mesh without the windings: tank wall (side A) with aluminum electromagnetic shielding.

The eddy current losses in the transformer tank for three models: original tank, tank wall with electromagnetic shielding and tank wall with magnetic shunt are showed in Fig. 8, Fig. 9, and Fig. 10, respectively. Note that the eddy current losses in the tank are larger in the original model (Fig. 8). For the analysis of Fig. 9 and Fig. 10 it can be seen that the tank wall (side A) protected by the magnetic shunts has a loss concentration bigger than the tank wall (side A) protected by the aluminum electromagnetic shielding.

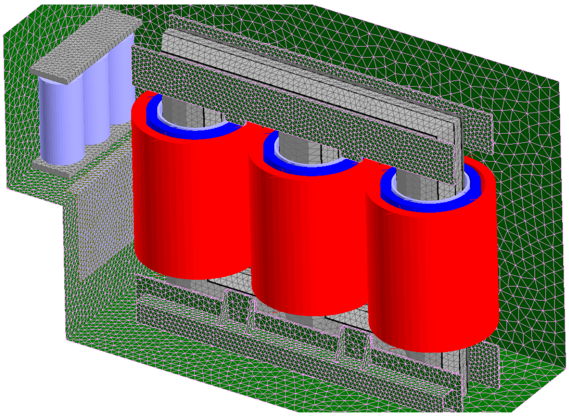

Fig. 7. 3D finite element mesh with the windings: tank wall (side A) with aluminum electromagnetic shielding. In this figure the windings are not meshed.

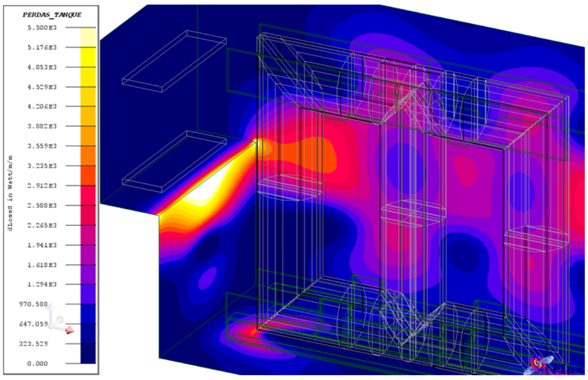

Fig. 8. Eddy current losses in the transformer tank: original model.

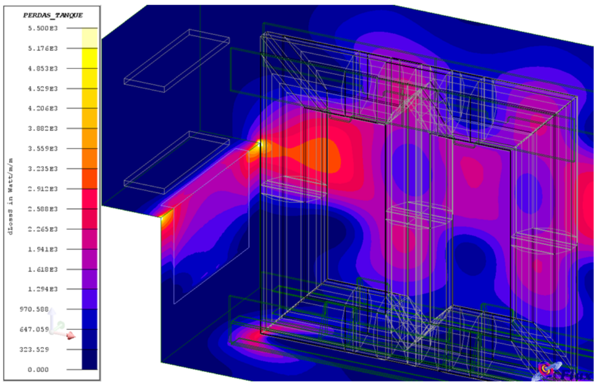

Fig. 9. Eddy current losses in the transformer tank: wall (side A) with aluminum electromagnetic shielding.

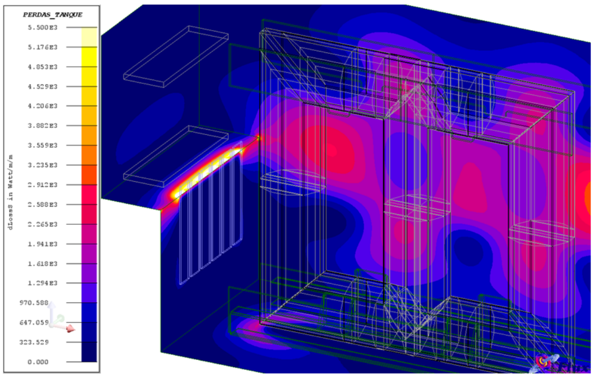

Fig. 10. Eddy current losses in the transformer tank: wall (side A) with magnetic shunts.

Thermal imagers capture images of infrared energy or temperature. They can detect heat patterns or temperature changes in equipment. Fig. 11 shows a thermal image of the tank wall (side A) with magnetic shunts. In this figure can be seen the presence of hot spots in position behind the magnetic shunts (red region). This picture serves as proof for the assertion that the magnetic shunts concentrate the eddy current losses at the top of shunts (see Fig. 10).

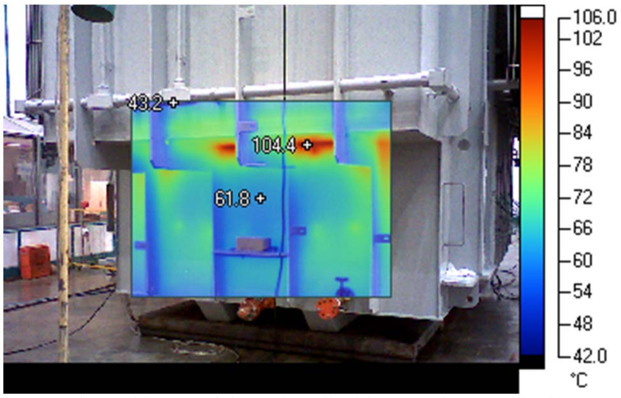

Fig. 11. Thermal image of the tank wall (side A) with magnetic shunts.

The magnetic field distribution in the oil for three models: original tank, tank wall with electromagnetic shielding and tank wall with magnetic shunts are showed in Fig. 12, Fig. 13, and Fig. 14, respectively.

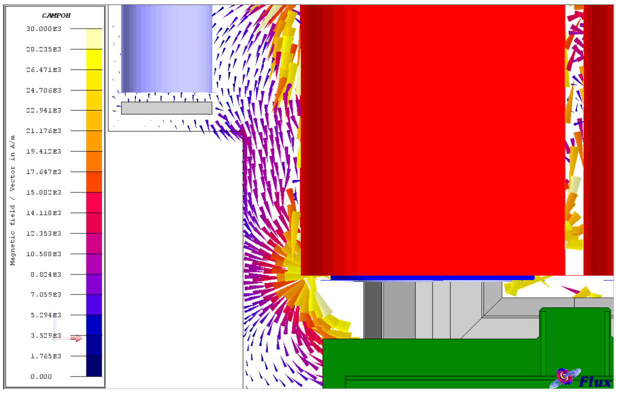

Fig. 12. Magnetic field distribution in the oil: original model.

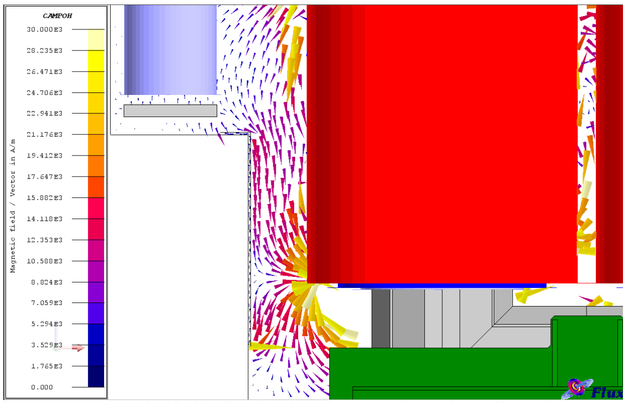

Fig. 13. Magnetic field distribution in the oil: tank wall (side A) with aluminum electromagnetic shielding.

In this paper, the clamping frame, the transformer tank and the electromagnetic shielding are modeled by surface impedance method. A conducting region described by surface impedance is the combination of: (i) an inactive volume region, (ii) the boundary of the region on which the impedance surface condition is applied. So, the magnetic field is tangent to the boundary. The state variables are not computed on the internal nodes of the volume region (inactive). Therefore, it is not necessary to mesh this region. Because of this, in this paper, the tank thickness is not considered in the 3D calculation domain and the clamping frame and electromagnetic shielding volumes are inactive volume regions.

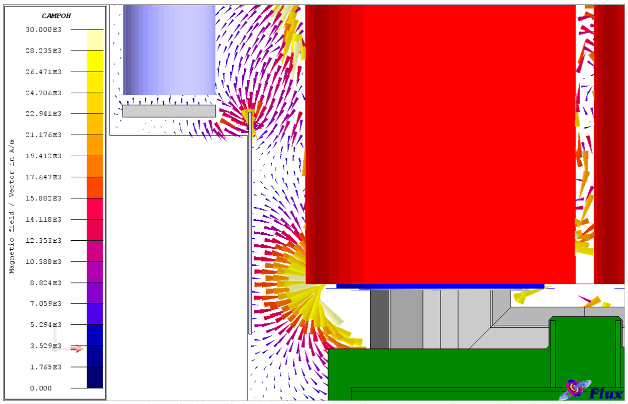

Fig. 14. Magnetic field distribution in the oil: tank wall (side A) with magnetic shunts.

In Fig. 12 and Fig. 13 it is possible to notice that there is only tangential component of the magnetic field in the tank walls and in the electromagnetic shielding, respectively. However when the magnetic shunts are used, it is observed that the magnetic flux tends to pass through the shunts (Fig. 14).

Table I shows the eddy current losses (per unit) in the structural metal parts. These values are in p.u. and the base value used is the total losses of the original model. The total losses, in this case, are the sum of the tank, upper clamping frame and lower clamping frame losses.

In this work all the numerical simulations were executed in a computer with processor Intel Core i7-980X, 3.33 GHz, 16GB RAM, Windows 7.

TABLE I
EDDY CURRENT LOSSES (PER UNIT) IN THE STRUCTURAL METAL PARTS

| | Original tank | Tank wall with electromagnetic shielding | Tank wall with magnetic shunts |
|---|---|---|---|
| Tank | 0.735 | 0.702 | 0.673 |
| Upper clamping frame | 0.096 | 0.097 | 0.093 |
| Lower clamping frame | 0.169 | 0.167 | 0.159 |
| Electromagnetic shielding | 0.000 | 0.003 | 0.000 |
| Total losses | 1.000 | 0.969 | 0.925 |

## IV. CONCLUSIONS

Losses in transformers are important because they are usually stated in the contract. Thus, manufacturers must be able to estimate them in order to escape paying penalties. This paper described some results obtained by R&D department of Siemens Ltda/TUSA Transformers, Brazil. The work analyzed the effects of electromagnetic shielding and magnetic shunts on the eddy current loss reduction in the transformer tank. The thermal image of the tank wall (side A) with magnetic shunts showed the presence of hot spots in the same region where the eddy current loss values are higher. In future works the magnetic field results will be validated by comparisons with measurement ones.

The use of surface impedance method for the modeling of tank, clamping frame and electromagnetic shielding of the transformer presented the following advantages: (a) thickness of the thin region which can be changed without modifying the geometry or the mesh in order to carry out parametric studies easily according to this thickness; and (b) the time of calculation which is reduced compared to the use of traditional volume elements.

When a volume conductive region with pronounced skin effect is described by using a surface region of the solid conductor type described by the surface impedance formulation, it is not possible to use for this region a magnetic nonlinear material. This aspect can be considered as a disadvantage of surface impedance method.

It is important to emphasize that if the clamping frame, the transformer tank and the electromagnetic shielding were modeled by volume elements, the computation time of 3D model would be impractical. Because of this the authors did not compare the computation time between the surface impedance method and the method using traditional volume elements.

Despite the eddy current losses are smaller in the tank with magnetic shunts, they are more intense locally. Thus, in this case, the best solution is to protect the tank wall (side A) using the aluminum electromagnetic shielding.

The transformer used in this paper is not a prototype, but a transformer sold to a customer. Because of this, the authors did not provide more details about the currents used in the numerical simulations, the nominal conditions, the eddy current losses in watts, the geometry data, the local values of magnetic inductions and magnetic fields, etc.

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## VI. BIOGRAPHIES

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His fields of interest are the design of electrical transformers, analytical and numerical methods in electromagnetics, electrical and magnetic sensors, and applied electronics.

**Mauricio Valencia Ferreira da Luz** obtained his electrical engineering diploma at the State University of Santa Catarina (UDESC) (Joinville, Brazil) in 1997.

He received the Master and Doctor degrees in electrical engineering from Federal University of Santa Catarina (UFSC) (Florianópolis, Brazil), in 1999 and 2003, respectively. In between April 2001 to October 2002 he studied at University of Liège (Belgium). Between 2003 to 2005, he was a professor at the University Center of Jaraguá do Sul (Jaraguá do Sul, Brazil). In December 2005, he became a permanent member at the Department of Electrical Engineering at UFSC. He has also been working in some research projects financially supported by the Brazilian Federal Research Councils (FINEP - CNPq) as well as by private companies.

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**Glauco de Melo Cangane** obtained his MBA in product engineering at the State University of São Paulo (USP) (São Paulo, Brazil) in 2007, electrical engineering diploma with emphasis in electrotechnics at the São Judas Tadeu University (USJT) (São Paulo, Brazil) in 2004 and electrotechnical Technician at Federal Technical School of São Paulo in 1998 (ETFSP). He works at Siemens Ltda/TUSA Transformers, Jundiaí, SP, Brazil, as a development engineer (R&D). His current position is R&D (Research and Development) Coordinator for transformers: supervision, coordination and management of 14 people in R&D/Engineering department, specialists in standards, materials, heating & cooling, CAE, mechanical calculations and electromagnetic area.

The main activities are related to the R&D activities to improve the product and process considering decrease the design cycle time (DCT), improve quality and manufacturing process, increase savings in materials (MCP - Material Cost Productivity), implement new technology, concepts, innovations and project management of all R&D Projects considering transformers and reactors up to 800 MVA, 800kV, with extensive product portfolio covering the domestic market (utilities and industries) and International (Latin America, the U.S. and Canada).

Mr. Cangane has 17 years experience in engineering, responsible for project management, research, development, technology and innovation of products and processes, projects, technical support, training, consulting, mechanical detailing, simulation and sales.

**Alexandre Komar** obtained his electrical engineering diploma at the University of São Paulo (USP) (São Paulo, Brazil) in 1987. Since 1993 he works at Siemens Ltda/TUSA Transformers, Jundiaí, SP, Brazil, as an electrical engineer. His current position is power transformer design manager: design management of electrical power transformers and reactors, leading nine engineers.

The main activities are related to the calculation of electric power transformers and reactors up to 800 MVA, 800kV, with extensive product portfolio covering the domestic market (utilities and industries) and International (Latin America, the U.S. and Canada); support for the development sector in creating new products, concepts and design.

Mr. Komar has 16 years experience as a designer of power transformers and reactors.

**Paulo do Amaral Avelino** obtained his electrical engineering diploma at the Fundação Valeparaibana de Ensino (FVE)/Universidade do Vale do Paraíba (UNIVAP) (São José dos Campos, SP, Brazil) in 1985.

Since 2000 he works at Siemens Ltda/TUSA Transformers, Jundiaí, SP, Brazil, started as mechanical design manager at engineering department. Since 2007 he is the general manager of engineering department for transformers.