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Non linear Heating Hazard Assessment on Transformer Covers and Tank Walls

***Abstract**. This paper evaluates the heating hazard on transformer covers and tank walls by means of an electromagnetic analytical formulation linked with thermal FEM. A non linear magnetic permeability approximation is introduced in the computation methodology, in which power losses are calculated into the thin skin depth penetration of electromagnetic wave using Poynting's Vector. The temperature is computed on metallic structural parts heated by electromagnetic induction. The accuracy of obtained results and non linear permeability approximation are validated experimentally.*

***Streszczenie.** W artykule dokonano ewaluacji zagrożenia nagrzaniem pokryw I ścian kadzi, używając wzoru analitycznego na pole elektromagnetyczne sprzężonego z metodą elementów skończonych dla analizy zjawisk cieplnych. W obliczeniach elektromagnetycznych wykorzystano nieliniową charakterystykę magnesowania i głębokość wnikania. Temperatura została obliczona w konstrukcyjnych elementach metalowych – wyniki obliczeń zostały zweryfikowane eksperymentalnie. (**Ocena zagrożenia nagrzewaniem pokrywy oraz ścian kadzi transformatora**).*

Keywords: Overheating hazard, Hot Spot, Transformer cover and tank wall, Poynting´s Vector.
Słowa kluczowe: zagrożenie przegrzaniem, gorące miejsce, pokrywa transformatora i ściany kadzi, wektor Poyntinga.

Introduction

Electromagnetic or stray fields when intruding into metallic structural parts of large power transformers cause eddy current losses lowering their efficiency. In addition high stray loss density values might give rise to local high temperatures, more important in terms of safety and reliability. One of these particular situations occurs when high current leads pass through steel cover plates and parallel to tank walls which are thermally hazardous elements in power transformers [1].

In the literature a large amount of papers focus their results on stray power losses estimation methods due to electromagnetic leakage flux [2, 3]. The field computation differs for the case of transformer covers where the field is tangential to the plate surface [4] and the tank wall where the field is normal to the iron surface [5]. But the correct prediction of the temperature distribution due to electromagnetic induction can only be considered by means of a coupled magneto-thermal analysis [6].

Transformer manufacturers demand a practical tool to clearly identify overheating hazard in large power transformers as its minimization and control plays a decisive role in the design of bushing plates and tank walls. By using commercial Finite Element Method (FEM) software packages, the mesh needs to be very fine to account for the thin skin depth penetration of electromagnetic flux into solid metal [7] leading to a huge number of elements. To avoid large models authors presented in [8] a practical methodology combining an electromagnetic analytical formulation with the thermal FEM to assess overheating hazard on transformer covers. Here the accuracy of the results is ensured by the proper identification of electromagnetic and thermal parameters such as material properties or heat exchange coefficients. This is done by means of a practical calibration process based on measurements.

In this paper the computation methodology [8] is extended to assess the temperature distribution in tank walls. Moreover, authors introduce for both, the transformer cover and the tank wall, analytical expressions, already available in the literature [9], to take into account non linear iron permeability.

Computation Methodology

A practical 3D methodology [8] combining an electromagnetic analytical formulation, based on the numerical integration of Poynting's vector, linked with thermal FEM is used in this paper.

In a 3D Cartesian coordinate system (x,y,z) the propagation in z-axis of power of electromagnetic fields at any point (x,y) in VA/m^2 can be formulated by *Poynting's Vector* $\mathbf{S}$, being its instantaneous value calculated as

$$\mathbf{S}(z,t)=\mathbf{E}(z,t)\times\mathbf{H}(z,t)=\frac{1}{2}\Re e\left[\mathbf{E}(z)\times\mathbf{H}^{*}(z)\right] \tag{1}$$

where $\mathbf{E}$ is the electric field and $\mathbf{H^*}$ is the complex conjugate of magnetic field vector. The complex power losses $\mathbf{S}_{av}$ over a metallic surface s (z=0) in VA/m^2 are

$$\mathbf{S}_{av}(z=0)=p_s+jq_s=\frac{1}{2}\frac{(1+j)}{\sigma\delta}H_{ms}^2 \tag{2}$$

where H_{ms} is the peak value of the electromagnetic field H at the plate surface.

$$\boldsymbol{Z}=(1+j)\frac{1}{\sigma\delta} \tag{3}$$

In (3) $\boldsymbol{Z}$ is the complex Surface Impedance (SI) and δ is the skin depth in a conductor defined as [7]

$$\delta=\sqrt{\frac{2}{\omega\,\mu\,\sigma}} \tag{4}$$

being ω the frequency of the source, μ the permeability and σ the electrical conductivity of the steel. The SI will be referred as linear or non linear SI depending on if constant or non linear permeability is used respectively.

Transformer Cover

For calculating stray losses in conducting steel plates, on the surface of which the field is incident having a tangential peak value of H_{ms}, authors applied the co-author Turowski's equation [9]. This equation is defined in (5) being x and y are the cartesian coordinates of each point.

$$P_s=a_p\iint_s\sqrt{\frac{\omega\mu}{2\sigma}}\frac{\left|H_{ms}(x,y)\right|^{2x_p}}{2}\,dx\,dy \tag{5}$$

Where H_{ms} may be calculated according to [8] for one conductor, single phase or three phase bushings. By means of (5) stray losses into the skin depth penetration are integrated on the entire plate area s. The factor a_p=1.3 to 1.5 is a linearization coefficient which takes into account the variation of the relative permeability inside solid steel. For non-magnetic plates $a_p \approx 1$. A semi-empirical correction factor of x_p=1 is used for non-magnetic metals, and x_p=1.05 to 1.14 for magnetic steel depending upon the structure of the investigated element, the nature of the field and the type of steel [9].

In this paper an analytical approximation for the non linear magnetic characteristic is used [9]

$$\sqrt{\mu_r}\,\mathbf{H}^2 = c_1\mathbf{H} + c_2\mathbf{H}^2 \tag{6}$$

where for structural steel c_1=310·10^2 A/m and c_2=7.9.

For the FEM thermal analysis the transient heat transfer equation is solved [10]

$$\rho C_p \frac{\partial T}{\partial t} = p_v + k_t \nabla^2 T \tag{7}$$

where k_t is the thermal conductivity, ρ is the density, C_p is heat capacity, T is the temperature and p_v is the volume density of power of the heat sources.

The penetration depth of the electromagnetic field into the metal, and consequently the thickness δ of the regions where heat sources are localized in the thermal model is calculated by means of (4).

Thus, with the electromagnetic analytical formulation the leakage power losses are computed for each surface region s_n, then they are exported to a thermal 3D FE model and introduced into the thin depth penetration as heat sources, linking in this way the two models. The steady state solution of (7) is the space temperature distribution, and its maximum value is known as the “Hot Spot”.

Tank Wall

The proposed methodology in [8] can be extended to the case of tank walls. Let us consider a steel plate of height h in the x direction and length L in the y direction. A current conductor passing parallel to the steel plate on the x direction, and at a distance a on the z direction, departs radial stray flux which intrudes normal into the iron surface. When calculating losses in tank wall where the field varies only in the xy plane, having a peak value of H_{mz0} at the surface ($z=0$), the problem is reduced to a 2D model [9]. From Maxwell equations, the field along the tank wall in y direction is

$$\mathbf{H}_{my}(y,z) = (1+j)\mu_0\sqrt{\frac{\omega\sigma}{2}}\int \frac{1}{\sqrt{\mu}} H_{mz0}(y,0)\,dy \tag{8}$$

The following analytical approximation [9] for the non linear permeability is used

$$\frac{1}{\sqrt{\mu}} = A_1 + A_2\sqrt{\mu}\,\mathbf{H} \tag{9}$$

where for structural steel $A_1 = 14\sqrt{\frac{Am}{Vs}}$ and $A_2 = 0.13\frac{m^2}{Vs}$.

Moreover, a factor k_s is used to compensate the value of losses in a plate of finite dimensions [11]

$$k_s = \frac{h}{\left(\frac{L}{h}\right)^2 + 1} \tag{10}$$

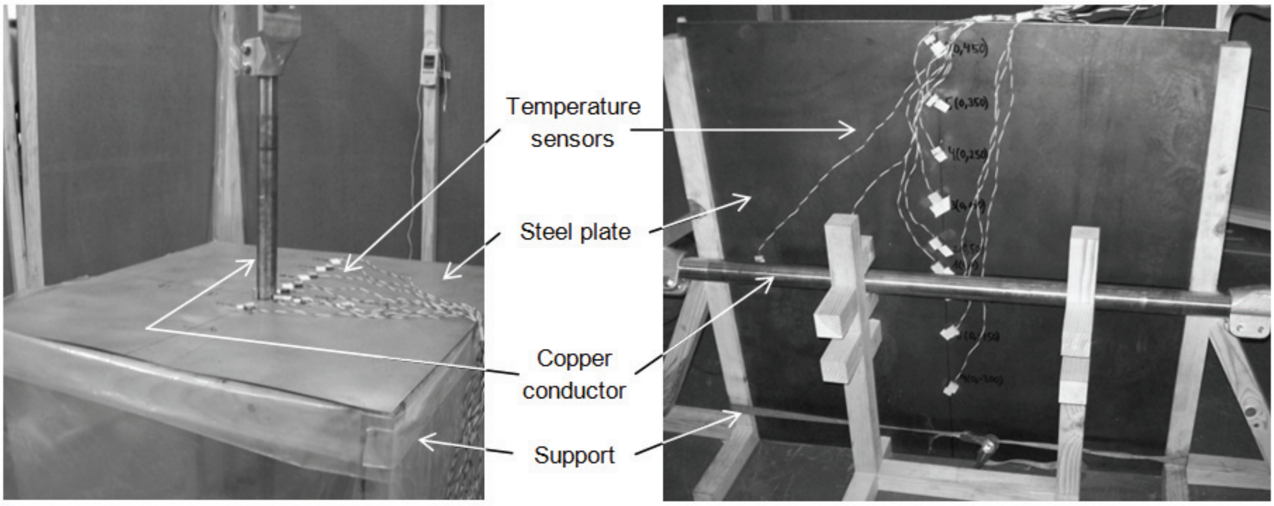
The actual power losses P_{act} are calculated (11) and introduced in the thermal FEM model (7) as heat sources.

$$P_{act} = k_s \cdot P_s \tag{11}$$

To choose the adequate data of electromagnetic and thermal parameters is essential for the accuracy of temperature results. Some parameters needed in the models related with boundary conditions and material properties might be inaccurate as they are usually taken from catalogues and literature. Therefore, the models are adjusted by means of a calibration process which identifies the appropriate input parameters for the simulation. The thermal model is calibrated first for low currents, and then simulations can be carried out for the same model with any number of conductors and different load conditions.

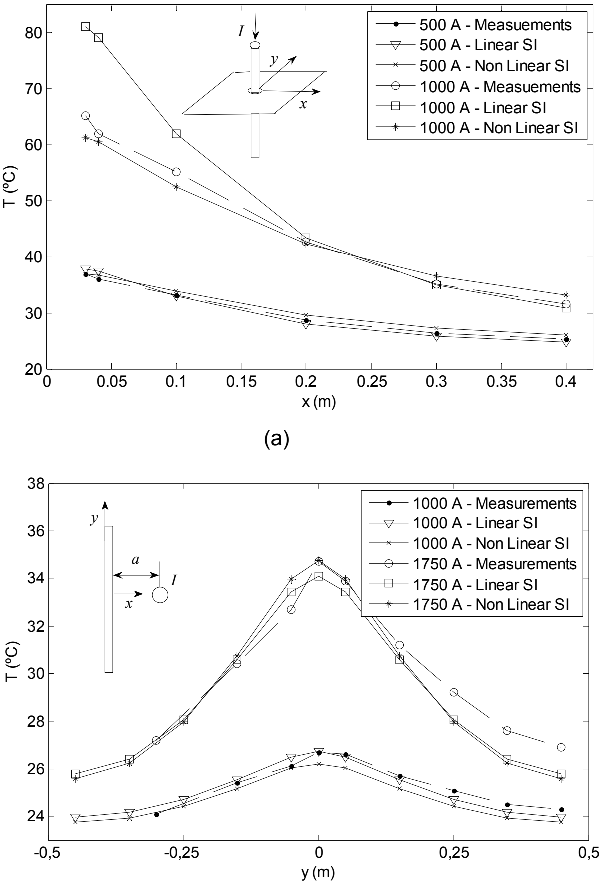
Experimental Validation

For validation of the above methodology a square steel plate of 1 m side and 6 mm of thickness is used for experimental setup. In the case of the tank cover, as seen in Fig. 1a, in the middle of the plate a hole of 60 mm diameter is done through which a solid copper conductor of 48 mm diameter is placed. Through the conductor flows a 50 Hz current. The steel plate is held by a wood closed-support which states the boundary conditions.



(a) (b)

Fig. 1 Laboratory setup for temperature measurement for a) transformer cover and b) tank wall.



(a)

(b)

Fig. 2 Temperature results compared with measurements a) over a cover plate and b) along a tank wall.

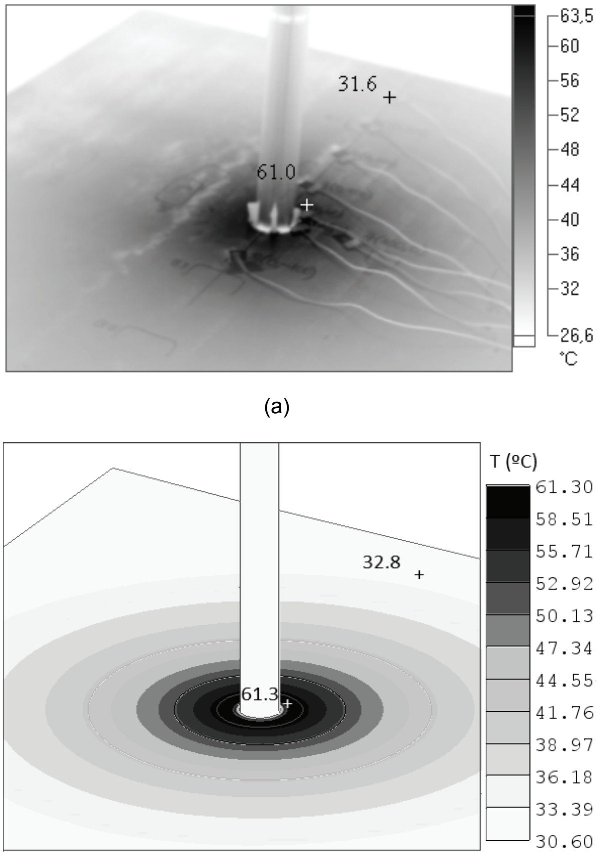
In the case of the tank wall, the copper conductor is placed parallel to the steel plate at a distance a of 50 mm as can be seen in Fig. 2b.

In the described conditions the temperature is measured by means of several temperature sensors Pt100 distributed on the steel plate until it reaches steady state. The ambient temperature is also measured during the tests as well as the temperature inside the support for the cover plate.

Simulation Results

For the thermal model of the transformer cover the volume limited by the skin depth penetration δ is divided into n sub-volume regions V_n, with surface s_n [8]. Power losses are computed (5) with the linear SI method (i.e. μ_r being a constant value) and with the non linear SI method (6) and exported to the thermal 3D FE model as heat sources p_v according to (7). Some parameters present in the FE thermal model as convective heat exchange coefficients or the material properties (ej. μ, σ) are identified by means of a calibration process [8].

Simulation calibrated parameters are shown in Table 1. The model was calibrated for both linear and non linear SI methods with a low current (500 A). After calibration, simulations are carried out for a load current of 1000 A as shown in Fig. 2a and compared with measurements. It can be seen from Fig. 2a how the non linear SI model better approximates the measured temperature, being the results for the linear SI model far higher. In Fig. 3, a 3D FEM simulation for the non linear model is compared with the thermal infrared imaging from tests for 1000 A where the accuracy of results shows up.



(a)

(b)

Fig. 3 Transformer cover test with 1000 A flowing through the conductor. a) Thermal infrared imaging compared with b) Thermal FEM simulation for the non linear model.

The simulation methodology is applied in the tank wall for a 2D FE model. Simulation results can be seen in Fig. 2b for calibration (1000 A) and load conditions (1750 A), and calibrated parameters for the linear and non linear SI models are shown in Table 1.

It can be seen from Fig. 2b how the non linear SI model better approximates the measurements, mainly at the hottest spot temperature sensor. Simulation results for the linear SI model are slightly lower than measured values. Note that the effect of the analytical approximation for non linear permeability is opposite of what happens in the cover plate. This is due to the permeability also appears on the magnetic field expression (8) dividing, therefore for strong fields, the permeability is lower, and the power losses are higher compared to the linear case.

Once the thermal model is calibrated for low currents, and tested for load conditions, the temperature distribution can be predicted for any load condition with accuracy. As the source current is raised, the differences between the linear and the non linear SI method increase. Table 2 shows the hottest spot temperature for the transformer cover and the tank wall for both, the linear and the non linear SI model at calibrated as well as higher load currents.

Conclusions

To evaluate the overheating hazard on large structural parts of power transformers a practical methodology taking into account electromagnetic skin depth penetration has been used. Losses are evaluated by means of an electromagnetic analytical approach linked with 2D and 3D FE models for the tank wall and cover plate, respectively. To take into account non linear iron permeability authors introduced in this paper analytical approximations.

Table 1. Simulation parameters and material properties for the linear and non linear calibrated models

Parameter	Linear SI	Non Linear SI
Transformer cover		
Steel electrical conductivity σ	$6.8 \cdot 10^6$ S/m	$6.8 \cdot 10^6$ S/m
Steel thermal conductivity k_t	52 W/mK	52 W/mK
Steel relative permeability μ_r	900	Equation (6)
Linearization coefficient a_p	1.4	1.5
Heat transfer coefficient h_c	5 W/mK	5 W/mK
Tank wall		
Steel electrical conductivity σ	$6.8 \cdot 10^6$ S/m	$6.8 \cdot 10^6$ S/m
Steel thermal conductivity k_t	52 W/mK	52 W/mK
Steel relative permeability μ_r	1000	Equation (9)
Linearization coefficient a_p	1.3	1.3
Heat transfer coefficient h_c	10 W/mK	7.5 W/mK

Table 2. Hottest spot temperature for linear and non linear models

	I (A)	Linear SI	Non Linear SI	Difference
Transformer cover	500	37.9 ºC	37 ºC	0.9 ºC
	1000	81.2 ºC	61.3 ºC	19.9 ºC
	3000	395 ºC	209.6 ºC	185.4 ºC
	4000	552.3 ºC	293 ºC	259.3 ºC
Tank wall	1000	26.7 ºC	26.2 ºC	0.5 ºC
	1750	34.1 ºC	34.7 ºC	- 0.6 ºC
	3000	53.3 ºC	60.1 ºC	- 6.8 ºC
	4000	74.9 ºC	105.7 ºC	- 30.8 ºC

An experimental setup for temperature measurements at high currents is presented. Measurements are compared with simulation results for the linear and non linear methods. It can be seen from the results how the non linear SI models better approximate the measured temperature in both, the transformer cover and tank wall.

For the same level of currents hot spots and overheating hazard clearly appear over transformer covers, while in the tank wall the measured values of temperature are lower.

The presented methodology is applicable to any number of conductors, drastically reduces the computation time during the design stage of large power transformers and allows to easy localizing the hottest spot temperature over transformer tank walls and cover plates.

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