3D Field Calculations of the Modular Transformer Heating under High Frequency Operation

Tomczuk B., Koteras D., Waindok A.
Opole University of Technology, Department of Industrial Electrical Engineering
ul. Proszkowska 76, 45-758 Opole, Poland
b.tomczuk@po.opole, d.koteras@po.opole.pl, a.waindok@po.opole.pl

***Abstract* — Eddy current losses in the transformer cores under high frequency operation have been computed, and 3D magnetic and temperature fields have been determined with FEM. The heating of the cores and rise in temperature of the windings (vs. time) have been calculated for the two different transformer constructions. Due to brevity of the short version, the results for one of them are presented in this paper. They have been compared with that ones from our prototype tests and a good agreement has been obtained.**

***Index Terms* — electromagnetic fields, thermal analysis, transformers, magnetic materials, eddy currents.**

I. Introduction

In low frequency operation (hundreds of Hz) the Joule losses in the transformer windings are the most important sources of warmth. For higher frequencies, the eddy current and hysteresis losses become more significant and they remarkably influence the transformer body heating.

Calculations of eddy currents or hysteresis losses in laminated cores are quite difficult [5], especially for the amorphous transformers [6]. Due to small thickness of the core layers (20-30 μm) it is well-nigh impossible to analyze the 3D magnetic field in each separate thin core scroll or in each thin sheet. To avoid the inconvenience, the core body can be assumed as a solid material with disparate parameters [4]. In our method, on the grounds of the power loss calculation, we determined the conductance σ and magnetic permeability values for the equivalent solid core material. Due to brevity of the paper, we don't go into details of the approach. We have presented the thermal 3D field analysis and its measurement verification, as the subject of this paper.

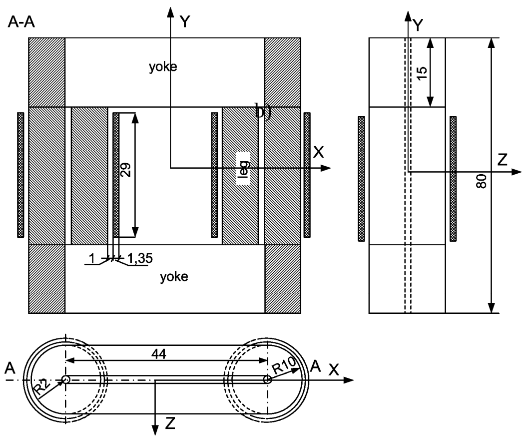

Fig. 1. Cross-sections and main dimensions of the analyzed transformer

The calculation of the heating could be done with using many methods. However, for 3D calculations, the field analysis should be carried out.

II. Physical Models of the Transformers

In our work, two 1-phase, modular transformers have been analyzed. Due to brevity of the paper, the results for one of them are presented, only. The assumed coordinate system and main dimensions (in mm) of the transformer are presented in Fig. 1. Its core is made of the amorphous ribbon. The excitation winding is divided into two symmetrical coils. Each one (of N=21 turn), with the resistance value R=0.057 Ω, is wound on separate leg (Fig. 1).

III. Mathematical Models

In order to calculate the core losses and the temperature distribution, FEM has been used. Due to symmetry of the object, only the halved cross-section has been considered.

A. Eddy current losses calculation

The eddy current distribution in the transformer core has been calculated with the software Elektra-SS (Opera-3D package), [2]. Its algorithm uses the combination of total and reduced vector potentials to model the time varying electromagnetic fields [3]. In regions where the eddy currents arise, the equation for a total vector potential $\vec{A}_T$ and an electric scalar potential V has to be solved

$$\nabla \times \frac{1}{\mu} \nabla \times \vec{A}_T = -\sigma \frac{\partial \vec{A}_T}{\partial t} - \sigma \nabla V \qquad (1)$$

The coils are wound using the Litz cable. Thus, for the mathematical modeling, we can neglect the eddy currents in thin little wires of the cable. The Joule losses in the coils were taken into account.

B. Temperature calculation

The Opera-3d/Tempo solver [2] has been adopted to calculate both static and transient thermal fields.

TABLE I
Material properties used in the thermal model

Property	Amorphous tape	Cooper	Air
Thermal conductivity κ [W/(m·K)]	54	401	0,031
Thermal capacitance *c* [J/(kg·K)]	449	384	1007
Mass density ρ [kg/m^3]	7860	8940	1.205

The heating phenomenon depends on: thermal conductivity κ [W/(m·K)], thermal capacitance c [J/(kg·K)], mass density ρ [kg/m^3], generated thermal power density Q [W/m^3] and the thermal power exchange between object and surroundings. The values of the main parameters, which have been assumed in our models, are included in table I.

The parabolic-elliptic partial differential equation for the temperature T has been solved [1]:

$$\rho\, c\frac{\partial T}{\partial t} - \nabla \bullet (\kappa \nabla T) = Q \qquad (2)$$

For the equation, we assumed two kinds of the boundary conditions. As the tested physical model of the transformer was placed on the insulation plate, on the bottom surface of the transformer the heat insulation has been assumed. On other surfaces the convection phenomenon has been adopted. Due to lack of the thermal radiation coefficient, in the Tempo software [2], we have modified the boundary condition by recalculation of the coefficient [1], according to equation:

$$h_{eq} = h + 4\sigma\varepsilon\left(\frac{T+T_0}{2}\right)^3 \qquad (3)$$

where: σ is Stefan-Boltzmann constant (5,67•10^{-8} W/(m^{2}K^4)), and ε is the emittance value, which can be supposed between 0 and 1. In our numerical models, the emittance ε=0.9 and the convection h=10 W/(m^{2}K) coefficients have been assumed.

IV. Calculation Results

First, the losses distribution in the transformer core has been calculated. The excitation current I_m=2.88 A, frequency f=10 kHz, equivalent core conductivity σ_{eq}=500 S/m and relative magnetic permeability μ_r=20713 (yoke) and μ_r=2067 (leg) have been assumed. Including the value of the Joule losses in the windings, the thermal power density Q= 277 560 W/m^3 in the coils has been determined, and assumed for the calculations. The calculated total core power loss value P=12.77 W, has been compared with the measured one P=12.68 W.

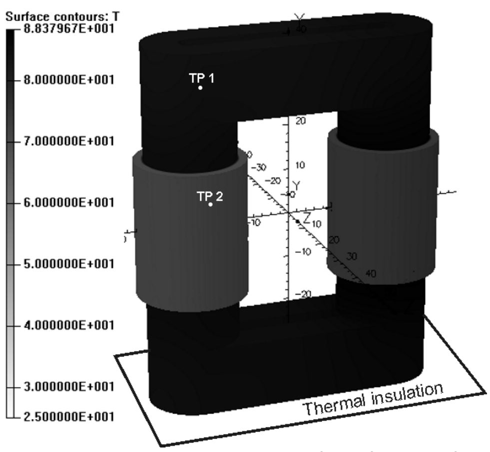

Fig. 2. Calculated temperature on the surface of the transformer

Next, the obtained losses distribution has been exported to the thermal transient model. In Fig. 2, the static thermal field distribution in the modular transformer is presented. In this short version of the paper, the heating transients (Fig. 3) are given for the two points denoted in Fig. 2. The heating curves have been verified experimentally using an infrared camera, and a good agreement has been obtained (Fig. 3).

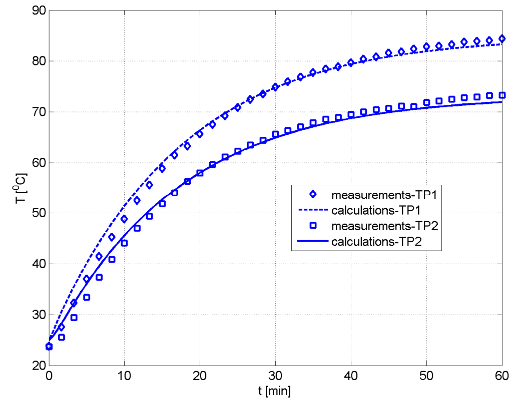

Fig. 3. Heating curves for TP1 and TP2 points (depicted in Fig. 2)

V. Conclusions

Due to difficulties with the laminated amorphous core modeling, the solid core material should be implemented. We determined the equivalent parameters for eddy current loss calculation for high frequency operation. In such a model, the obtained eddy current loss distribution is adequate for the thermal field analysis. For high temperature values, it is important to take into account the radiation coefficient. We have used the complex boundary condition, where the radiation coefficient has been implemented indirectly according the nonlinear expression (Eq. 3).

The method presented in the paper can be used in the CAD designing process of the chokes and transformers, which operate under high frequency excitation. In such a case the eddy currents and their heating effect mustn't be neglected. In full version of the paper, the analogical calculation results for the ferrite transformer will be given.

Acknowledegments

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