3D FIELD ANALYSIS IN 3-PHASE AMORPHOUS MODULAR TRANSFORMER UNDER INCREASED FREQUENCY OPERATION

TRÓJWYMIAROWA ANALIZA POLOWA DLA TRANSFORMATORA 3-FAZOWEGO AMORFICZNEGO BUDOWY MODUŁOWEJ ZASILANEGO PODWYŻSZONĄ CZĘSTOTLIWOŚCIĄ

Streszczenie: Przedstawiono wyniki obliczeń strat mocy w rdzeniu oraz rozkładu temperatury w transformatorze 3-fazowym z rdzeniem amorficznym budowy modułowej, dla dwóch wartości częstotliwości wyższej od technicznej. Do trójwymiarowych analiz pola wykorzystano Metodę Elementów Skończonych (MES).

Abstract: The calculations results of the losses and temperature distributions in 3-phase transformer with modular amorphous core, under two values of the frequency which are higher than the power system one, have been presented. For the 3D field analyses the Finite Element Method (FEM) was used.

Słowa kluczowe: analiza trójwymiarowa pola, temperatura, indukcja magnetyczna, straty wiroprądowe

Keywords: 3D field analysis, temperature, magnetic flux density, eddy current losses

1. Introduction

The 3-phase and one-phase transformers are widely used in many appliances. In a lot of electrical devices they are operating under with higher frequency supplying than power system one. The eddy current losses in their magnetic cores depend strongly on supplying frequency. Thus, nowadays the magnetic circuits of the transformers are manufactured using amorphous ribbon, which characterise much lower losses than the grain oriented silicon steel [6]. Its thickness is about 30 µm, thus it is well-nigh impossible to analyze the 3D magnetic field in each separate thin core scroll or in each amorphous thin sheet.

Calculations of the eddy currents or hysteresis losses in laminated cores are quite difficult [9], especially for the amorphous transformers [4, 5, 6]. Thus, in the 3D analysis all designers assume the magnetic core as a solid region. However it is difficult to determine the equivalent parameters for such a solid core. In this work we have determined those parameters and calculated the eddy current losses values in magnetic core which have been compared with the measured ones.

2. Physical object and its numerical model

2.1. Geometry of the transformer

In our work, the 3-phase transformer with amorphous modular core was investigated. The rated power of the transformer, under f=50 Hz frequency supplying, is equal to S=10 kVA. The assumed coordinate system and main dimensions (in mm) of the transformer geometry are presented in Fig. 1. The supplied coils have N=116 turns which are divided into two sections. The first one is wound with N₁=20 turns and the second one is N₂=96 turns.

![Fig. 1. Main dimensions of the analysed transformer](image-url)
2.2. Numerical model

In order to the numerical analysis for the magnetic and thermal fields the Finite Element Method has been applied. Due to, the symmetry of the analysed object, the numerical models have included half of the analysed area only.

In the regions where the eddy currents arise, the partial differential equations for the total vector potential \( \mathbf{A} \) and an electric scalar potential \( V \) has to be satisfied

\[
\begin{align*}
\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} &= -\sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla V \quad (1) \\
\n\nabla \cdot \sigma \nabla V + \nabla \cdot \sigma \frac{\partial \mathbf{A}}{\partial t} &= 0 \quad (2)
\end{align*}
\]

where: \( \sigma \) - electrical conductivity, \( \mu \) – magnetic permeability of the material.

The module Elektra SS from Opera 3D package has been employed for the eddy current distribution in the core. The algorithm of that module are based on the combination of total (\( A_x \)) and reduced (\( A_y \)) vector potentials for modeling the time varying electromagnetic fields [1]. As the coils are wounded with wire of small cross section the eddy current losses in the coils have been neglected. However, the Joule losses in the coils have been taken into account, naturally.

The thermal field in the transformer geometry has been analysed using the Opera-3d/Tempo solver [3]. In the transformer area, the Poisson equation (Eq. 3) for the temperature \( T \) model has been solved [2]

\[
\nabla \cdot (\kappa \nabla T) = -Q
\]

where: \( \kappa \) - thermal conductivity [W/(m•K)], \( Q \) - feed thermal power density [W/m³].

The Dirichlet's condition on the calculation region boundaries has been assumed. The ambient temperature \( T_0=25^\circ \text{C} \) has been applied at the edges. On the transformer solid, the convection and radiation phenomena has been adopted. The equivalent radiation coefficient \( h_{eq} \) (7]) has been calculated with the expression (Eq. 4)

\[
h_{eq} = h + 4\sigma_B \varepsilon (T + T_0)/2 \quad (4)
\]

where: \( \sigma_B \)-Stefan-Boltzmann constant \( 5.67 \cdot 10^{-8} \text{[W/(m²•K⁴)]} \), \( \varepsilon \)-the emittance value.

Inside of the coils, the Ohmic losses density values were calculated with the well-known relation

\[
Q = \left( R I^2 \right)/V_{coil} \quad (5)
\]

where: \( R \)- winding resistance [Ω], \( I \)– rms value of the current intensity [A], \( V_{coil} \)– volume of the winding [m³].

3. Calculation results

We analyzed the transformer supplied which has been supplied with sinusoidal current under two frequencies \( f_1=500 \text{ Hz} \) and \( f_2=250 \text{ Hz} \). The number of the turns coil in each phase was equal to \( N=20 \). The assumed amplitudes of the currents for the phases A and C were equal to \( I_{Am}=I_{Cm}=3.64 \text{ A} \), and for the phase B the amplitude \( I_{Bm} \) was equal to \( 3.22 \text{ A} \). Due to low values of the average magnetic flux density inside the magnetic circuit, the two different values of the relative magnetic permeability \( \mu \), have been adopted. For the yoke region the value \( \mu=20713 \) has been assumed. As the magnetic flux in each column is perpendicular to ribbon direction winding the relatively small value of permeability has taken \( \mu=2067 \).

The amorphous cores are built as the laminated structures. The thickness of the lamination ribbon is approximately is equal to \( 30 \mu \text{m} \). Due to difficulty in the modelling of each layer the 3D eddy current problems should be solved using a solid geometry of the core. Thus, the equivalent conductivity of the core should be determined. Lately, it was introduced the technique for the calculation of the equivalent conductivity for a stack of silicon steel sheets [8]. However, the approach is not useful for the amorphous laminated magnetic circuits. Thus, we determined the equivalent conductivity from the tests of the physical model. For field analyses the equivalent conductivity was assumed \( \sigma_{eq}=450 \text{ S/m} \). For frequency \( f=500 \text{ Hz} \) the total core losses are equal to \( P_{Fe}=270 \text{ W} \). Although the amorphous type conductivity is equal to \( \sigma=0.769 \cdot 10^6 \text{ S/m} \), the equivalent one for the solid core field analysis should be significantly lower.

Nowadays is almost impossible the field modeling in the actual structure of the core lamination. For the 3D numerical analyses of
the calculated magnetic cores we substitute a real laminated core for the solid one of the same exterior dimensions. Thus we need to replace the real magnetic circuit by the solid geometry with equivalent parameters (magnetic permeability, electrical conductivity). In our paper the assumed equivalent conductivity was calculated using below relation

\[
\sigma_{eq} = \frac{1}{k_{Jb}} \left( \frac{d}{b} \right)^{0.89} \cdot \sigma_{Am}
\]  

(5)

where: \(d\)- thickness of the amorphous ribbon, \(b\)-average length of the amorphous ribbon in leg, \(\sigma_{Am}\)-electrical conductivity of the amorphous tape material.

\[\text{(5)}\]

The adequate fields presented in Figs. 2 and 3 are similar in distributions for both analysed frequencies. Due to the assumed low value of the electrical conductivity (\(\sigma_{eq}=450 \text{ S/m}\)) to the numerical model nearly the same level of the magnetic flux density \(B\) inside of transformer legs, have been obtained. In the yokes of the object the maximal values of the \(B\) are occurred near the transformer windows. For the frequency \(f_2=250 \text{ Hz}\) the maximal values are slightly higher than those frequency \(f_1=500 \text{ Hz}\). The eddy current densities for the two frequencies \((f_1=500 \text{ Hz}, f_2=250 \text{ Hz})\) a quite different each from other, naturally. For frequency \(f_1\) the maximal values is lower than \(J=9 \text{ kA/m}^2\), while for the twice lower frequency maximal value is about \(J=5.4 \text{ kA/m}^2\).

\[\text{Fig. 2. Field distributions on the surface XZ1, f}_1=500 \text{ Hz}\]

\[\text{a)magnetic flux density} \quad \text{b)eddy current density} \]

\[\text{Fig. 3. Field distributions on the surface XZ1, f}_2=250 \text{ Hz}\]

\[\text{a)magnetic flux density} \quad \text{b)eddy current density} \]

In figures 2 and 3 we presented the distributions of the magnetic flux and the eddy currents densities at the points of the surface XZ which is parallel to the XZ plane (Fig. 1). The surface is shifted by 1 cm from the plane XZ and the noted as XZ1. Figures 2a and 2b concern the frequency value \(f_1= 500 \text{ Hz}\). In the figures 3a and 3b the magnetic flux and eddy currents distributions are presented obtained under \(f_2=250 \text{ Hz}\) frequency of the supplying.

The obtained spatial distributions of the eddy current losses inside the magnetic core has been taken as the input data for the thermal model. In Figs 4 and 5, the static thermal field distributions in the 3-phase transformer with modular amorphous core are presented.
Due to supplying of the lower part of the winding \((N_1=20\) turns) the temperature of the supplied coil is slightly higher than the upper one. Maximal. For the frequency \(f_1=500\) Hz the temperature on the transformer body reaches \(90^\circ\)C. For the lower frequency \((f_2=250\) Hz) the maximal temperature is equal to \(53^\circ\)C. In this ranges of the temperature for the numerical calculations the radiation phenomena should be taken into account [7].

5. References

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