Influence of the air gap between coils on the magnetic flux inside the modular amorphous transformer core has been studied. Finite Element Method (FEM) was used for the 3D field analysis. Calculated fluxes in the columns of the magnetic core have been verified experimentally.

1. INTRODUCTION

Transformers are used in many enterprises of industry. In power system, the transformers must be used at these points where there is a transition between voltage levels [5]. Cores of the traditional transformers are mainly manufactured from thin sheets of high-grade silicon steel [2]. In the ends of fifties the amorphous ferromagnetic materials were invented [6]. The amorphous materials characterize slight power losses, which are several times lower than in grain oriented silicon steel [4]. Thus it is willingly used for building the magnetic cores of small power transformers.

Typical amorphous cores were manufactured in two types. In the first type (C-cores) amorphous ribbon is wound, impregnated and sawed into two halves. In the second one the ribbon is wound for rectangular shape with overlapping joints in the yoke part [7]. In this work was analysed innovated modular construction of the amorphous core, where the core separated parts are manufactured independently in form of cylinders from the amorphous strip [8]. The core with coils is quick and easy assembled.
2. ANALYSED OBJECT AND CALCULATION MODEL

Rated power of the tested prototype transformer is equal $S = 10$ kVA. The nominal value of the current in primary winding is $I_{1N} = 15.2$ A. In the secondary windings the current intensity is equal to $I_{2N} = 26$ A. The primary (inner) coil is wounded with $N_1 = 191$ turns, while the secondary (outer) one has got $N_1 = 116$ turns. The coil system has incomplete layers cling to the air gap between primary and secondary windings. Fig. 1 shows the winding configuration with axial height of 167 mm and smallest air gap of 3 mm between primary and secondary coils. It is visible, that the air gap is situated at the bottom part of the winding. Thus, the gaps at the central and upper parts are larger and the object is not symmetrical in relation to the $XY$ plane. For the two layers clinging to the air gap, the distance to the top yokes are greater. For example, the internal layer of the outer coil are 8 mm from the yokes, (Fig. 1).

![Fig. 1. View of the analysed object and cross-section of the windings](image)

FEM was used for 3D magnetic field analysis. Finite element grid consists of quadrilateral elements. As the transformer is symmetrical about the $XZ$ plane, the mathematical model included only half leakage region. Due, to the core lamination the iron losses were neglected. In addition in our mathematical model the anisotropy of the amorphous alloys was considered.

The calculation model was based on the combination of two scalar potentials: total ($\psi$) and reduced ($\phi$) one [1]. In current free regions, Laplace’s equation governs the field

$$\text{div} \left[ \mu \ \text{grad} (\psi) \right] = 0. \quad (1)$$

In winding conductors, the elliptic partial differential equation with the reduced potential $\phi$ is obligatory.
\[
\text{div} \left[ \mu \text{grad}(\phi) \right] - \text{div} \left( \mu \mathbf{H}_s \right) = 0.
\]

The \( \mathbf{H}_s \) arises from the current excitation coils [3].

The effect of normal ducts and insulation between wires is negligible. Moreover, due to the non load current, the sum of the total ampere-turns in the two coils of one leg is assumed to be non zero.

3. CALCULATION RESULTS AND MEASURING VERIFICATION

We have studied influence of the air gap dimension \( \delta \) between the coils on the magnetic field distributions under short-circuit state. Range of the \( \delta \) variation was 1–7 mm. In Figs. 2a and 2b we presented \( B_z \) component of the magnetic flux density as the 3D histograms. They relate the minimal and maximal values of \( \delta \) That distributions concern axial cross-section about the middle column (YZ plane) under nominal values of the current intensity in each coil.

![3D histograms](image)

Fig. 2. \( B_z \) component values at YZ plane: a) for \( \delta = 1 \) mm, b) for \( \delta = 7 \) mm

Rys. 2. Wartości składowej \( B_z \) na płaszczyźnie YZ: a) dla \( \delta = 1 \) mm, b) dla \( \delta = 7 \) mm

Outside the core, the enlargement of \( \delta \) distance influences mainly the magnetic flux density values between the coils. Inside the core, in the middle part of the legs (Fig. 3), the differences between magnetic fluxes for \( \delta = 1 \) mm and \( \delta = 7 \) mm reach 25%.

From Fig. 3 we can see that the flux inside the columns, in the vicinity of the narrowest gap size, is approximately two times higher then the flux in the cross-section of the column near the biggest air gap. In the air area, the differences between the densities of the magnetic fluxes are circa 20% (Figs. 2a and 2b).
The $\delta$ value significantly influences the leakage inductance, naturally. It was calculated with magnetic field energy. The inductance values are given in table 1.

<table>
<thead>
<tr>
<th>$\delta$[mm]</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_z$[mH]</td>
<td>0.827</td>
<td>1.037</td>
<td>1.250</td>
<td>1.463</td>
</tr>
</tbody>
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Calculated values of the magnetic fluxes, inside of the magnetic circuit, were measured and verified with five 5-turn probes wounded on the legs. The measurement results concern the air gap $\delta = 3$ mm (Fig. 4).

![Fig. 3. Values of the magnetic fluxes inside the leg for various $\delta$](image1)

![Fig. 4. Comparison of the calculated and measured values of the magnetic fluxes inside the leg](image2)
5. CONCLUSIONS

Innovative modular construction of low power transformers has been studied by using Finite Element Method. Influence of the air gap size between the windings on the magnetic field distributions has been studied. The $\delta$ dimension influences field in the air gap between the coils. Thus, the leakage inductance value is changing. Inside the core the $\delta$ variation causes changing the magnetic flux distributions only in the middle part of the three columns. Their values differ approximately 25%, for the $\delta$ variation from 1 mm to 7 mm. Calculations and tests were made using circular coils. A good agreement between calculated and measured values was obtained. However, it is reasonable to assume the method can be applied to rectangular-shaped coils.

REFERENCES


WPŁYW SZEROKOŚCI KANAŁU MIĘDZYCEWKOWEGO NA POLE MAGNETYCZNE TRANSFORMATORA Z AMORFICZNYM RDZENIEM MODUŁOWYM

Analizowano wpływ szerokości kanału międzycewkowego na rozkład pola magnetycznego w transformatorze amorficznym budowy modułowej. Do 3-wymiarowej analizy polowej wykorzystano Metodę Elementów Skończonych. Obliczone wartości strumieni wewnątrz kolumn rdzenia magnetycznego zostały zweryfikowane pomiarowo.