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Shunt Regulation Analysis of The Short-Circuit Inductance based on 3D Magnetic Field in High Reactance Transformer with Movable Shunt

Streszczenie. *W artykule przedstawiono trójwymiarową analizę pola magnetycznego w transformatorze rozproszeniowym (HLR). Obliczenia pola zostały wykonane metodą elementów skończonych (MES). Transformator rozważany w obliczeniach składał się z rdzenia oraz dwóch uzwojeń oddzielonych ruchomym bocznikiem wkładanym w okno transformatora. Wzięto pod uwagę różne pozycje bocznika względem rdzenia transformatora, jak również grubość pakietu blach z którego jest on wykonany. Uwzględniono nasycenie magnetyczne rdzenia i warstw bocznikowych. Dzięki analizie 3D wskazano miejsca nasycenia magnetycznego. Obliczone wartości reaktancji rozproszenia porównano z zmierzonymi i uzyskano dobrą zgodność.* ***Trójwymiarowa analiza pola magnetycznego w transformatorze rozproszeniowym (HLR)***

Abstract. *Analysis of the 3D magnetic field in high leakage reactance (HLR) transformer is presented. The field calculations have been executed with the Finite Element Method (FEM). The transformer considered consisted of a magnetic core and two windings separated by movable shunt stacked from oriented steel sheets. Various locations and thickness of the shunt have been taken into account. Magnetic saturation of the core and shunt laminations was taken into account. Thanks to the 3D analysis the magnetic saturation spots were indicated. The calculated leakage reactance values were compared with the measured ones and a good agreement has been obtained.*

Keywords: finite element method, high leakage transformer, shunt, welders power supply.
Słowa kluczowe: metoda elementów skończonych, transformator rozproszeniowy, bocznik, źródła zasilania spawarek .

Introduction

A lot of papers and books have already been performed on the calculation of magnetic fields in electrical devices [8]. Many calculations of electromagnetic parameters were carried out also for transformers. The innovative designing of such objects have also been based on analyses of magnetic field distributions using both two-dimensional and three-dimensional mathematical models. It concern also the so called High Leakage Reactance (HLR) transformers. They are special, regulating transformers and they are still used as reliable power sources. For example, they are used in high-current systems [12,13] and for an electric arc excitation. They can supply some welding apparatus and discharge lamps without applying of some electronic devices. In this way, we do not introduce some additional harmonics into a power grid except those resulting from the specificity of the electric arc.

HLR transformers as well as other electromagnetic devices are built from a magnetic core formed from thin laminations of magnetic material and from windings fixed on the core. They produce relatively high leakage magnetic flux which splits not only on the windings but also on the armature of those devices. For example, the movable shunt providing the changeable magnetic coupling between primary and secondary windings in HLR transformers makes possible infinitely adjustable secondary voltage to keep the secondary current to be constant.

The HLR transformers' leakage system calculation was started from a two-dimensional field analysis with the Finite Difference Method (FDM) [18]. Due to the unlimited leakage magnetic flux, the 2D method of integral equations was also used [18]. These calculations were mainly related to short-circuit reactance determination [15, 17]. In order to speed up the design method of HLR transformers the scaled models were also used [23].

2-D mathematical models well reflect the reality in magnetic flux distribution for symmetrical or infinitely long objects, mainly. In the physical objects however, there is a change in the nature of the magnetic field at the ends of such objects. Following to the 2-D analyses, the superposition method of 2-D magnetic field solutions was given [19].

Taking into account the unlimited magnetic leakage field, FDM and finite element method (FEM) are troublesome. Because of that, B. Tomczuk developed a method of integral equations [9, 10]. The calculations described above were mainly focused on the HLR transformer cores without shunts. One of the authors (B. Tomczuk) also used the 2-D analysis to calculate the magnetic systems with a fully inserted shunt or with the fixed shunt being a part of the transformer core [16, 17].

Due to the difficulties mentioned above, some threedimensional models, based on the method of boundary integral equations (BIE), were introduced in the research of HLR transformers [9]. The method was used equally well as the finite element method (FEM) to calculate not only HLR transformers but also the chokes with large air gaps [18, 20, 22].

After developing the computer code in Fortran language and execution it within DOS operation system, Fredholm's integral equations with respect to the three-dimensional magnetic field description were solved for calculating of the current transformer inductances, as well [20, 21, 22].

The analysis of the magnetic cores with partially extracted shunts requires not only the three-dimensional approach but also a very precise discretization of the air gap areas and the shunt edges. The authors' achievements in the research focused on the field analysis in unbounded 3D regions have made possible to carry out the FEM analyses for the described issues. Moreover, the improvement of commercial software made them more popular. Therefore, for the calculations of HLR transformers FEM has been used successfully, which is presented in this work.

With the development of numerical technology and the increase in computing power, those methods worked out in the 20th century can be used nowadays for calculation of HLR transformers, as well. Thus, the HLR transformer with the shunt partially inserted into the core window was researched. This paper focuses on the magnetic flux density distribution depending on the shunt fixing relative to the transformer window, as well as on the change of leakage reactance depending on the thickness of the shunt lamination. The finite element method implemented in the commercial ANSYS - Maxwell software was used for the calculations. In order to speed up the execution time, all symmetry conditions of the analyzed area should be used, which was also effected in this work.

Mathematical description

In the ANSYS-Maxwell software, the selected partial differential equations (PDE) of the magnetic field are used. Maxwell's equations are fundamental in every field analysis. The first (1) and second (2) Maxwells' equations are the basis ones [6].

$$rot\,\boldsymbol{H} = \vec{J} \tag{1}$$

$$div\,\boldsymbol{B} = 0 \tag{2}$$

To **simplify** the field analysis, the magnetic vector potential has been used frequently:

$$\boldsymbol{B} = rot\,\boldsymbol{A} \tag{3}$$

In Fig. 1 is shown a relative simple HLR transformer with magnetic shunt partially inserted in the magnetic core. This shunt can be extracted from the transformer window depending on the demanded short-circuit reactance of the windings. For the calculations, the main dimensions in the geometry are given in table. 1.

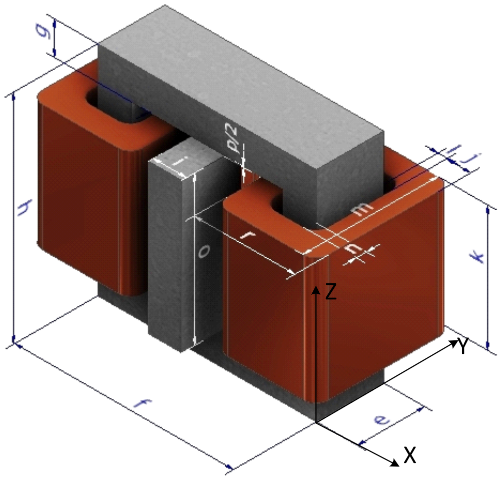

Fig. 1. Dimensions of the calculated transformer

Table 1. Main dimensions (in millimeters) of the calculated transformer.

e	f	G	h	i	j
80	260	40	260	40	29
k	**l**	**M**	**n**	**o**	**p**
150	11	121	12	178	2

After testing the enlargement of the external space out of the core, we assumed the area under the field analysis. For limiting of the calculated region, the Dirichlet's conditions have been taken into account for each component *u* of the vector potential:

$$u(P) = g(P) \text{ for } P \in S \tag{4}$$

where:
- $u(P)$ - the function sought at points inside the R-region,
- $g(P)$ - specified area function for points P belonging to the S edge of the R area.

Due to the nature of the leakage magnetic field and symmetry of the analyzed object, it is necessary to assume the appropriate symmetry conditions of all space. The even and odd symmetry planes were fixed, which allowed to include only a quarter of the presented transformer under during calculations.

First, we applied the anti-symmetry (odd symmetry) rules. They can be mathematically described using the simple condition at the plane *YZ* showed in figure 2.

$$\boldsymbol{A}_{1(-x1,y1,z1)} = -\boldsymbol{A}'_{1(x1,y1,z1)} \tag{5}$$

The symmetry conditions concern the plane which halves the height of the transformer core and the windings. To analyze a quarter of this object we assumed the symmetry rule applied on the plane *XY*.

$$\boldsymbol{A}_{2(2x2,y2,-z2)} = \boldsymbol{A}'_{2(x2,y2,z2)} \tag{6}$$

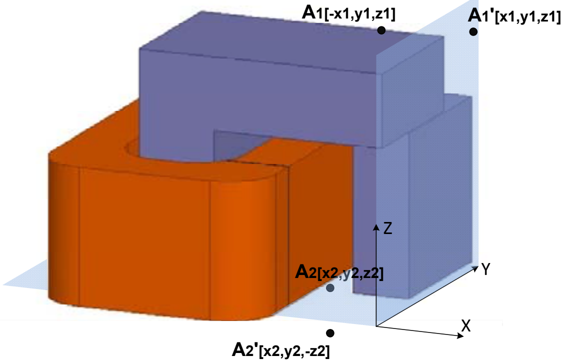

Fig. 2. A quarter of the HLR transformer with the symmetry and anti-symmetry planes

One of the most important elements in FEM is the appropriate discretization of the object. Figure 3 shows a grid made of tetrahedrons for the described transformer [2]. Including the air layer near the iron of the core and shunt, the space around their corners had to be particularly discretized so that the fine mesh of elements be used in the vicinity of the iron. To set the boundary conditions and to describe the anti-symmetry and the symmetry planes, in the ANSYS-Maxwell program the Default option was chosen, what contains the Natural and Neumann problem, equations (4) and (7).

$$\left(\frac{\partial u}{\partial n}\right)(P) = g(P) \text{ dla } P \in S \tag{7}$$

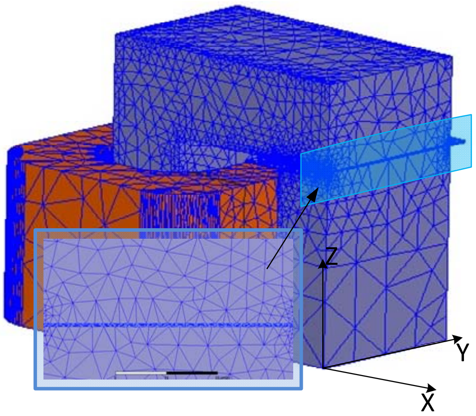

Fig. 3. The axonometric view of the finite elements' grid

For accurate discretization, the object was divided into 400k tetrahedrons. The region that requires focusing the largest number of elements and the most accurate discretization is the gap between the shunt and the transformer yoke.

As input data of the calculations, the 3500A value of the winding magnetomotive force and the power frequency f=50Hz were assumed. The turn number of each transformer winding was 350. The results presented in Chapter 3 concern this data. On the basis of the magnetic field distribution, a magnetic flux was determined to pass the surface located in the middle of the primary winding coil and passing through half of its surface. We integrated the magnetic flux density according to the equation (8).

(8) $$\Phi = \int_S \vec{B} \cdot \vec{dS}$$

Knowing the flux, from a simple relationship, the inductance of the coil was determined. followed by the leakage reactance of the primary winding, equations. (9) and (10).

(9) $$L = \frac{\Phi}{I}$$

(10) $$X_L = \omega L$$

3-D Calculations of HLR - transformer

In the first step, the conditions for the symmetry and anti-symmetry planes described in the previous chapter were introduced. Figures 4 and 5 show the magnetic field distribution for the whole model and for a quarter of the transformer.

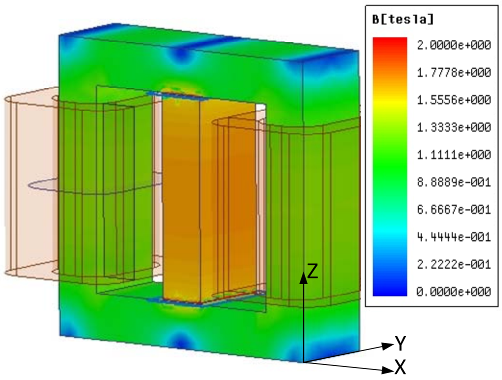

Fig. 4. The distribution of magnetic flux density for the whole model of transformer

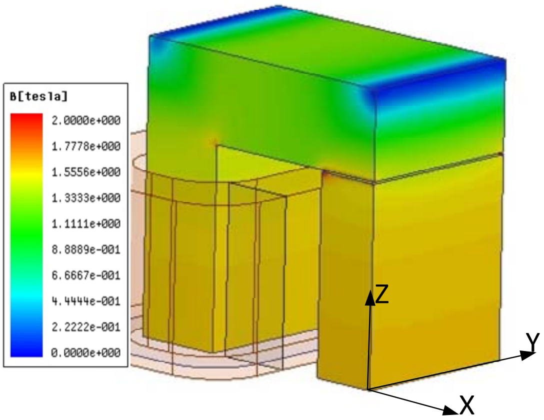

Fig. 5. The distribution of magnetic flux density for the ¼ model of the transformer

In the next step, the magnetic field distribution for the variable shunt position in relation to the transformer window was analyzed. The projection of the shunt from the window was made with a step of 5 mm. After analysis of the field for a transformer with a partially extracted shunt, the leakage reactances of the windings were calculated. The results for the primary winding were shown in figure 6. For the fully inserted shunt, a good agreement was obtained with the results from the 2D analysis [14]. The accordance (dignity) is caused by the fact that the magnetic field of this object with a completely shifted shunt is mainly concentrated in the window of the transformer, and the flux through the shunt determines the total leakage flux.

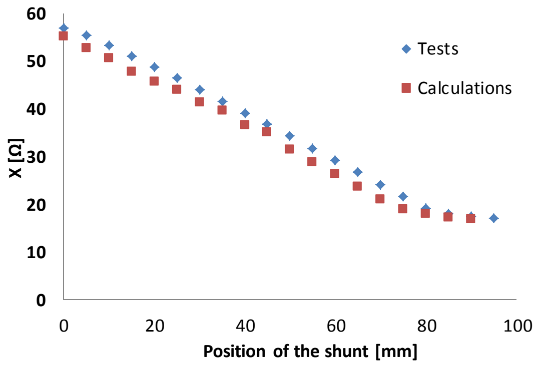

Fig. 6. The reactance of transformer winding with extracted shunt

The leakage reactance was measured for the series opposing windings. For the needs of the measurements (avoiding overheating of the windings), the magnetomotive force of each winding was limited to 350A. For the same value of this force, the leakage reactance of the windings was calculated. In Figure 7, the quarter of the core with the primary transformer winding was calculated. Thanks to the field analysis we could determine some hot spots of the core and shunt. It was noticed when the shunt is pulled out (extracted) from the core window. Its corners and the adjacent parts of the core are going to saturation. This phenomenon was impossible to observe using two-dimensional mathematical models.

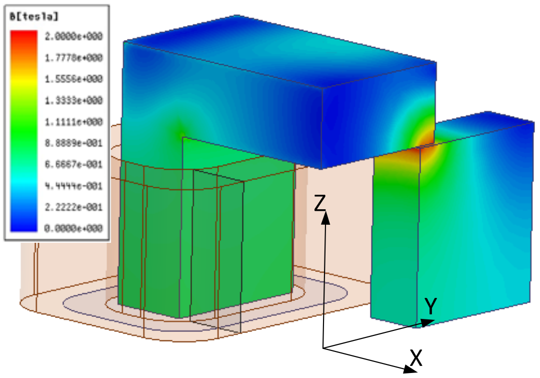

Fig. 7. Saturation of the plate package in the corner of the extracted shunt

One of the ways to change the leakage reactance is changing the width of the shunt inserted into the transformer window.

The characteristic presented in figure 8 confirms the almost linear dependence of the leakage reactance on the shunt width. However, the use of a wider shunt package is associated with heavier and difficult to extract massive construction of the movable part. On the other side, the narrower shunt is willing to magnetically saturate and limits the output minimal current. limits the current adjustment range. Taking into account the above, the considered in this paper transformer was performed for the shunt width of 40mm. After the calculation, the obtained results were confirmed by testing the actual model. The appropriate choose of the shunt is important for designing the devices for electric arc supply. For the HLR transformers to welding apparatus, the shunt should be light and easy movable, whereas this of the transformers for discharge lamps' supplying can be stationary (motionless) and relatively heavy.

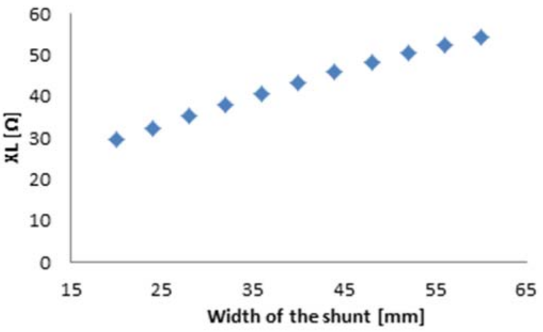

Fig. 8. The reactance of the primary winding of the transformer

Conclusion

The presented 3D mathematical modeling of the magnetic field distribution allows to predict the so called "hot spots" of the magnetic field in the regulating transformers. Moreover, after the calculation of the integral parameters of the field, the nominal data of HLR transformers can be determined. Leakage reactances are the main parameters for the transformers. Thus, they were tested on the prototype and a good agreement have been obtained. Electromagnetic forces and reactances places with the design the selected object in a different examples without having to perform tests on the real, physical object.

The article presents two different methods of welding current adjustment. Changing the width of the shunt is not very effective. However, it can by well used in solutions were the current adjustment is not necessary. Much better results were obtained by changing the shunt extraction from the transformer window. The leakage reactance has been changed almost three times, which allows for the proportional current change. The advantage of this type of solution is a smooth change in value across the entire range. This solution enables the construction of systems allowing for dynamic adjustment of the welding current [4, 15].

During the calculations, it was noticed that in the shunt corners during its extraction from the transformer window, the part of the plate pack goes into saturation. This phenomenon should be taken into account when designing welding transformers. In this case, shunts are used, which partially saturate. This will be the subject of further research by the authors of this article. Adjusting the current in the welding process allows combining more material groups in their wider range of thicknesses. Freedom of welding current adjustment improves the welder's work comfort by giving the possibility to adjust the chosen parameter to personal preferences. The welding current adjustment can be done by changing the reactance of the welding transformer.

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