Bronislaw TOMCZUK, Dariusz KOTERAS

Opole University of Technology

doi:10.15199/48.2017.06.03

3D magnetic and thermal fields for in the transformer with homogenised amorphous C-core under high frequency

Abstract. *In this paper, calculations of magnetic field, including eddy currents phenomenon and thermal field in the 1-phase modular amorphous transformer (C-core) under f =1 kHz frequency supplying, were carried out. Using analytical and iterative methods the equivalent electrical conductivity of the core, has been obtained. 3D field problems were analysed using the electrodynamic potentials within the finite element method (FEM). The selected thermal models have been verified experimentally.*

Streszczenie. *W niniejszej pracy analizowano rozkłady pola magnetycznego, z uwzględnieniem zjawiska prądów wirowych i pól temperaturowych w 1-fazowym amorficznym transformatorze modułowym (z rdzeniem typu C) przy zasilaniu napięciem o częstotliwości f= 1 kHz. Do wyznaczenia zastępczej przewodności elektrycznej rdzenia wykorzystano metody: iteracyjną oraz analityczną. Trójwymiarowe zagadnienia analizowano z wykorzystaniem potencjałów elektrodynamicznych zaimplementowanych w metodzie MES. Wybrane modele termiczne weryfikowano pomiarowo. (**Trójwymiarowe pola magnetyczne i termiczne w transformatorze z homogenizowanym amorficznym rdzeniem pracującym w wysokiej częstotliwości**).*

Keywords: 3D magnetic and thermal field modelling, amorphous modular transformer, eddy currents losses, equivalent electrical conductivity.
Słowa kluczowe: Trójwymiarowe modelowanie pól magnetycznego i termicznego, modułowy transformator amorficzny, Straty z prądów wirowych, zastępcza przewodność elektryczna.

Introduction

Many everyday articles and electrical devices in industry have the magnetic circuits made of the soft ferromagnetic materials. Depending on application of the ferromagnetic, various properties are required. They characterized by different values of the main properties. In Fig 1 are presented annual the percentage share values of soft magnetic materials [1].

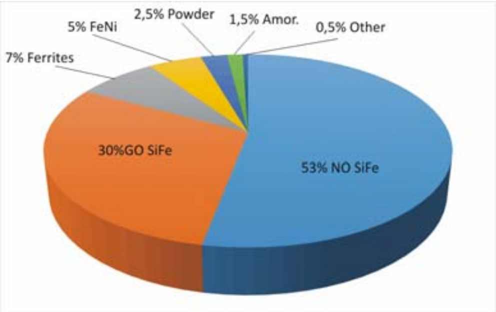

Fig.1. Annual the percentage share values of soft magnetic materials [1]

Nowadays, more often the magnetic circuits are operating under increased frequency of supplying. They can be manufactured either from a solid, (pressed powder) or from laminate sheets with grade oriented, or amorphous steel. In all of these materials the power losses are created [2, 3]. They consist mainly of the hysteresis losses and the eddy current ones. Under high frequency of supplying these losses are main source of the transformer heating. The active materials used in the transformers have different properties and limitations. For example, limit of the operation temperature for some insulating materials. Thus, there is need the determination the temperature of the transformer parts as exactly as possible. The amorphous ribbons are characterized by low power losses. They are used for building of the transformers which are working under higher frequency [4]. However, the calculations of eddy current and hysteresis losses for the laminated cores, with using the 3D field analysis, are quite difficult [5], especially for the amorphous cores [4, 6, 7].

The field analysis for each separate thin scroll or in each amorphous thin sheet (from 20 to 30 μm) is well-nigh impossible. Thus, to calculate the core losses we propose some homogenization of the core laminations. It can be carry out when the core body is assumed from solid material with disparate parameters [8]. ones When the operation frequency is higher than the technical one (50 Hz) The eddy current losses are much more greater than the hysteresis ones. Thus, we have neglected the hysteresis losses in the field analysis in the amorphous core.

Physical object and its numerical model

The 1-phase transformer with modular, amorphous C-core from iron-based alloy, has been investigated. In Fig. 2 is presented the outline of the analysed core with and its main dimensions with the cutting out of the winding. The drawing is placed inside the assumed Cartesian coordinate system.

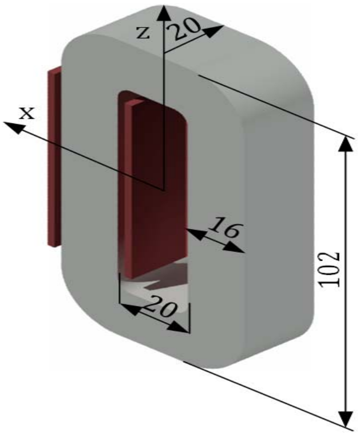

Fig.2. Outline of the investigated object

The excitation winding is wound with N = 21 turns. Its resistance value equals to R = 0.094, (Fig. 2). The coil is wound using the Litz cable. Thus, in our simulations we can neglect the eddy currents in the coil. Our numerical modelling includes 3D calculations of magnetic and thermal fields with using Finite Element Methods (FEM). For the magnetic calculations the Elektra SS module was used. The thermal analysis has employed the Tempo module from the commercial package Opera 3D. The value of the relative magnetic permeability of the amorphous material was assumed, μ_r=2138.

Numerical model

Magnetic field calculations

Determination of eddy currents distributions is possible with the Elektra SS sub-package, under time harmonic field excitation. Algorithm of that module is based on combination of two magnetic vectors. The first is a total one A_t, while the second is called the reduced one A_r [9]. In the regions where the eddy currents arise, the differential partial equation for the vector A_t and the electric scalar potential V has to be solved:

$$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}A_t\right) = -\sigma\frac{\partial A_t}{\partial t} - \sigma\nabla V \tag{1}$$

where σ is the electrical conductivity, μ is the magnetic permeability of the homogenized core material.

$$\mathrm{div}\left[\sigma\mathrm{grad}(V)\right] + \mathrm{div}\left(\sigma\frac{\partial A_t}{\partial t}\right) = 0 \tag{2}$$

In the conducting regions an additional equation, derived from Biot-Savart law, has been introduced [9].

Thermal field calculations

The Opera-3d/Tempo of the package solver [8] has been adopted to analysis both - static and transient thermal fields. In the case of the static model, the Poisson equation for temperature T has been solved [10, 11]

$$\mathrm{div}\left[\kappa\mathrm{grad}(T)\right] = -Q \tag{3}$$

where κ is the thermal conductivity and Q is the density of the thermal power.

For calculation of the transients, under heating process, the partial differential equation has to be satisfied

$$\rho c\frac{\partial T}{\partial t} - \mathrm{div}\left[\kappa\mathrm{grad}(T)\right] = Q \tag{4}$$

where ρ is the mass density and c the thermal capacitance.

In the thermal calculations were assumed three kinds of boundary conditions. The first one concerns the so called perfect insulation i.e. the plane where the analysed transformer has been settled.

$$\kappa gradT \cdot n = q \cdot n = 0 \tag{5a}$$

where n is the normal vector to the surface.

The second boundary condition applies the ambient temperature which is assumed (T_0 = 25 ^{0}C) as Dirichlet's condition. The third condition is assumed for such surfaces where the convection phenomenon takes place.

$$\kappa\nabla T \cdot n + h\left(T - T_0\right) = 0 \tag{5b}$$

where h is the convection coefficient [W/(m^{2}K)].

For the latter one, the equivalent coefficient h_{eq} is applied

$$h_{eq} = h + 4\sigma_B\varepsilon\left(\left(T + T_0\right)/2\right)^3 \tag{5c}$$

where σ_B is Stefan-Boltzmann constant, ε is the emittance value.

The equation above includes not only the convection but also radiation of the heated up transformer body. The boundary conditions allow to take into account the convection and the radiation phenomena, in our numerical models [4].

Analytical determination of the equivalent conductivity. In the literature are presented some analytical ways of the equivalent conductivity σ_{eq} determination [8, 12]. They relate to laminated cores manufactured with grain oriented silicon steel sheets where each sheet is coated by insulating material. The first method included thickness of steel and the width of the stack. The principle of the method includes the equality of the power losses in the homogenized material and the power losses in the stack of the sheets. Based on this equivalence, the equivalent conductivity of the homogenized core has been determined.

$$\sigma_{eq1} = k\left(\frac{d_S}{a_S}\right)^2\sigma \tag{6}$$

where k is the stacking factor, and d_S, a_S –thickness and width of the sheet, σ – material conductivity.

Using the Farady's law,after determination of the power losses (due to eddy currents) in the homogenized core, the analytical expressions have been obtained.

$$\sigma_{eq2} = \frac{\sigma}{N^2} \tag{7}$$

where N is number of the sheets in the core.

From the expression above we can see that the simplified relationship are independent from the frequency. It is due to the equation is destined for relatively lower frequencies. In this paper we were investigated the usefulness above relations for the amorphous transformers which are operating under various sinusoidal frequencies.

Calculations results and measurement verifications

Magnetic field analysis

For the first case , we assumed the applied frequency of the supplying sinusoidal wave was f = 1 kHz. The values of amplitudes of the excitation current were changed from 0.4 A to 4.4 A. Thus, the magnetic flux density B_m inside the core varies from 0.1 T till 0.8 T.

At the beginning we tested the simulations of the core losses with the assumed values σ_{eq} which have been determined with using the equations 6 and 7. For the analysed amorphous transformer, the values of the equivalent conductivity were equal to σ_{eq1} = 0.39 S/m and σ_{eq2} = 1.59 S/m, respectively. Calculated values of the core losses (for both equivalent conductivities) are many times lower than 1% of the measured ones. Thus, the presented equations (6 and 7) are completely useless, for the amorphous laminated cores.

For determination of the σ_{eq} we proposed the iterative method for calculation of the equivalent conductivity. For the stacks of amorphous materials and silicon sheets, the iterative attitude has been precisely described in [13].

In this paper we have studied the C-core transformer from amorphous strip. Using the iterative method which has been worked for the amorphous sheets, we improved its' usefulness for the core presented in Fig. 2. We have simulated the substitute electric conductivity of the core versus the magnetic flux density values. The graph of the coefficient values (σ_{eq}) versus the magnetic flux density B_m of the core is presented in Fig. 3. Obtained values, of the equivalent electrical conductivity, are at least one thousand times lower than the amorphous material conductivity and are changed from 300 S/m to 500 S/m. For the lower values of the B_m (0.1 till 0.3 T) we can suppose the average value

400 S/m. The σ_{eq} value slightly increases, to reach the maximum value nearly 500 S/m and then decreases (for 0.3T till 0.8 T) to 300 S/m. In the field modelling the excitation current are assumed. Thus, the higher value of the σ_{eq} caused the stronger reduction of magnetic field density B_m in the centre of the core. For higher values of B_m we recommend slightly smaller values of the equivalent conductivities.

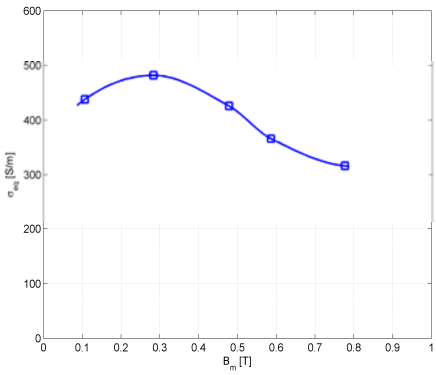

Fig. 3. Relation σ_{eq}=f(B_m) for supplying frequency f = 1 kHz.

More detailed calculation results concern the numerical model with the assumed amplitude of the excitation current of I_m=1.94 A. The magnetic flux density inside the magnetic core amounts to 0.5 T. The parameter σ_{eq} was obtained with using our iterative method of the core homogenization. In this case, the equivalent conductivity of the core has been assumed as σ_{eq} = 420 S/m. For the conductivity σ_{eq}, the calculated and measured total core losses are approximately the same, and approximately amount to P_T = 3.50 W. This value is very small which is observed in real amorphous cores.

The histogram of the magnetic flux density magnitude inside of the core is presented in Fig.4. Due to the low value of the equivalent conductivity of the core the distribution of the magnitude is pretty regular. The only exceptions are the edges of the core. Concurrently, the values of the eddy currents density are lower inside the core than in the proximity of its edges (Fig. 5).

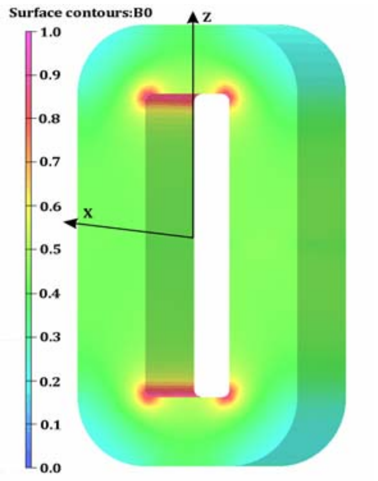

Fig.4. Magnetic flux density histogram

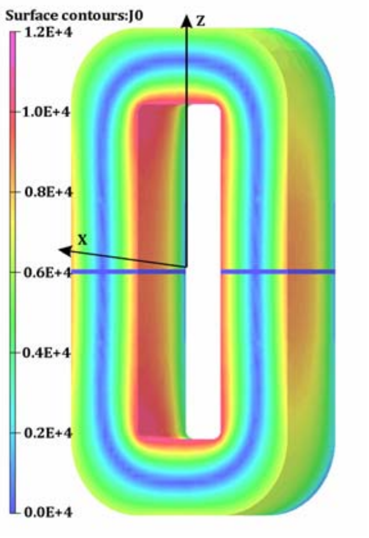

Fig.5. Eddy currents density distribution inside the core

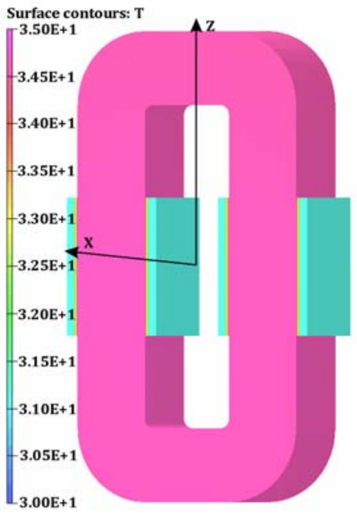

Fig.6. The temperature histogram inside the core

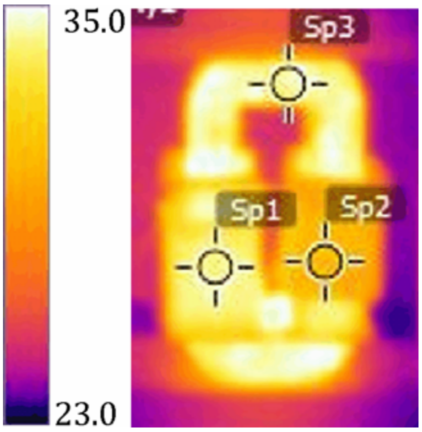

Fig.7. Measured temperature on the surface transformer

Thermal analysis

The obtained values of the power losses in the core were used as the input data for the thermal analysis. At the beginning of our study, the static thermal models were created. The spatial distribution of the temperature in the transformer core is presented in Fig. 6. For the relatively small current value (I_m=1.94 A), the maximal temperature of the transformer is lower than 35 ^{0}C.

The measurement tests, using the infrared camera FLIR i7, confirm our analysis of the thermal field. In figure 7 is shown measured spatial distribution on the analysed transformer. In general, the calculated values of the temperature not exceed 35 ^{0}C. The calculated temperature is nearly the same on whole core, which is visible in Fig. 6. We additionally depicted the three points in which the transients of the temperature have been observed.

The authors created the transient thermal models, as well. We have studied the temperature rising in the core. The thermal numerical models were verified by measurements. In Fig. 8 we compared the calculated and measured heating curves versus the time. The curves concern the middle area of the transformer yoke. One curve is resembling to the other one. It confirmed the rightness of our model of the field of temperature.

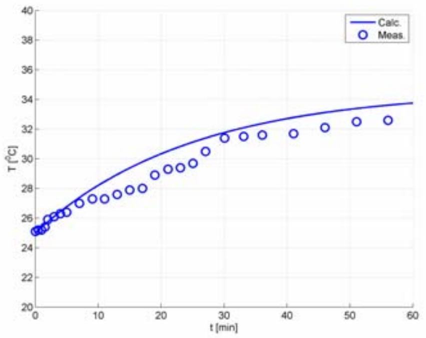

Fig.8. Calculated and measured heating curves in the middle of the yoke

Conclusions

The 3D numerical analysis of the magnetic and thermal fields of the amorphous transformer was described in this paper. The analytical determination values of the equivalent electrical conductivity (σ_{eq1} = 0.39 S/m and σ_{eq2} = 1.59 S/m) caused the wrong values of the eddy current losses. They were lower than 1 % of the measured ones.

Our own iterative numerical models have significantly improved the homogenization of the core. It allowed to carry out the 3D simulations of the magnetic and thermal fields, including the heating caused by eddy currents in the core. Thus, for the homogenization of the core lamination, should be used our iterative method for determination of equivalent conductivity. The electrical conductivity value (σ_{eq} = 420 S/m) is many times lower than the value of the material of the amorphous ribbon. It is due to many amorphous strip layers in the core and air insulation between them.

In the 3D analysis, the laminated amorphous core has been replaced with the solid one, with the calculated equivalent conductivity [13]. For the investigated range of the magnetic flux density (0.1 till 0.8 T), the value of the equivalent electrical conductivity has changed from 300 S/m till 500 S/m. Using such a value σ_{eq} it is possible to calculate of the spatial power losses distribution and then carry out the thermal analysis. After thermal measurement verifications a good agreement (with the numerical analysis results) was obtained. The relatively small differences were arisen since the maximal temperature is relatively low level. Due to small value of the excitation current the temperature is lower than 34 ^{0}C. However, the tests confirm the correctness of the numerical analysis.

Authors*: Prof. Bronislaw Tomczuk (Ph.D., D.Sc.), Opole University of Technolgy, Department of Electrical Engineering and Mechatronics, ul. Proszkowska 76, 45-758 Opole, E-mail: b.tomczuk@po.opole.pl; Dariusz Koteras (Ph.D., D.Sc.), address as above, E-mail: d.koteras@po.opole.pl.*

REFERENCES

[1] Tumanski S., Handbook of magnetic measurements, CRC Press Taylor & Francis Group, Boca Raton, (2011)

[2] Tumanski S., Baranowski S., Single strip tester of magnetic materials with array of magnetoresistive sensors, *Przegląd Elektrorechniczny*, 83 (2007), 46-49

[3] Lyskawiński W., Sujka P., Szeląg W., Baranski M., Numerical analysis of hysteresis loss in pulse transformer, *Archives of Electrical Engineering*, 60 (2011), No 2, 187-195.

[4] Koteras D., Transformers with low core losses- field analysis and measurement verification, Opole University of Technology Publishing, Opole, (2015)

[5] Zakrzewski K., Power Effect in Magnetic Lamination Taking into Account Elliptical Hysteresis Approach, *International Symposium on Electromagnetic Fields in Mechatronics,* Prague, Czech Republic, (2007)

[6] Sieradzki S., Rygal R., Soinski M., „Apparent core losses and core losses in five-limb amorphous transformer of 160 kVA," *IEEE Trans. Magn.,* 34 (1998), No. 4, 1189-1191

[7] Tomczuk B., Numerical Methods for Field Analysis of transformer Systems, Opole University of Technology Publishing j, Opole, (2007)

[8] Wang J., Lin H., Huang Y., Sun X., A new formulation of anisotropic equivalent conductivity in laminations, *IEEE Trans. Magn.,* 47 (2011), No. 5, 1378–1381

[9] Cobham, OPERA Manager User Guide Version 13*,* Cobham Technical Services, Oxford, (2009)

[10] Lienhard IV J. H., Lienhard V J. H., A Heat Transfer Textbook, 3rd red., Phlogiston Publishing, Cambridge , (2002)

[11] Tomczuk B., Koteras D.,3D field analysis in 3-phase amorphous modular transformer under increased frequency operation, *Archives of Electrical Engineering,* 64, (2015), No. 1, 119-127

[12] Bermúdez A., Gómez D., Salgado P., Eddy-Current Losses in Laminated Cores and the Computation of an Equivalent Conductivity, *IEEE Trans. Magn.,* 44 (2008), No. 12, 4730-4738

[13] Tomczuk B., Koteras D., Waindok A., The influence of the leg cutting on the core losses in the amorphous modular transformers, *Compel the International Journal for Computation and Mathematics in Electrical and Electronic Engineering,* 34 (2015), No. 3, 840–850