Slawomir WIAK, Pawel DRZYMALA, Henryk WELFLE
Lodz University of Technology

Nonlinear phenomena in tank of transformer and power losses computations

***Abstract**. The paper presents the design methodology of magnetic screens based on the three-dimensional field calculations. In this paper a new approach on the designing of the magnetic screens covers located on the tank is presented, so as to determine the optimal geometry (i.e. their thickness), that minimizes the aggregate losses not only in the tank but also in the configuration screen - tank. The transformer model was developed using the field-circuit oriented excitation. The load corresponds to the actual transformer's grid connected operating conditions. The electromagnetic field analysis leads to the identification of high loss density points in the structure.*

***Streszczenie.** W pracy przedstawiono metodologię projektowania ekranów magnetycznych na podstawie trójwymiarowych obliczeń polowych. Zaprezentowano nowe podejście w projektowaniu ekranów magnetycznych umieszczonych na ściankach kadzi w celu ustalenia jej optymalnej geometrii (grubości), w celu minimalizacji łącznych strat nie tylko w kadzi, ale również w konfiguracji ekran - kadź. Model transformatora został opracowany jako polowo-obwodowy. Przyjęto znamionowe obciążenie transformatora. Przeprowadzona analiza pola elektromagnetycznego ma na celu identyfikację obszarów o wysokiej gęstości strat w badanym obiekcie. (**Analiza zjawisk nieliniowych oraz strat w kadzi transformatora**).*

Keywords: High power transformer, transformer tank, magnetic screens, power losses, 3D modeling.
Słowa kluczowe: Transformatory dużych mocy, kadź transformatora, ekrany magnetyczne, straty mocy, Modelowanie 3D.

Structure of the transformer

To build 3D structure of the transformer OPERA-3D code has been exploited. The electromagnetic field calculations are based on combining in predefined subdomains magnetic vector potential, total and reduced magnetic potential formulas.
The computer model of the transformer is created for over 24 millions finite elements ("Fig. 1"). FEM mesh has been defined more dense in the tank subdomains. Tank is divided into sub-domains with high dense mesh using Layer option. The transformer core "step geometry" is substituted by smooth outer surface of the core, while the computer model is being created.

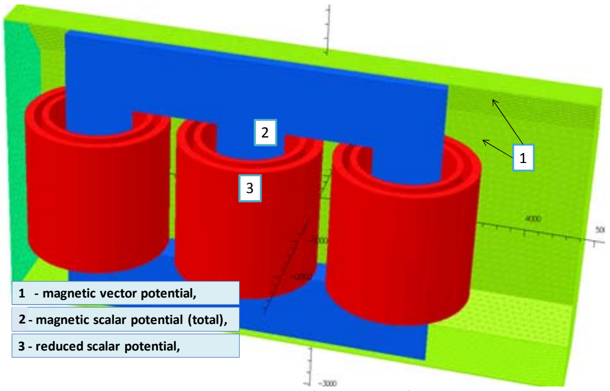

Fig. 1. The mesh and geometry of the transformer

The field and losses computation has been carried out for real material characteristics of the core and tank. It is assumed the core is built up of steel sheets without eddy current.

Applying the mixed potential formula allows authors to reduce the number of nodes, especially in the windings, which leads to reducing of the number of equations to be solved. The potentials governing the problem are:
- Φ - reduced scalar potential (i.e. areas of the coils),
- ψ - magnetic scalar potential (i.e. area of core, oil and screen),
- A - magnetic vector potential (i.e. area of tank and cover),
- V - electric scalar potential (i.e. areas of the coils).

Computation and analysis of field distribution in the tank

Electromagnetic field distributions in the screens have been computed by use of ELEKTRA harmonic module of OPERA 3D package. Number of elements and their type strongly affects the time and the accuracy of the results of the calculations. Computation time increases in the case when the electromagnetic field is defined by the formula of magnetic vector potential. In such a case the number of elements should be increased. It is well known the highest values of leakage field, and losses in the tank could be generated as the effect of eddy current generation in short-circuits.

Applying the magnetic screens, designed and proposed by authors, leads to changes of the electromagnetic field and losses distributions.

The screen structure in the form of electrical sheets has much better detailed properties of magnetic flux (first of all magnetic permeability), with lower values of power losses per the unit [W / kg] (there are no eddy currents).

Flux density distributions in the tank affect the increase of eddy currents in the area of tank and the transformer cover. It may lead to incorrect and emergency operation of the transformer and in extreme cases of leaks of tank-cover and off the unit from use. Such a methodology is successfully implemented in OPERA-3D code engaged by authors.

Magnetic flux density distributions in the screen and in the gaps between the screens are shown in "Fig. 2".

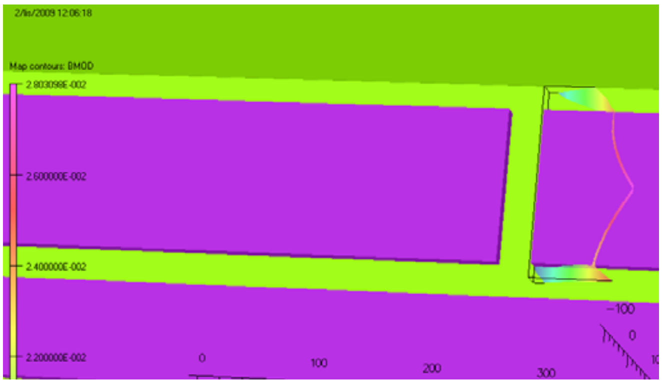

Fig. 2. The flux density module value map in the gap (on the surface) at the upper package of screen near transformer cover for selected time period.

The current density module distributions in the tank without and with screen for selected the time period are shown in Fig. 3 and Fig. 4.

It should be underlined that there is no available literature with the knowledge concerning the strategy of magnetic screens designing. It is of course due to specific structure of the high power transformers, designed and manufactured as individual structure.

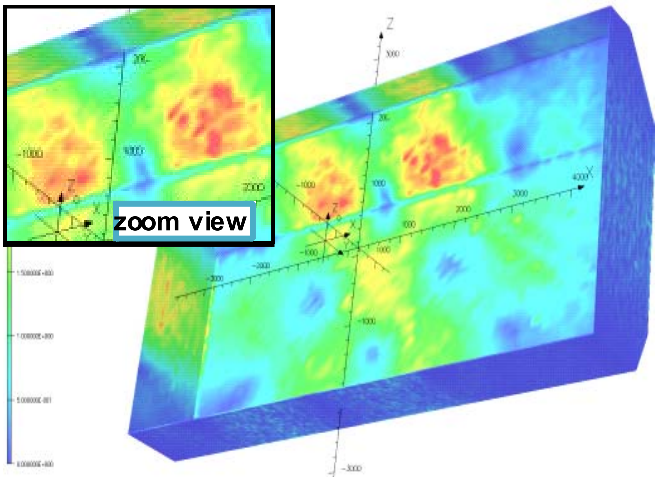

Fig. 3. Distribution of the current density module in the transformer tank without a screen for selected time period.

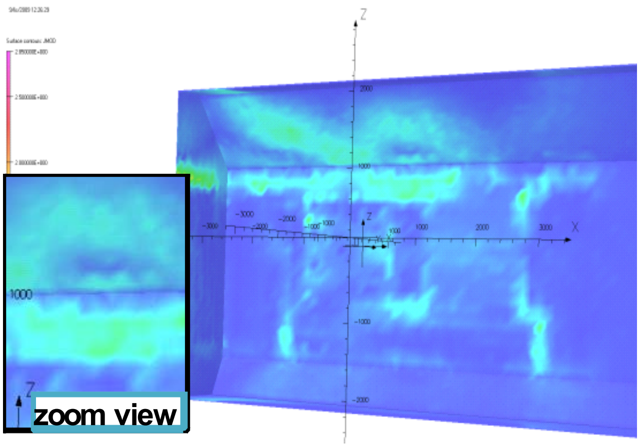

Fig. 4. Distribution of the current density module in the transformer tank with a screen for selected time period.

Fig. 5. Computing equipment used in the project

Computing equipment used in the project

Calculations were made on two blades:
To solve equation were used the IBM BLADE H CENTER equipped with 3 blades containing 2 processors (4 cores Nehalem microarchitecture) which gives twenty four of 64 bit cores and 96 GB RAM.
To mesh the model were used the IBM BLADE S CENTER equipped with 2 blades containing 2 processors (4 cores Nehalem microarchitecture) which gives sixteen of 64 bit cores and 96 GB RAM.

Power losses calculation in transformer

The method of discretization along the plane of the tank will depend on the depth of field strength penetration according to this exponential function of the wave equation Fig 6.
Solutions of Maxwell's equations are defined by formula (1) (2).

(1) $$H_m = H_{ms}\, e^{-\alpha z}$$

(2) $$E_m = \frac{\alpha}{\gamma} H_{ms}\, e^{-\alpha z}$$

Electromagnetic wave propagation coefficient in space is defined by formula (3).

(3) $$\alpha = \sqrt{j\omega\mu\gamma} = (1+j)k = \sqrt{2}\, k\, e^{j\frac{\pi}{4}}$$

In the case of the conductive subdomains (e.g. the tank) electromagnetic wave equation in the metal has a constant propagation coefficient "k" of the electromagnetic wave in space. Equivalent skin depth "δ" in the ferromagnetic is defined as the inverse formula of the propagation constant.

This value of equivalent skin depth δ corresponds to the e-times reduced the amplitude of the field in respect to its value at the surface. To solid steel (tank) it could be estimated as: depending on the saturation of the steel it could be estimated the equivalent skin depth (for 50Hz) is approximately of 3-5 mm. In our case (case of electromagnetic wave propagation) the tank is defined as unbounded metal space. The above means the tank is represented by the equivalent skin depth. Consequently the special attention should be paid to fine mesh generation, which means high dense mesh.

The power losses (for tank, screens, flat bars, steel connector) have been computed having electromagnetic field distribution, computed for three-dimensional transformer structure. Losses have been calculated numerically as the integral of the current density and field strength for each subdomain.

The power losses per unit volume for each subdomain, like: tank, steel connector, flat bars are defined by formula (5), then being recalculated per unit volume. The power losses of the tank without screen, and with screening of the transformer are also computed.

(4) $$k = \sqrt{\frac{\omega\mu\gamma}{2}} = \frac{1}{\delta}$$

Local maximum current density distribution is about 4 A/mm2.
The 3D computer model of the transformer tank is created, while the FEM mesh is generated basing on the value of equivalent skin depth.
The power losses per unit volume in tank and cover are defined by the following formula:

$$p = \frac{P}{V} = \frac{\int_V J \times E \, dv}{V} = 3.4 \ kW \ / m^3 \qquad (5)$$

where: p - power losses per unit volume, P - power losses in tank and cover, V – volume of tank and cover

Summary

1. Field distribution on the surface of the tank is very important and affects the accuracy of the calculation of eddy current losses. Distribution eddy current can be achieved only through the numerical field analysis with high discretization of mesh.
2. In this paper 3D computer model of complex structure of the high power transformer has been defined.
3. In HV transformers is needed to eliminate losses from eddy currents in the tank by the use of effective screening with magnetic screens.
4. In the process of screens designing, it is so important the screens positioning on the tank. It leads to defining the screen structures and influence on the power losses reduction, which gives the value of the coefficient of total power losses reduction

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***Authors**: Professor Slawomir Wiak Ph.D.,D.Sc., Lodz University of Technology, Institute of Mechatronics and Information Systems, Stefanowskiego 18/22, 90-924 Lodz, Poland, e-mail: slawomir.wiak@p.lodz.pl; Ph.D. Pawel Drzymala, Lodz University of Technology, Institute of Mechatronics and Information Systems, Stefanowskiego 18/22, 90-924 Lodz, Poland, e-mail: pawel.drzymala@p.lodz.pl; Ph.D. Henryk Welfle, Lodz University of Technology, Institute of Mechatronics and Information Systems, Stefanowskiego 18/22, 90-924 Lodz, Poland, e-mail: henryk.welfle@p.lodz.pl.*