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Mathematical modeling the temperature field of power transformer

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High voltage transformer is one of the most important elements of the power system. Due to this reason, it is crucial to properly design and build from mechanical side as well as thermal side. Nowadays, designers of power transformers are using from the many programs that allow you to reduce design time. Additionally, thanks to them, designer can quickly and effectively bring new changes in the construction and see what will be their impact on the work of the transformer.

This paper shows design assumptions of the mathematical model of power transformer, the similitude theory which was used to maintain an appropriate scale, and interface of Ansys CFX program, in which simulations of temperature field of power transformer was made.

KEYWORDS: high voltage power transformers, similitude theory, Ansys CFX, mineral oil

1. Introduction

High voltage power transformer is one of the most important and most expensive components of the power system. It plays a crucial role because of its correct functioning depends the work of both transmission lines and other industrial equipment. Distribution and transmission of electricity at voltages, that are most beneficial economically, belong to the basic tasks of power transformer [1, 2]. For this reason, it is important that it is properly designed and made both from the mechanical and thermal side.

At the design stage, team of transformers' designers must pay attention to the many factors that may have a significant impact on the proper operation of the transformer. One of these factor is the temperature of the windings and insulation system, which is provided for the work of the transformer. This temperature has a significant effect on the length of operation of the electric power equipment [3]. Furthermore, constructors are obliged to fulfill series of requirements set by the customers and the European Union's standards and regulations. Currently, to accelerate and shorten the design time of new power transformers, constructors use a variety of computer programs that support the design process. These include primarily software such as Auto CAD, Inventor, Catia, COMSOL Multiphysics, Ansys etc. They enable designers to quickly and easily modify design of the device and observation of how this changes affect the work of the transformer in real conditions. The average time, which is necessary to design a new transformer, is approximately about two months. It often happens that the production takes place shortly after the start of design work. During this time, it is necessary to create a full drawing documentation of most elements [4]. Therefore, an appropriate tool which allows for quick and accurate design is essential.

In this paper, the theory of similarity, Ansys CFX interface, and an example of distribution of temperature field in the power transformer filled with mineral oil, were presented.

2. Basic principles

In chapter similarity theory, the number of similarities, formulas for calculating the cooling surface in the model and briefly sketched the principle on which it bases its operation program Ansys, were presented.

In order to maintain appropriate model scale, the similarity theory was used. This theory allows to certain extent reflect the actual object based on the relationship between the physical parameters that have impact on the analyzed phenomenon, e.g. the flow of mineral oil in power transformer cooling channels. Therefore, the use of the similarity theory makes it possible to construct a laboratory models, which allow carry over and generalization of test results for similar systems without the need to repeat them [5, 6].

Three conditions must be fulfilled to consider two phenomena of heat exchange for similar. These conditions are similarities geometric, hydrodynamic and thermal. When the shapes and dimensions of the figures are similar geometrical similarity condition is satisfied. Most frequently ratio of the two characteristic linear dimensions is taken as scale of similarity e.g. cable diameter ratio of the radii of its curvature. The second condition of maintaining of similarity of heat exchange is hydrodynamic similarity. It consists in the fact that any two points in a fluid configuration will be in a second arrangement different speeds, but in proportion to each other. Additional proportionality must be expressed constant ratio. The third and last condition of similarity is to preserve the same relative temperature distribution in two layouts of temperature comparative [5, 6].

By the use of the theory of similarity, in similar layouts numerical values, which are dimensionless and are called number of similarity, may be determined. They are criteria of similarity in terms of: kinetic – the Reynolds number (*Re*), direct heat exchange – Nusselt number (*Nu*), physical properties of the factor – Prandtl number (*Pr*), heat transfer by convection – the Pecelta number (*Pe*), the force of momentum and gravity – Grashof number (*Gr*), and the Rayleigh number (*Ra*). This latter number lets you specify when the heat transfer in fluid is carried out by means of convection, and when the conductivity. In the course of analyzing the physical phenomena in the model and the real object designation of all the numbers it is not necessary. For example, assuming that there is only exchange heat with the free movement determining the number *Re* is not required. Grashof number *Gr* and the Nusselt number *Nu* decide about the similarity of the layouts. In addition, if the identity of the Nusselt number is occured, the heat transfer factor α for the model based on equation (1) may be designated [5, 6]:

$$Nu = \frac{\alpha \cdot \delta}{\lambda} \rightarrow \alpha = \frac{Nu \cdot \lambda}{\delta} \tag{1}$$

where: α – heat transfer factor, δ – characteristic dimension connected with liquid flow, λ – thermal conductivity coefficient.

Two types of convection take place in power transformer and in designed model: from the horizontal surface (cover) and on the vertical wall (tank and heat radiators).

Dependence (2a) allows determining of the heat transfer factor α for vertical surfaces for a range of Rayleigh numbers $Ra < 10^9$, whereas the equation (2b) is used for numbers $Ra > 10^9$ [5]:

$$\alpha = \frac{\lambda}{\delta}\left[0.68 + \frac{0.67\,Ra^{1/4}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}}\right]^2 \tag{2a}$$

$$\alpha = \frac{\lambda}{\delta}\left[0.825 + \frac{0.387\,Ra^{1/6}}{\left[1 + (0.492/Pr)^{9/16}\right]^{8/27}}\right]^2 \tag{2b}$$

where: Pr – Prandtl number described in equation (3), Ra – Rayleigh number described in equation (4):

$$Pr = \frac{\upsilon \cdot \rho \cdot c_p}{\lambda} \tag{3}$$

where: ρ – density, υ – kinematic viscosity, c_p – specific heat,

$$Ra = \frac{\beta \cdot g \cdot \delta^3 \cdot \Delta T}{\alpha \upsilon} \tag{4}$$

where: β – thermal expansion coefficient, g – acceleration of gravity, ΔT – temperature difference between heat source and temperature of the cooling liquid.

For a horizontal surface heat transfer factor α assumes the forms described in equation (5a) for the Rayleigh number range $Ra < 10^7$. For the Rayleigh number range $Ra > 10^7$ factor α is described by equation (5b):

$$\alpha = \frac{\lambda}{\delta} 0.54 Ra^{1/4} \tag{5a}$$

$$\alpha = \frac{\lambda}{\delta} 0.15 Ra^{1/3} \tag{5b}$$

When the heat transfer factor α will be calculated the heat flux, on the basis of the relation (6), may be calculated:

$$q = \alpha (T_s - T_p) \tag{6}$$

where: T_s – the wall surface temperature, T_p – fluid temperature.

In power transformers can be laid based on some of relationship, which bind together the losses which occur during normal operation of the transformer, cooling surfaces, and apparent power. The equations (7) and (8) describe these relationships [1, 2].

$$\frac{\Delta P_2}{\Delta P_1} = \sqrt[4]{\left(\frac{S_2}{S_1}\right)^3} \tag{7}$$

$$\frac{Ach_2}{Ach_1} = \sqrt{\frac{S_2}{S_1}} \tag{8}$$

where: ΔP_1, ΔP_2 – total sum of power losses in consideration transformers, S_1, S_2 – apparent power, A_{ch1}, A_{ch2} – cooling surfaces.

Based on outlined above equations, it can be concluded that if the transformer is larger, its cooling conditions deteriorate. This is because the losses in the power transformer grow faster than its cooling surface.

In order to model heat transfer by: heat sources → paper impregnate with insulating liquid → insulating liquid → tank → air, many programs using CFD methods (Computational Fluid Dynamics) are currently used. Ansys CFX, which uses differential equations of Navier–Stokes, belongs to one of them. These equations describe laminar and turbulent flow without taking additional information [7, 8]. Formulas (9), (10) and (11) describe the motion of an incompressible fluid.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{9}$$

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U \times U) = -\nabla p + \mu (\nabla^2 U) + g(\rho - \rho_{ref}) \tag{10}$$

$$\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p U T) = \nabla \cdot (\lambda \nabla T) + S_E \tag{11}$$

where: U – velocity, p – pressure, μ – viscosity, S_E – heat sources.

Based on equation (12), which is given below, windings temperature is determined:

$$\frac{\partial (\rho c_p T)}{\partial t} = -\nabla \cdot (\lambda \nabla T) + S_E \tag{12}$$

3. Design assumptions

3.1. Introduction

In this chapter the steps that should be follow to perform simulations of distribution temperature field of power transformer in Ansys CFX, were presented. In addition, the model of power transformer and distribution of temperature field in transformer, was presented.

3.2. The interface of Ansys CFX

Ansys CFX is one of the most popular simulation programs used for modeling phenomena connected with the flows such as multiphase flows, chemical reactions, heat conduction, radiation and so on. The modern interface allows the user to perform quick and efficient optimization of the construction with use of Workbench platform.

Figure 1 shows the iterations in Ansys CFX, that must be done to complete the simulation. These iterations in the following paragraph are discussed [9].

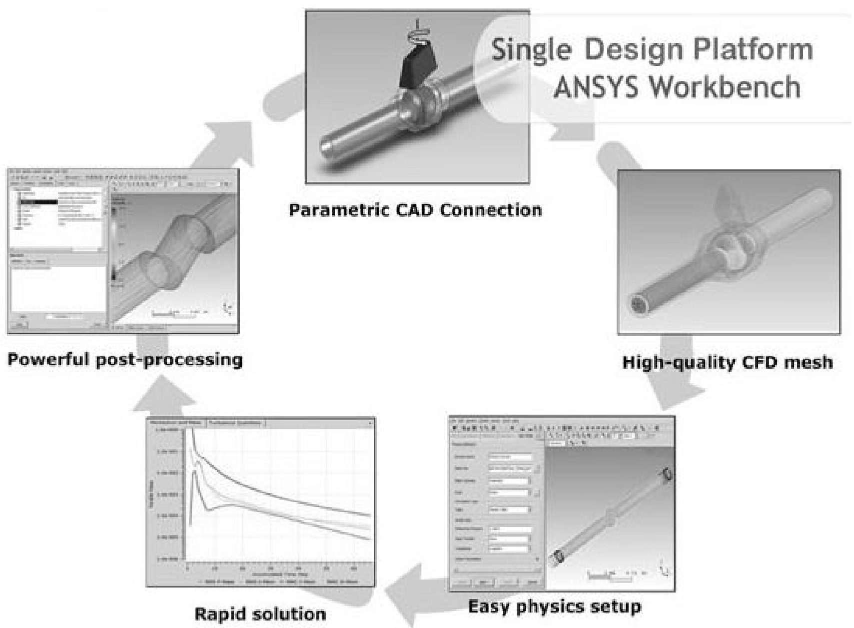

Fig. 1. The particular iteration in Ansys CFX [9]

The program allows to link the CAD model with the Workbench platform. As a result, there is a possibility to quickly prepare geometry for the simulation in Design Modeler module. On this basis, using efficient computational tools prepares mesh in Ansys Meshing, which is suitable for simulated phenomenon. In the next step, to PRE–CFX module appropriate boundary conditions should be given, the right materials, that are already defined in the program, should be chosen. Then, the module CFX– Solver calculations are carried out. By utilizing an advanced postprocessor in CFD–Post, which allows to obtain numerical data and present them in a graphical user easily and efficiently can verify the results of simulation. Additionally, the program uses many images, animations and gives the possibility to create reports with the results of calculations. With the integration of program in the Workbench, the program allows the use of tools to optimize parametric (Design Xplorer).

3.2. The assumptions of mathematical model

In this section, the design assumptions of the mathematical model made in the program Ansys CFX are presented. A simplified mathematical model of the geometry of power transformer is shown in Figure 2. It was made in the Design Modeler module. Additionally, in the Figure 3 the mesh of mathematical model of power transformer was shown.

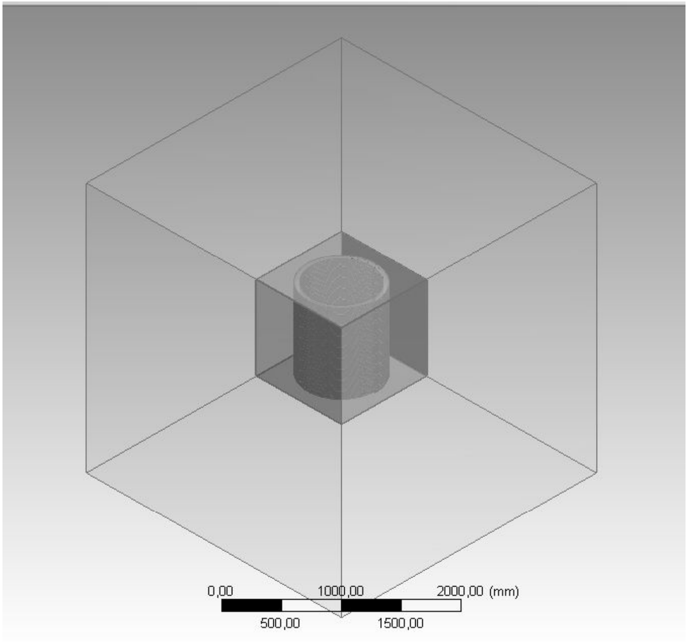

Fig. 2. The simplified mathematical model of power transformer geometry

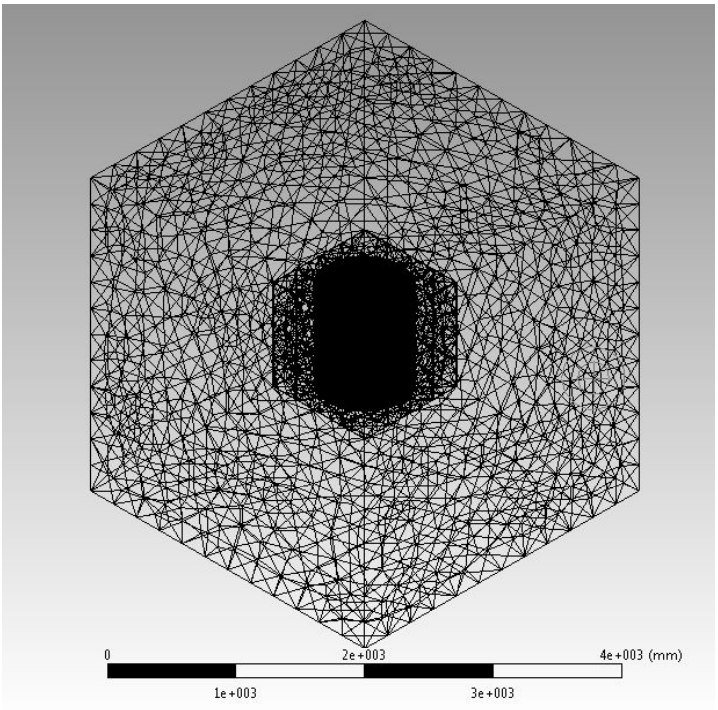

Fig. 3. The mesh of mathematical model of power transformer

The mathematical model consists of following elements:

- copper windings,
- new slot paper,
- insulating liquid (new mineral oil),
- tank,
- air around model of transformer.

Mesh model was built with coarse elements, whose number does not exceed 62000. This made it possible to achieve good accuracy of the obtained results and significantly reduce simulation time.

It was assumed that cooling surface will be equal 6 m^2. In order to simulate of temperature field of power transformer, it was necessary to calculate losses. Losses on the basis of equations (8) and (9) were determined. Other data, which appear in above mentioned equations are presented in Table 1.

The mathematical model of power transformer has been filled with new mineral oil. Its thermal and physical properties are temperature dependent. For this purpose, a special feature in the program Ansys CFX was used. Thermal properties of new mineral oil have been taken from [10–15]. In addition, the new winding paper with thickness of 0.5 mm and which thermal properties are also temperature dependent, was simulated. New winding paper parameters have been based on the results of work [16]. It was assumed that the initial temperature T is 20 ° C, because that value is taken as the average year–round. The value of the air pressure has been set at 1 atm [17].

Table 1. Other data used in simulation

	Power losses [W]		Cooling surface [m^2]	
10 MVA power transformer [*]	P_2	64181	A_{ch2}	287
The model of power transformer	P_1	195	A_{ch1}	6

[*] the technical documentations of 10 MVA power transformer manufactured by Power Enginnering Inc.

3.3. Results

In this section simulation results of temperature field (Fig. 4) of mathematical model of the power transformer are presented.

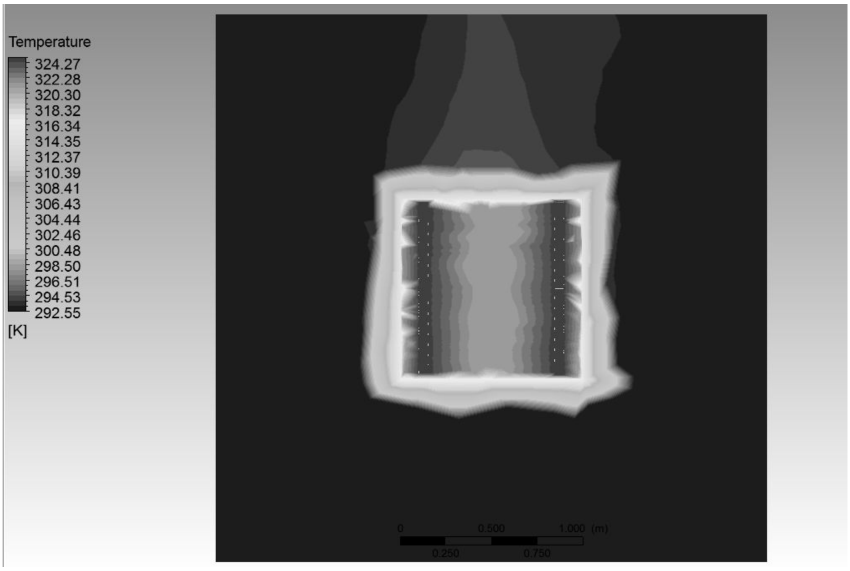

Fig. 4. The distribution of temperature field in mathematical model of power transformer filled with mineral oil

In Figure 4 the results of simulation of temperature field of the model of new power transformer filled with mineral oil have been converted. Based on the results it can be concluded that the maximum temperature which was obtained for given values amounted to 324.27 K (51.12°C). Whereas, temperature drop between the hotspot and the surroundings amounted to 31.12 K. The simulations suggest that the maximum temperature that was achieved did not exceed the maximum temperature for power transformers with natural cooling, which according to the standard [17] is 65°C. Obtained temperature drop $\Delta T_{wind.\text{–}air}$ between the windings and the air is also is housed in border of standards.

In the further scientific work, refinement of mathematical model and simulation for other insulating liquids with varying degrees of aging and moisture are assumed.

4. Summary

Currently, in order to shorten design time of new transformers, constructors use computer programs that support the design processes. One of them is Ansys. This program gives designer a lot of opportunity. Apart from number of advantages, which are listed in the article, it has also drawbacks. The user using Ansys must have highly efficient computer equipment, which will be able to effectively carry out the simulation. Due to the more increased demand for electricity and thus increased demand for transformers companies, producing power transformers will have to invest in these types of programs in order to meet demands of market.

References

[1] Jezierski E., Transformatory. Podstawy teoretyczne, Wydanie III, WNT, Warszawa, 1965.

[2] Jezierski E., Transformatory, WNT, Warszawa, 1983.

[3] Gościński P., Dombek G., Nadolny Z., Bródka B., Analiza współczynnika przejmowania ciepła cieczy elektroizolacyjnych wykorzystywanych, jako izolacja w urządzeniach elektroenergetycznych, Poznan University of Technology Academic Journals. Electrical Engineering, vol. 82, pp. 219–226, 2015.

[4] Bródka B., Sapała J., Łopatkiewicz R., Obliczanie wydajności układu chłodzenia ON–AN transformatora energetycznego średniej mocy, Poznan University of Technology Academic Journals. Electrical Engineering, vol. 82, pp. 227–233, 2015.

[5] Wiśniewski S., Wiśniewski T. S., Wymiana ciepła, WNT, Warszawa, 2009.

[6] Stefanowski B., Jasiewicz J., Podstawy techniki cieplnej, WNT, Warszawa, 1977.

[7] Pechanek R., Kindl V., Skala B., Thransient thermal analysis of small squirrel cage motor through coupled fea, Science Journal, pp 560–563.

[8] Torriano F., Chaaban M., Picher P., Numerical study of parameters affecting the temperature distribution in a disc–type transformer winding, Applied Thermal Engineering 30, pp 2034–2044, 2010.

[9] www.ansys.com, 2016.

[10] Dombek G., Wpływ wybranych czynników na właściwości cieplne cieczy elektroizolacyjnych, praca doktorska, Poznań 2016.

[11] Dombek G., Nadolny Z., Liquid kind, temperature, moisture, and ageing as an operating parameters conditioning reliability of transformer cooling system, Eksploatacja i Niezawodność – Maintenance and Reliability, vol. 18, pp. 413–417, 2016.
[12] Gościński P., Dombek G., Nadolny Z., Bródka B., Obliczenia numeryczne rozkładu temperatury w transformatorze, Obliczenia numeryczne rozkładu temperatury w transformatorze, Przegląd Elektrotechniczny, No. 10, pp. 46–49, 2016.
[13] Dombek G., Nadolny Z., Przybyłek P., Rola rodzaju cieczy elektroizolacyjnej w rozkładzie temperatury transformatora, Poznan University of Technology Academic Journals. Electrical Engineering, vol. 85, pp. 281–291, 2016.
[14] Dombek G., Nadolny Z., Przybyłek P., Badanie czynników wpływających na zdolność cieczy elektroizolacyjnych do transportu ciepła, Przegląd elektrotechniczny, Vol. 90, No. 10, pp. 148–151, 2014.
[15] Dombek G., Nadolny Z., Measurements of the selected thermal properties of insulating liquids used in the high voltage power transformers, Computer Applications in Electrical Engineering, vol. 11, pp. 189–198, 2013.
[16] Łopatkiewicz R., Wpływ wybranych czynników na przewodność cieplną izolacji uzwojeń określającą rozkład temperatury w transformatorze praca doktorska, Poznań 2012.
[17] PN–EN 60076–2:2011, IDT Przyrosty temperatury transformatorów zanurzonych w cieczy.

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