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Investigation of Heat Transfer in High-Capacity Power Transformers Having Modifications Preventing explosions

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Abstract—Results of numerical simulation of complex conjugate heat transfer in a high power electric transformer are presented. Simulation of the flow and heat transfer inside a transformer with static blast protection was carried out. Analysis of test calculations performed in the FlowVision software suit was carried out. Comparison of the performance of created numerical model against the real experimental data from the thermal tests of the transformer was made.

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INTRODUCTION

This article is the continuation of the work [1] and it contains the results of investigations concerning the heat transfer in the high-power transformers calculated in the FlowVision software suit [2, 3]. Nowadays, investigations allowing the development of blast protected transformers are carried out. However change in design required for the development of blast protected transformers may lead to the degradation in the transformation performance at normal mode. For example, the temperature increase caused by the decrease of the heat transfer may lead to the degradation of the insulating materials [4]. A design concept concept based on introduction of static elements protecting a transformer from explosion was investigated in this paper. Calculations of convection and heat transfer were the models of the HV oil-filled transformer of the 4th size have been performed [5].

MATHEMATICAL MODEL

Mathematical modeling of the physical processes accompanying natural convection of the oil in the transformer tank was performed using the FlowVision software system. A single-phase model was used for modeling of the basic design of the transformer and its modifications. Relatively small variation in the oil density in an oil filled transformer allows modeling the buoyancy force using the Boussinesq approximation. In this paper, the linear dependence on the oil density from the temperature is used. The following equations are solved:

The equation of continuity for the incompressible liquids:

$$\frac{\partial V_i}{\partial x_i} = 0; \qquad (1)$$

The momentum equation:

$$\begin{aligned}&\frac{\partial V_i}{\partial t} + \frac{\partial}{\partial x_j} V_i V_j \\ &= -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_i}\mu(T)\left(\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i}\right) + \frac{\rho - \rho_0}{\rho} g_i;\end{aligned} \qquad (2)$$

The energy equation:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial}{\partial x_i}(\rho V_i h) = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right); \qquad (3)$$

the oil state equations:

$$\rho(T) = \rho_0(1 - \beta T); \qquad (4)$$

$$h = h_0(T_0) + \int_{T_0}^{T} c_p(T)' dT'; \qquad (5)$$

The oil viscosity is specified (by table) as function of temperature:

$$\mu = \mu(T); \qquad (6)$$

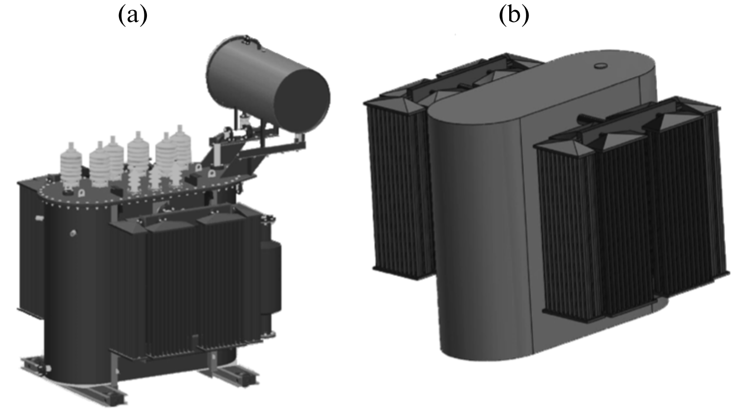

Fig. 1. Tank of the transformer with radiators: (*a*) external view and (*b*) internal volume.

The energy equation for the yoke and coils:

$$\rho_s c_s \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(\lambda_s \frac{\partial T}{\partial x_i}\right) + Q, \tag{7}$$

In these equations c_p is the specific heat of the oil at the constant pressure, c_s is the specific-heat of the solid body, g is the gravitational acceleration, h is the specific oil enthalpy, T_0 is reference temperature, ρ_0 is the oil density at reference temperature, P is static pressure, Q is the volumetric heat generation rate in yoke, T is temperature, t is time, V_i is the i-th component of the velocity vector, β is coefficient of volume expansion, λ and λ_s are coefficients of heat conductivity of oil and yoke, μ is the coefficient of the oil viscosity, ρ is oil density, and ρ_s is yoke density.

The method of the numerical integration of the equations, implemented in the software is based on the finite-volume approach that assumes the integration the partial differential equations over the volumes of the cells constituting a computational grid. The developed numerical algorithm [2, 3] applies the idea of splitting the Navier–Stokes equation system (equation of continuity and momentum equation) on the speed equation and pressure equation. Time integration of the equations is carried out by the implicit method.

The FlowVision software suit works on computers with the heterogeneous parallel architecture combining the intermode MPI exchanges with the threads parallelization on a node as on a computer with shared memory. Application of the mixed parallelization allows achieving t good scale operation with the large number of processors [6, 7].

Geometrical Model of the Transformer

The geometrical model of the transformer discussed was created on the basis of data about standard industrial transformer. Cooling is performed by means of natural convection through the external radiators and the walls of the transformer. The tank with the external radiators constitutes the basis for the geometrical model (Fig. 1) in which the active part is added later.

The active part of the transformer consists of the magnetic conductor and coils (Fig. 2). The transformer coil consists of the high-voltage winding, low-voltage winding, stabilizing winding, taping, and separator end section for coils and some windings. There are clearances between coils for the oil circulation. The separator end sections are designed in such a way that they do not cut off the free flow of the cooling fluid towards the heat-producing coils and from them.

The static protection of the transformer (Fig. 3) consists of plates fixed in the tank of the transformer. Plates are made of a special material. They are fixed to the tank of the transformer with the manufacturing clearance which allows oil flow near the wall of the transformer and transfer of heat to the wall. In the model under consideration, the 10 mm clearance was left between plates and the wall of the transformer tank providing convective heat exchange.

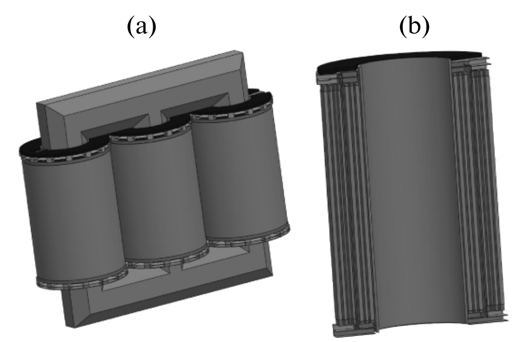

Fig. 2. (*a*) Active part of the transformer and (*b*) cross section of the coil.

Fig. 3. External view of the static protection.

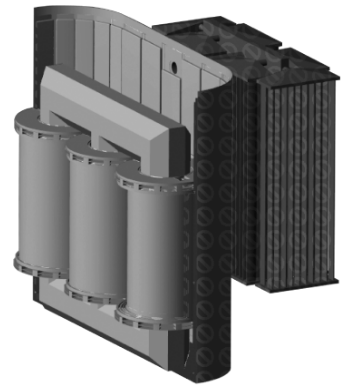

Fig. 4. Computational domain protection of the oil filled transformer with elements of the blast protection.

Numerical Model of the Transformer

The computational domain (Fig. 4) consists of several subregions:

(1) oil—internal volume of the tank free for fluid flow;

(2) insulator—heat-insulating elements of the transformer;

(3) steel—magnetic conductor;

(4) copper—high-voltage and low-voltage windings; and

(5) protection—plates of the static protection.

The conjugate boundary condition for the energy equation is specified at the common boundaries of subspaces. In subregions ‘Steel’ and ‘Copper’, the volumetric heat generation is specified by the corresponding volumetric heat sources. Reference values for calculations are as follows: ambient temperature: $T = 293$ K; ambient pressure: $P = 101000$ Pa.

Investigation of grid convergence for the geometrical model of the transformer with the static protection was carried out on three grids: coarse (1384322 cells), medium (2820112) (Fig. 5), and fine (5698470). For generation of the fine grid, the first and the second levels of adaptation were specified in all narrow clearances. Thus, the fine grid resolves the clearances in transformers.

Results show (Fig. 1) that the use of the medium computational grid (2820112 cells) does not lead to the essential loss of the solution accuracy. Besides that, the time of integration of the governing on this grid is considerably less in comparison with calculations on the fine grid.

RESULTS OF CALCULATIONS

Calculations of the factory tests of the transformer were carried out for verification of the created model [8]. Heat testing a transformer consists of several stages:

(1) idle running test by operating voltage—to measure losses in magnetic conductor;

(2) short circuit test by operating current—to measure losses on the ohmic resistance of coils;

(3) short circuit test by equivalent current when losses on the ohmic resistance of coils are equal to the sum of the heat losses in the two previous tests.

The first two tests give an indication about losses in the transformer under operating conditions. The results are as follows: 4.9 kW for the magnetic conductor and 26.04 kW for coils. Those data are required for

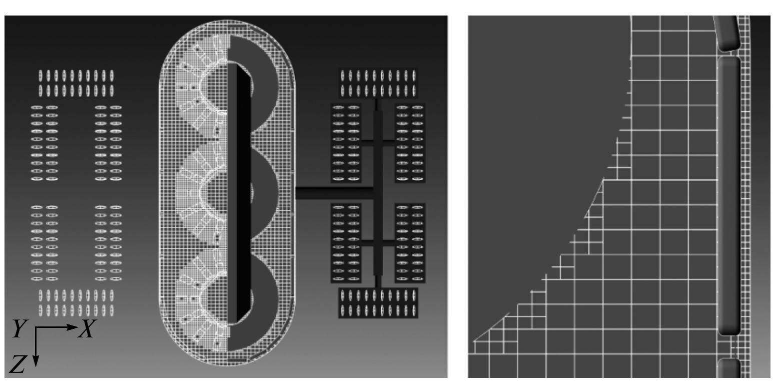

Fig. 5. Medium computation grid.

the simulation of the nominal operation of the transformer.

The third test simulates the operating mode of the transformer under thermal load. In order to get the heat release of 30.94 kW on coils, it was required to apply the current of 239.74 A. This experiment included measuring the temperature of the upper oil layers. The temperature was 58.7°C relative to the ambient temperature.

The limit value of the measured temperature for each type of the transformer is given in [5]. It is necessary to mention that, when designing a new model of transformer, the maximum temperature is usually calculated by the engineering methods [9, 10] without consideration of the local overheated zones. Computational Fluid Dynamics (CFD) (the FlowVision software in our case) allows computing the distribution of temperature in the entire transformer. Therefore, a designer has an opportunity to prevent overheating.

It is seen from the results of the third test calculations (Fig. 6) that the calculated temperature of the upper layers of the oil is 78.5 or 58.4°C relative to the ambient one (taken to be 20°C). This value agrees well with the experimental value. The average temperature of the oil in the entire tank is 72.6°C. Full verification requires more detailed measurements and additional calculations. However, the obtained results demonstrate that FlowVision provides reliable predictions of complex heat transfer in an oil filled transformer.

For simulation of the standard operation of the transformer the heat release equal the sum of the losses obtained in the two first tests was specified in the magnetic conductor and coils.

Calculations show that the temperature of the upper layers of the oil did not considerably change and stays within 78–80°C (see Fig. 7). However, at the operating condition, the temperature distribution of the upper layer of the oil became more inhomogeneous as a result of heat emission in the magnetic conductor. The average temperature in the tank was 72.7°C, which is very close to the value obtained in the calculations of the short circuit test.

Adiabatic boundary conditions were specified the side surface of the transformer tank for the definition of the maximum influence of the static protection on the heat exchange processes in the transformer.

It is seen from the calculation data (Fig. 8) that the temperature of the upper layers of the oil stays within 89–91°C. Thus, if we exclude the side wall of the transformer from the heat exchange process with the ambient medium (all heat exchange goes via external radiators), the temperature of the upper layers increases by ~10°C. The average temperature obtained in this calculation is 83.3°C. Hence, the increase is 10.5°C as compared to the previous calculations. These results show the considerable role of the heat exchange via the sidewall of the transformer.

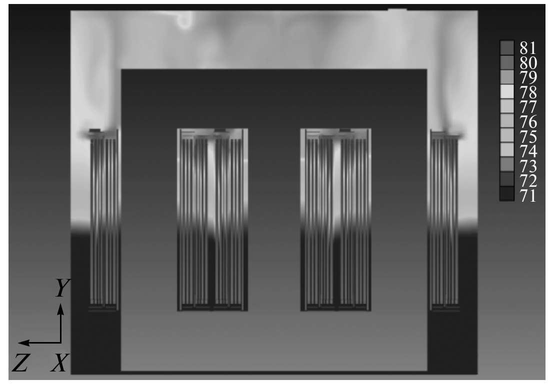

Fig. 6. Distribution of the oil temperature in the tank of the oil filled transformer calculated under the conditions of the short circuit test.

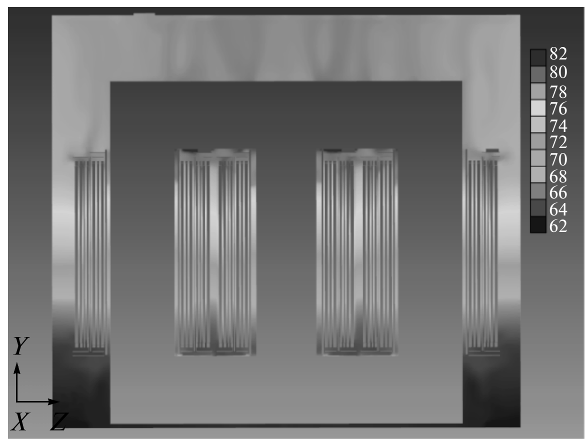

Fig. 7. Distribution of the oil temperature in the tank of the transformer in working mode.

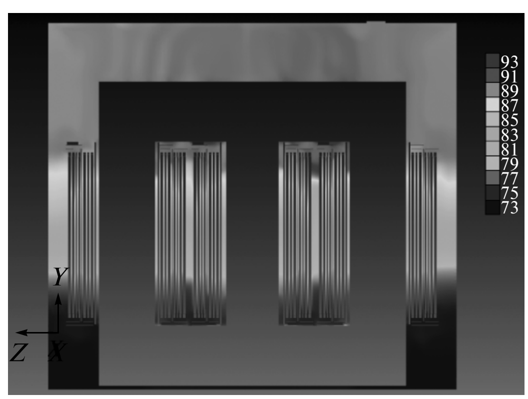

Fig. 8. Distribution of the oil temperature in the tank of the transformer in working mode with adiabatic boundary condition on the side wall of the transformer.

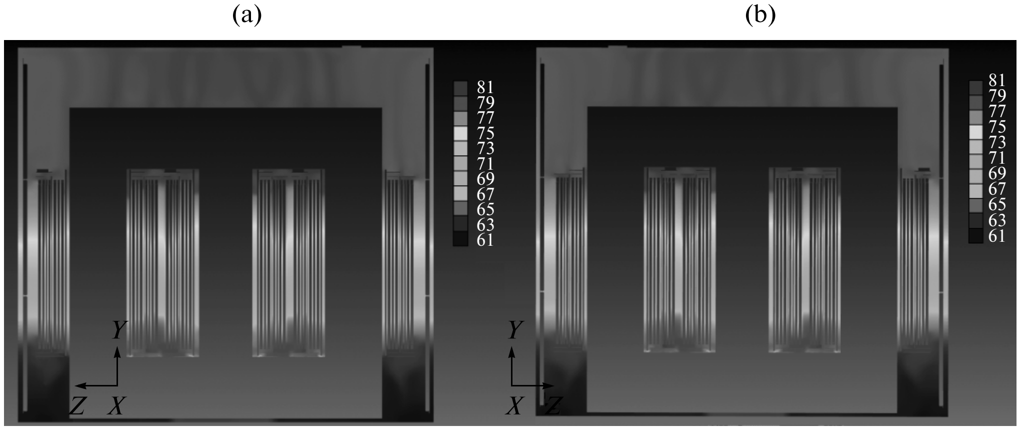

Fig. 9. Distribution of the oil temperature in the transformer tank at the operating condition with blast protection elements manufactured from the (a) heat-conductive and (b) heat-insulating material.

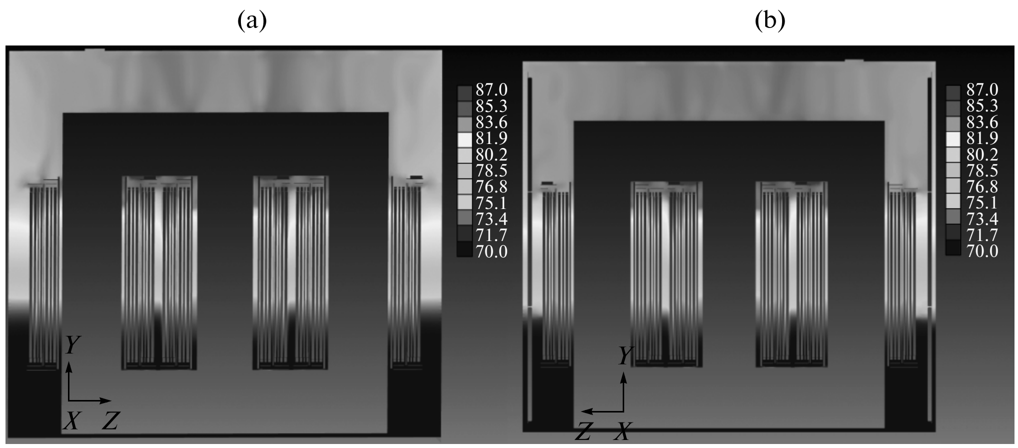

Fig. 10. Distribution of the oil temperature in the transformer tank at the overload condition by 10%: (a) basic design and (b) modified design.

Let us consider the same model of the transformer with the static protection described above (Fig. 3). The material of the static protection may have different thermal conductivity. For this purpose the calculation of the transformer with the installed protection is carried out for the heat-conductive and heat-insulating materials (Fig. 9).

The obtained values of the average temperature for the heat-conductive and heat-insulating materials were 72.9 and 73°C, correspondingly. Thus the convection and heat exchange in the transformer practically do not depend on the heat conductivity of the coating material.

It should mentioning that introduction of the constructive elements for blast prevention into the transformer increases the average temperature by only 0.1°C, while the complete elimination of the sidewalls of the tank from the heat exchange process increases the average temperature by more than 10°C. It may be concluded that the installation of the static protection practically does not decrease the heat removal rate via the sidewall of the transformer tank.

Let us consider the basic transformer and the modified transformer under the overload condition by 10% in power. For this purpose we increase the heat emission in coils and in the magnetic conductor by 10%.

The average temperature value of the oil in the tank of the transformer (Fig. 10) for the basic and modified designs is 77.8 and 78°C. Thus, the temperature of the oil in both schemes increased by 5.1°C.

Calculation data for the heat exchange in the basic and modified models of the high-voltage, oil-filled transformer of the 4th size at different modes are given in Table 2.

It is seen from the table that introduction of the static protection increases the average temperature of the oil by 0.2°C, whereas the oil temperature increases by 101°C in the basic model with the adiabatic wall. Thus, though the installation of the protection isolates

Table 1. Grid convergence study

	Coarse grid	Medium grid	Fine grid
Average oil temperature in the tank, °C	32.6	30.51	30.02
Maximum oil temperature in the tank, °C	38.63	36.31	35.93
Maximum winding temperature, °C	40.53	37.8	37.31

Table 2. Average temperature of the oil in the tank relative to the ambient temperature at different modes for different configurations of the transformer

Mode	Basic design	Modified design (heat-insulating material)	Modified design (heat-conducting material)	Basic design with adiabatic walls
Short-circuit conditions	52.6°C	–	–	63.5°C
Operation conditions	52.7°C	52.9°C	52.8°C	63.3°C
Overload conditions by 10% in power	57.8°C	58°C	–	–

the sidewalls, it does not make worth the heat exchange in the transformer. This paradoxical effect is explained by the fact that the heat protection creates a channel along the sidewall of the transformer, thereby increasing the oil motion speed and, correspondingly, intensifying the heat exchange.

As a result, one an say that this modification practically does not disturb the heat exchange process with the environment through the sidewall of the transformer tank. Consequently, the increase of the average temperature in the tank is negligible for such configuration of the transformer.

CONCLUSIONS

The paper presents numerical investigation of the influence of the blast protection, introduced into an industrial transformer on the heat exchange processes inside the transformer. The basic geometrical model was made on the basis of the high-voltage, oil-filled transformer of the 4th size. Comparison with the factory heat tests was made. Analysis of calculations showed good agreement of the computed data with experimental ones. The basic transformer geometry was modified to the blast -resistance level by means of introducing a static protection system. It was demonstrated that the heat conductivity of the material does not influence on the heat exchange in the transformer. This is explained by higher rate of the convective heat transfer relative to the diffusive heat transfer through the protection system. It is also shown that the introduction of the static protection leads to the increase of the temperature by 0.1°C. At the same time. the complete elimination of the side walls of the tank from the heat exchange process increases the temperature by 10.5°C. Increase of the power load by 10% leads to the proportional increase of the temperature both in the case of the basic model and blast protected one. Results of the numeric modeling allow stating that modification of the stock transformer to the explosive level practically does not change the average and maximum temperatures of the oil in the transformer tank.

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