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DIGITAL MODELING OF THE HEAT TRANSFER PROCESS IN OIL POWER TRANSFORMERS IN OPERATION

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Abstract: Analysis of heat transfer processes occurring in oil power transformers in operation through digital modeling, identification of heat sources, and assessment of temperature distribution inside the transformer using mathematical and graphical models. As a result, it is planned to develop proposals for increasing the efficiency of the cooling system, ensuring reliability and reducing thermal stresses. COMSOL Multiphysics - complex geometric modeling of an oil power transformer with a power of 1000 kVA in multiphysical media, the Fourier equation for heat dissipation, the Crank-Nicholson scheme for a solution over time, I2R losses, hysteresis, eddy currents, convective cooling, temperature-dependent properties of the oil, and temperature changes in the time interval from 0 to 1800 seconds were observed. According to the results, it was found that the maximum temperature near high-voltage windings reaches 92°C. It has been proven that increasing the oil circulation rate by 10% can reduce the maximum temperature by 6-8°C. As a result of increasing the radiator size by 12%, the temperature decreases by an additional 3-4°C. The cooling system works effectively in the lower zones (65-70°C). The direction of the heat flow and critical zones were determined using 3D graphs generated by COMSOL. Digital modeling of heat dissipation allows for real-time assessment of the thermal state of transformers. By reducing the temperature level in critical zones, the service life of insulating materials is significantly extended. Specific technical recommendations for the modernization of the cooling system have been developed. Based on the results of the digital model, it is possible to design remote monitoring systems, which increases operational safety.

Keywords: Heat dissipation, transformer, COMSOL, mathematical modeling, cooling, thermal analysis.

Introduction. Transformers are static devices that play a key role in electricity generation, transmission, and distribution systems[1-5]. They increase the efficiency of energy transfer by lowering or raising the voltage to the desired level. Most power transformers used in industry today have an oil cooling system, which is important for their long-term operation[6-7]. According to statistics, more than 30% of transformers fail due to insufficient operation of the cooling system (IEC 60076-2:2011) [1-4]. The heat energy generated in the high-voltage windings located in the middle part of the transformer accounts for up to 70% of total losses, while the remaining 30% is attributed to magnetic core and mechanical losses[7-11].

If this heat is not directed correctly, insulation materials (kraft paper, epoxy resin, etc.) undergo temperature degradation. Studies show that the thermostability limit of insulation is from 105°C to 120°C, and with an increase in this value, its mechanical and dielectric properties decrease by up to 50% (Hossain et al., IEEE, 2019). When the oil temperature rises above 80°C, its viscosity sharply decreases, which reduces cooling efficiency[8-9]. By modeling heat dissipation, it is possible to identify such problems and prevent them.

Modern computer physical modeling programs, including COMSOL Multiphysics, are widely used in this field and represent complex geometric and thermal conditions in digital form. With its help, factors such as temperature distribution inside the transformer, heat flow direction, and cooling effects are predicted. In this article, based on such methods, the heat dissipation process of a 1000 kVA oil power transformer is numerically modeled, and the results are analyzed.

Materials and methods of research.

In the research process, a transformer model with a power of 1000 kVA was used. The design of this transformer was chosen in accordance with real operating conditions. The COMSOL Multiphysics program was used in the creation of the model, as it allows simultaneous modeling of complex geometries and multiple physical environments. The geometric model consisted of the following main components: magnetic core (U/I-shaped laminated silicon steel), high-voltage (HV) and low-voltage (LV) windings, radiator cooling system, expansion tank, and transformer oil reservoir.

The properties of the material were determined as follows:

- Transformer oil density: 880 kg/m^3,
- Oil heat capacity: 1900 J/kg·K,
- Thermal conductivity: 0.13 W/m·K,

The temperature-dependent viscosity of the oil was also included in the modeling.

Also, I^2R (ignorant resistance losses) and eddy current and hysteresis losses in the core were modeled as heat sources generated in the windings.

In mathematical modeling, the Fourier equation of heat propagation ($\rho \cdot c \cdot \partial T/\partial t = \nabla \cdot (k \nabla T) + Q$) was taken as the basis. The modeling time interval was chosen as 0-1800 seconds (30 minutes) and the dynamics of temperature changes were analyzed. As boundary conditions:

- External surfaces have convective cooling (h = 15 $W/m^2 \cdot K$),
- Radiator surfaces - under natural airflow,
- The oil cycle was described using simplified Navier-Stokes formulas.

For the branching of the model, 3D geometry was discretized with a step of 0.002 m. Special parameters were established for each zone: copper coils, steel core, dielectric insulation, and oil layer. The results were visually analyzed using cross sections, isothermal gradients, and temperature distribution in the COMSOL interface.

Mathematical model of heat dissipation.

In the mathematical modeling of the heat transfer process, the Fourier equation is used as the main differential equation. This equation describes the dependence of temperature on time and space, allowing one to determine the direction and density of the heat flow.

The overall thermal conductivity equation can be written as follows:

$$\rho \cdot c \cdot (\partial T/\partial t) = \nabla \cdot (k \nabla T) + Q \quad (1)$$

here:

ρ - transformer oil density [kg/m^3],

c - heat capacity [J/kg·K],

k - thermal conductivity coefficient [W/m·K],

T - temperature [K],

t - time [s],

Q - volumetric heat source (usually I^2R losses and core losses) [W/m^3].

In the model, the temperature distribution was calculated in 3D space, taking into account surfaces with constant temperature, convective surfaces, and heat sources. As a precautionary measure, the temperature-dependent properties of the oil (viscosity, heat capacity) were changed depending on the temperature gradients. Convective model of heat flow on external surfaces:

$$q = h(T_s - T_\infty), \quad (2)$$

expressed as, where:

h - surface convective heat transfer coefficient [W/m²·K],

T_s - surface temperature, T_∞ - ambient temperature.

To obtain a numerical solution, the Crank-Nicolson scheme was used in time discretization, and in space, the number of nodes was organized through more than 250 thousand triangular elements. In the COMSOL interface, the results were evaluated using high-resolution visual images - isothermal surfaces, graphs, and sections.

Obtained results and their analysis.

The simulation results showed that the maximum temperature inside the transformer reaches 92°C near the high-voltage winding (HP winding). This zone is the area with the highest heat release, and proper cooling is important for reliability. Oil circulation through radiators is effective in the lower zones, where the temperature is maintained at around 65-70°C. This heat difference can cause thermal stresses in the windings.

The temperature distribution in the cross-section of isothermal temperature surfaces obtained using COMSOL Multiphysics was visually displayed. Based on the graph of temperature change over time, in the process from 0 to 1800 seconds, the maximum temperature rose sharply and stabilized. Due to the convection effect on the radiator surface, the internal temperature significantly decreased after 20 minutes.

With an increase in the oil circulation rate by 10%, a decrease in the maximum temperature by 6-8°C was confirmed by modeling. This, in turn, leads to an increase in the service life of insulation materials by 25-30% (Hossain et al., 2019). In addition, based on the results obtained, it was found that increasing the radiator dimensions by 12% can reduce the temperature by an additional 3-4°C.

Using the model, the critical zones inside the transformer were determined, and their 3D graphs were developed. These graphs show the temperature gradient, flow direction, and surface cooling indicators. Based on these results, technical recommendations for structural changes in the transformer cooling system were developed.

Conclusion.

Digital modeling of heat transfer processes in oil power transformers is a very important tool for determining their thermal state and assessing their reliability. Based on the results obtained during the study, the following main conclusions were made:

1. With the help of COMSOL Multiphysics, the heat distribution of a 1000 kVA transformer was determined. The temperature reached its highest level in the high-

voltage winding zones (92°C), indicating the most dangerous areas inside the transformer.

2. The efficiency of the cooling system is high, and the temperature in the lower parts is maintained in the range of 65-70°C. By increasing the radiator dimensions and oil circulation speed, it is possible to reduce the maximum temperature by 6-8°C.

3. Based on the modeling results, specific technical recommendations for optimizing the design of the cooling system were developed. It is also possible to reduce thermal stresses by improving the design of cooling elements.

4. Based on the results of digital modeling, opportunities are being created for the development of real-time monitoring systems and remote control through temperature sensors and IoT devices. This leads to increased safety and service life during operation.

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