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RESEARCH OF THE QUESTION OF INCREASE OF EFFICIENCY OF COOLING OF THE POWER EQUIPMENT OF HYDROELECTRIC POWER PLANTS

Abstract: *Improving the cooling efficiency of power transformer windings with a cross-sectional width of the radial channel less than 3 mm, by improving the geometric parameters of the cooling system while reducing the material consumption of the electric machine is an important area of research. Excess oil pressure in the winding channels increases with increasing serial number of the coil. It was found that with increasing oil velocity at the inlet to the horizontal channel, the values of excess pressure in it increase in quadratic degree. It is established that a lifting force occurs in the oil of the horizontal channel, as evidenced by the increase in excess pressure near the upper boundary of the channel.*

For the first time, an analytical dependence of the excess oil pressure in the radial channel of the disk winding of the power transformer on the oil flow rate at the inlet to this channel was obtained. The dependences of the excess pressure in horizontal channels with a cross-sectional width of 1 mm on the velocity of oil at the inlet to this channel were obtained, which allows to calculate the speed by which it is possible to organize through circulation of oil in the channel provided that excessive pressure in the channel is prevented. situations.

A new mathematical model of interconnected heat exchange and hydrodynamic processes in the disk windings of a power transformer is proposed, which, unlike the existing ones, takes into account the width of the horizontal channel less than 3 mm, which allows to predict the heat distribution in the winding and determine possible locations overheating of coils and premature destruction of insulating materials.

Keywords: *transformer; heat exchange; power equipment; hydroelectric power station; oil cooling system.*

Introduction

Today, hydroelectric power plants occupy a significant share in the generation of electricity. The advantages of using hydroelectric power plants include: the use of renewable energy; low cost of electricity; quick exit to the mode of delivery of working power after inclusion of station. All power equipment is located in the hydroelectric power plant building. Depending on the purpose, it has its own division. In the engine room there are hydraulic units that directly convert the energy of water current into electrical energy. There are all kinds of additional equipment, control and monitoring devices, switchgears, as well as a transformer station. The key to the continuous operation of the entire power plant is the efficient and reliable operation of the transformer station and each power machine separately.

Among the most important tasks facing science are the improvement of existing and the development of new, more advanced energy systems. The criteria that determine the choice of electric machines for operation in power systems are the reliability and cost of power transformer equipment. In most cases, efficient methods of cooling windings are used to create competitive transformer equipment. One such method is the natural circulation of coolant in the horizontal and vertical channels of the windings.

In modern economic conditions, one of the key issues in the field of transformer construction is to reduce the material consumption of electrical machines. This, in turn, leads to a reduction in the overall dimensions of the transformers, for example by reducing the width of the radial channels in the system of its thermal protection. However, it should be borne in mind that this will worsen the heat dissipation conditions from the active part of the transformer to the environment.

Reducing the amount of heat removed from the windings can cause significant transformer overheating, cause premature aging of the insulation and lead to an emergency situation.

The aim of the work is to study the nature of the movement of transformer oil in the transformer winding with a radial channel width of 1 mm.

Literature review

Transformers are the most important equipment in the transmission and distribution system, which effectively serve a variety of needs, internal and external distribution, medium voltage, high voltage, additional high voltage and the use of ultra-high voltage. A large number of publications are devoted to the problems of cooling power transformers [1, 2]. With the help of mathematical analysis and experimental measurements, the diagnosis of the distribution of oil transformers in terms of mechanical strength of the winding. Analysis of temperature rise at different loads is very important because it allows to determine the load capacity and overload of the transformer under different operating conditions and to adhere to the variable ambient temperature [3].

In the vast majority of scientific works on transformer construction, studies of heat dissipation processes from transformer windings with a radial channel width of at least 3 mm are presented.

The simulation of the increase of the transfer coefficients for the rise of gas bubbles in the liquid is carried out and experiments are carried out to study this phenomenon, which provides a new way of cooling oil transformers [4].

Essential fluids offer the potential for safer and more environmentally friendly power transformers. This can save significant civilian costs in installations, reducing fire safety requirements and simplifying containment. These advantages have been used in voltage distribution for almost four decades in many applications [5].

Under normal operating conditions, equations describing thermal phenomena in a transformer are established. Algorithms for predicting temperatures at critical points in non-stationary states occurring on load / time diagrams have been developed [6]. It is proposed to determine the conductivities of thermal protection materials depending on the temperature and constant capacitances of equivalent thermal circuits of the transformer.

To date, a study of the methodology for creating thermal protection systems for power equipment. The creation of a metal system of thermal protection, which is easy to manufacture, and the study of its strength and thermophysical characteristics is considered in [7].

Thorough studies of the basic rules of design of windings of power transformers [8] and the main modes of operation of power equipment [9].

The method of modeling turbulent flows using turbulence models that have the form of algebraic expressions is described in [10]. The proposed models of turbulence make it possible to simplify the software implementation of the equations describing the turbulent behavior of fluid flowing and increase the speed of computation.

In [11] the results of application of the original nonlinear nonstationary thermal model of oil power transformers are given. The main advantage of the created model is the exact consideration of the influence of heat transfer of nonlinear convection on the thermal transition process [12]. The purpose of the study is to determine the accuracy of the parameters obtained in the transformer in normal operation. To this end, the exact calculation of the distribution of power losses required and proposed in [13].

In most cases, effective methods of cooling windings are used to create competitive transformer equipment [14, 15].

One such method is the natural circulation of the coolant in the horizontal and vertical channels of the windings, provided that the width of the horizontal channels is not more than 3 mm. Implementation of this type of cooling reduces the material consumption of the transformer by reducing its overall size, exclude pumps from the cooling system by changing the forced circulation to natural, reduce the weight and size of the transformer, which, in turn, will reduce costs.

Problem formulation

Addition to the apparent benefits of replacing the type of coolant circulation in the transformer windings, there are a number of problems that need to be addressed [16]. Among them: oil stagnation in the horizontal channels of the windings, local overheating of the coils, the formation of zones in which the amount of oil flowing is insufficient for efficient heat removal from the coils. In this regard, it is necessary to accurately predict the nature of the temperature field of such windings to develop measures to ensure reliable cooling of the transformer windings. Existing methods for calculating the thermal state of windings are used only in cases where the width of the cross section of the horizontal channels is more than 3 mm. Therefore, theoretical and experimental study of hydrodynamics in the cooling channels of the windings with the size of the horizontal channels less than 3 mm and the natural circulation of the cooling medium is an urgent task.

A cylindrical coordinate system (an arbitrary point has coordinates $P(x,r,\varphi)$) was chosen to study the thermal processes in the transformer windings. The coordinate system is selected so that the coordinate axis OX is directed vertically upwards. Thus, the decomposition of the free fall acceleration vector in the selected coordinate system will look like:

$$g_{OX} = -g; \quad g_r = 0; \quad g_\varphi = 0 \tag{1}$$

where g is the numerical value of the free fall acceleration vector, g = 9,81 N/kg.

When studying the temperature field of transformer oil, it is considered that the medium is continuous. The state of a continuous medium is characterized by macroscopic parameters: velocity, temperature and pressure. To determine these parameters, consider the basic equations that describe the heat transfer in a liquid.

The energy equation of a fluid moving in a cylindrical coordinate system has the form:

$$\begin{gathered} \frac{\partial t}{\partial \tau} + W_x \frac{\partial t}{\partial x} + W_r \frac{\partial t}{\partial r} + \frac{W_\varphi}{r} \frac{\partial t}{\partial \varphi} = \\ = \frac{1}{\rho c_p} \cdot \left(\frac{\partial}{\partial x}\left(\lambda \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial r}\left(\lambda \frac{\partial t}{\partial r} \right) + \frac{\partial}{r^2 \partial \varphi}\left(\lambda \frac{\partial t}{\partial \varphi} \right) + \frac{\lambda \cdot \partial t}{r \cdot \partial r} \right) + \frac{q_v}{\rho c_p} \end{gathered} \tag{2}$$

where:

q_v – the average density of heat loss in the volume of the conductor, W/m^3,

W – fluid flow rate, m/s,

λ – the thermal conductivity of the liquid, W/(m·K),

ρ – fluid density, kg/m^3,

c_p – heat capacity of the liquid, J/(kg·K).

However, equation (2) includes the values of the oil flow velocity projections on the coordinate axes. To determine them, it is necessary to attach to (2) the equation of motion (Navier-Stokes) in cylindrical coordinates:

$$\begin{aligned}
&\rho\cdot\left(\frac{\partial W_x}{\partial\tau}+W_x\frac{\partial W_x}{\partial x}+W_r\frac{\partial W_r}{\partial r}+\frac{W_\varphi}{r}\frac{\partial W_x}{\partial\varphi}\right)=\rho\cdot g_x-\\
&=\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(2\mu\frac{\partial W_x}{\partial x}\right)+\frac{\partial}{\partial r}\left(\mu\left(\frac{\partial W_x}{\partial r}+\frac{\partial W_r}{\partial x}\right)\right)+\\
&+\frac{\mu}{r}\cdot\left(\frac{\partial W_x}{\partial r}+\frac{\partial W_r}{\partial x}\right)+\frac{\partial}{r\cdot\partial\varphi}\left(\mu\left(\frac{1}{r}\cdot\frac{\partial W_x}{\partial\varphi}+\frac{\partial W\varphi}{\partial x}\right)\right)
\end{aligned}$$

$$\begin{aligned}
&\rho\cdot\left(\frac{\partial W_r}{\partial\tau}+W_x\frac{\partial W_r}{\partial x}+W_r\frac{\partial W_r}{\partial r}+\frac{W_\varphi}{r}\frac{\partial W_r}{\partial\varphi}-\frac{W_\varphi^2}{r}\right)=\rho\cdot g_r-\\
&-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left(\mu\left(\frac{\partial W_r}{\partial x}+\frac{\partial W_x}{\partial r}\right)\right)+\frac{\partial}{\partial r}\cdot\left(2\mu\frac{\partial W_r}{\partial r}\right)+\\
&+\frac{2\mu}{t}\cdot\left(\frac{\partial W_r}{\partial r}-\frac{\partial W_\varphi}{r\cdot\partial\varphi}-\frac{W_r}{r}\right)+\frac{\partial}{r\cdot\partial\varphi}\left(\mu\left(\frac{1}{r}\cdot\frac{\partial W_r}{\partial\varphi}+\frac{\partial W_\varphi}{\partial r}-\frac{W_\varphi}{r}\right)\right)
\end{aligned}$$

$$\begin{aligned}
&\rho\cdot\left(\frac{\partial W_\varphi}{\partial\tau}+W_x\frac{\partial W_\varphi}{\partial x}+W_r\frac{\partial W_\varphi}{\partial r}+\frac{W_\varphi}{r}\frac{\partial W_\varphi}{\partial\varphi}-\frac{W_\varphi\cdot W_r}{r}\right)=\rho\cdot g_\varphi-\\
&-\frac{\partial p}{r\cdot\partial\varphi}+\frac{\partial}{\partial x}\\
&\left(\mu\left(\frac{\partial W_\varphi}{\partial x}+\frac{\partial W_x}{r\cdot\partial\varphi}\right)\right)+\frac{\partial}{\partial r}\left(\mu\left(\frac{\partial W_\varphi}{\partial x}+\frac{\partial W_x}{r\cdot\partial\varphi}\right)\right)+\\
&+\frac{2\mu}{r}\cdot\left(\frac{\partial W_\varphi}{\partial r}-\frac{\partial W_r}{r\cdot\partial\varphi}-\frac{W_\varphi}{r}\right)+\frac{\partial}{r\cdot\partial\varphi}\left(2\mu\left(\frac{1}{r}\cdot\frac{\partial W_\varphi}{\partial\varphi}+\frac{\partial W_\varphi}{\partial\varphi}\right)\right)+\\
&+\frac{\partial}{\partial r}\left(\mu\left(\frac{\partial W_\varphi}{\partial r}+\frac{\partial W_r}{r\cdot\partial\varphi}-\frac{W_\varphi}{r}\right)\right)
\end{aligned}\tag{3}$$

Results and Discussions

To calculate the unknown in (3) the value of pressure p, we use the continuity equation:

$$\frac{dW_x}{\partial x}+\frac{dW_r}{\partial r}+\frac{dW_\varphi}{r\cdot\partial\varphi}+\frac{W_r}{r}=0\tag{4}$$

Thus, the process of convective heat exchange in cylindrical coordinates is described by equations (2)-(4). Under the condition of stationary heat exchange, the time derivatives become equal to zero.

Thermal models of the horizontal channel of coil windings with a radial width of 50 mm are accepted as object of research. The surface area of each coil is 500 mm^2.

Initial conditions for solving this model:

- initial oil temperature 60℃;
- ambient temperature 30℃;
- heat flux density 3500 W/m^2.

It is obvious that increasing the flow rate of oil at the entrance to the radial channel of the thermal protection system of the power transformer will lead to a significant increase in the intensity of heat transfer from the heated copper coils to the cooling medium. However, for a comprehensive assessment of the positivity of such external influences, it is necessary to analyze the dependence of the excess pressure of transformer oil in the horizontal channel of power equipment on the speed of the medium at its inlet. To do this, artificial values of oil velocities were set on the right vertical boundary of the channel. The studies were performed for the following velocities: 0.1 m/s, 0.5 m/s, 1 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 8 m/s, 9 m/s and 10 m/s.

The resulting calculations of the velocity field and excess pressure in the horizontal channel at a speed of 0.1 m/s at the entrance to it are shown in Figure 1.

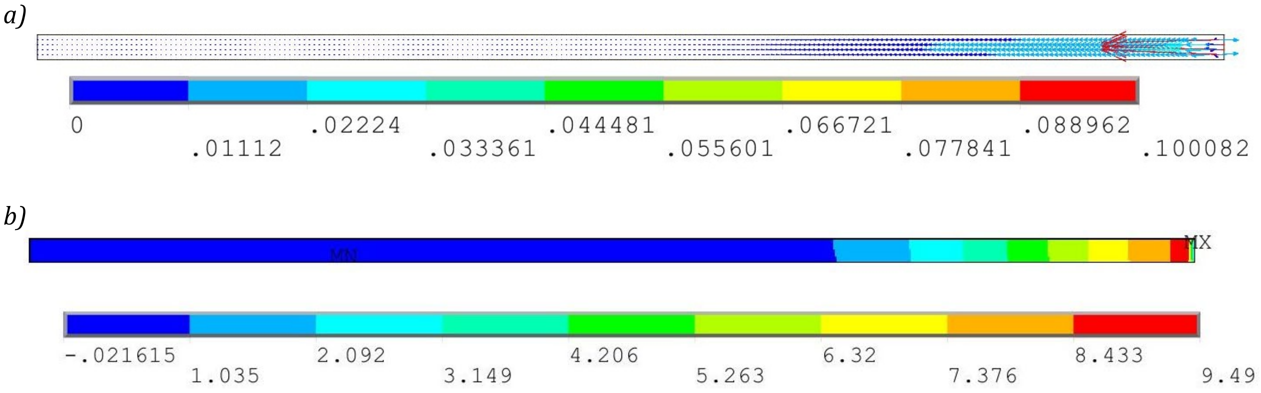

FIGURE 1. *Distribution of oil velocities in the radial channel of the transformer (a) and the distribution of excess oil pressure (b) in the radial channel of the transformer at a speed at the entrance to the radial channel of 0.1 m/s*

Figure 1 shows that in the right part of the channel of the thermal protection system of power equipment there is not only the movement of oil into the channel, but also leakage from it in the upper and lower part of the channel. This indicates that it is easier for the fluid to overcome the velocity applied at the inlet to the channel (0.1 m/s) and push the oil back than to push all the oil along it.

The high density of current lines in the right part of the channel (Fig. 1a) indicates the intense movement of fluid in this part of the model, however, with advancing to the left along the channel, the intensity of current lines decreases significantly, and about one-fifth of the channel length disappears. The pressure distribution (Fig. 1b) completely repeats the contours of the velocity field, and in the area where there are no current lines, the numerical values of excess pressure fluctuate around 0 Pa. The choice of the side of the channel to which the speed is applied has no effect on the final result. Also, the results are not significantly affected by the direction of the applied load, ie the effect on the model of the positive sign speed applied to the left limit is identical to the effect of the negative speed on the right border of the channel.

In general, the identical nature of the velocity and overpressure fields is observed under all the conditions under consideration. It is obvious that the area where there is intense movement of fluid in the radial channel depends on the speed of the oil at the inlet. However, at the speed of the oil at the entrance to the channel, equal to 1 m/s, the separation of the liquid from the walls of the right part of the channel begins to be observed. This phenomenon can be investigated especially clearly at a speed of 10 m/s at the entrance to the channel. The nature of the distribution of excess pressure at the oil velocity at the inlet to the horizontal channel, equal to 1 m/s and 10 m/s is identical to the nature at 0.1 m/s. The only significant difference is the displacement of the point with the lowest pressure in the right part of the channel, which is caused by the separation of the flow from the walls and the formation of a vacuum zone. It is obvious that even if there is an oil velocity at the entrance to the radial channel equal to 10 m/s, it is impossible to organize the through circulation of oil along the entire channel. This is evidenced by the presence of zones of the channel, in which the excess pressure fluctuates around 0 PA, and in which there are virtually no current lines. As calculations have shown, the accepted values of velocities allow to obtain results that fully reflect the nature of the dependence of excess oil pressure on the velocity of its flow at the entrance to the horizontal channel (Fig. 2).

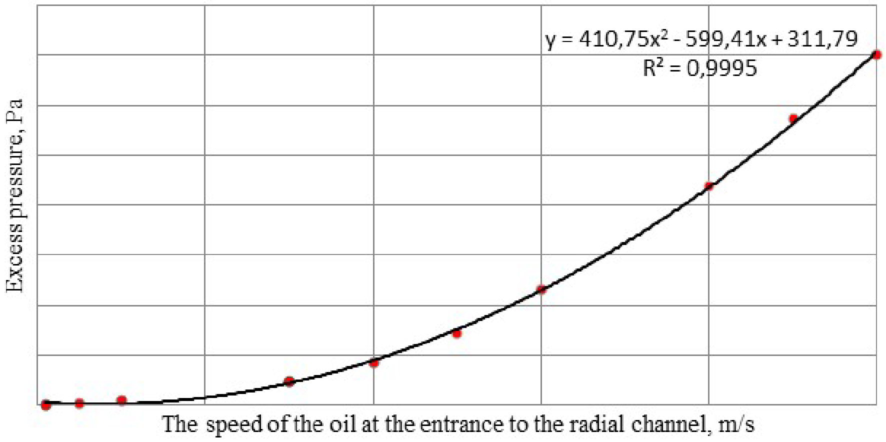

FIGURE 2. *Dependence of excess oil pressure on the speed of its flow at the entrance to the horizontal channel*

The maximum excess pressure in the channel (mark "MX" in Fig. 1b) is taken as the excess pressure, which is shown in the diagram.

Excessive pressure of the cooling medium in the thermal protection system of power equipment is the parameter that can cause premature failure of the transformer and lead to an emergency situation. Thus, it is necessary to estimate the value of the maximum excess pressure in the radial channels of the transformer. An approximation equation is found for this

$$y = 410.75x^2 - 599.41x + 311.79 \qquad (5)$$

where:

x – speed of the oil at the entrance to the radial channel, m/s,

y – maximum value of excess pressure, Pa.

To study the temperature field of the oil by the method of mathematical modeling, a winding model was created. Figure 3 shows the temperature field in the radial channel of the transformer.

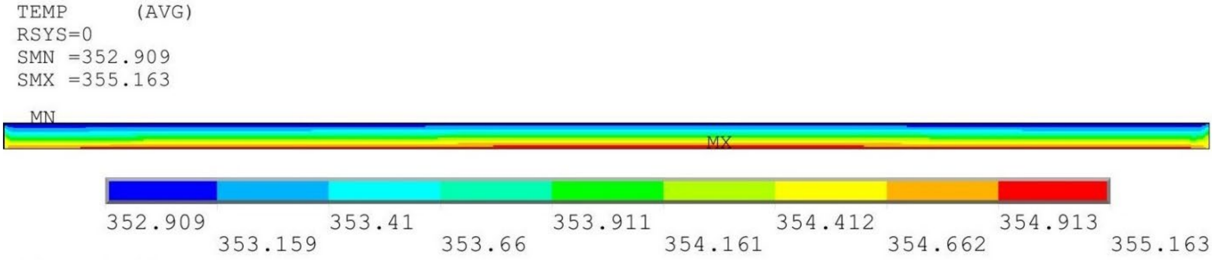

FIGURE 3. *Oil temperature field (K) in the radial channel of the transformer*

It is obvious that the oil temperature in the radial channel of the transformer changes its values in the range of 20°C. This means that there is almost no through circulation of the coolant in the channel. Cold oil does not flow into the channel, and heated does not flow out of it. Almost all the heat released into the radial channel is redistributed between the coils that form it, due to the thermal conductivity of the oil. Convection heat transfer is almost completely absent. A characteristic phenomenon is that the lowest temperature in the radial channel is observed on the surface of the upper coil, and not at the entrances to the channel. Thus, the heat flow will be directed in the direction of the zone with a lower temperature, namely in the upper coil. It is obvious that the temperature maximum of the oil (mark "MX" in Fig. 3) is observed in the central part of the channel. This is due to the lower temperature of the coils near the vertical channels through which most of the heat is removed. Thus, Figure 3 clearly shows the lack of efficient circulation of coolant in the radial channel of the disk winding of the power transformer.

Therefore, the heat in the horizontal channel is transferred from coil to coil due to the thermal conductivity of the oil, except for the side parts of the channel, in which there is through circulation due to the close location to the vertical channels. In radial channels, oil conducts heat almost like a solid, as evidenced by the characteristic temperature distribution.

Conclusions

The value of excess oil pressure in the radial channel of the thermal protection system of power equipment is quadratically dependent on the speed of the oil at the inlet to the channel. Therefore, increasing the speed of the oil will lead to a much greater increase in excess coolant pressure.

In a radial channel 1 mm wide, fluid circulation is detected in the areas located at the entrance to this channel. This circulation is sufficient to remove sufficient heat from the coils and prevent overheating of the active part of the transformer. However, it is almost impossible to organize the through circulation of the cooling medium in the conditions under consideration.

The presence of an artificial speed of oil at the entrance to the radial channel can not organize through circulation in it. In addition to the fact that it is technically impossible to organize the presence of this speed without making changes to the design of the transformer, it will lead to a significant increase in excess pressure in the radial channels, which can disrupt the electric machine and cause an emergency.

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