Thermal computer simulation of the power transformer TM-160/10

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Annotation. Power transformers represent the largest part of capital investments in transmission and distribution of substations. In addition, disconnections of the power transformer cause significant economic damage to the electrical network. One of the most important parameters that determine the resource of a transformer is the temperature of the hottest point, which is determined by the density of the heat fluxes. An important task is to improve the quality of transformers, develop the most advanced technologies for their production, create and use the most modern and highly efficient materials, and reduce energy losses during their operation. The solution of these problems is impossible without deep understanding and study of the thermal regimes of the transformer.

Introduction

Power transformers represent the largest part of capital investments in transmission and distribution of substations. In addition, disconnections of the power transformer cause significant economic damage to the electrical network. One of the most important parameters that determine the resource of a transformer is the temperature of the hottest point, which is determined by the density of the heat fluxes. It was shown in [1-3] that the maximum temperature is a function of loads, overloads, cooling regimes and time. An important task is to improve the quality of transformers, develop the most advanced technologies for their production, create and use the most modern and highly efficient materials, and reduce energy losses in their work [4]. The solution of these problems is impossible without deep understanding and study of the thermal regimes of the transformer.

The increased loads of the transformer lead to operating modes with temperatures exceeded permissible values. This leads to the deterioration of insulation, decreases of the service life and reliability. Protecting the transformer from overheating due to unacceptable operating temperatures is associated either with the need to reduce the load, that is a violation of its basic function, or with the use of cooling boosting means.

The purpose of this work is to simulate the thermal conditions of the transformer, to study the distribution of heat fluxes and temperatures in the transformer under various cooling regimes and power losses.

In accordance with the current standards the temperature difference of any part of the transformer is the temperature difference between this part and the cooling medium. Permissible excess temperatures of the active part of the transformer affect the internal device, dimensions, load capacity, cost and operating modes of the transformer. Control over the conformity of the temperature of the most heated point of the transformer to the permissible temperature is difficult for transformers, so its determination by experimental methods or by means of modeling is an actual task.
Calculation of power oil-filled transformer parameters

The core oil-filled three-phase transformer TM-160/10 was chosen as an object of investigation. The values of its parameters are presented in Table 1. Calculation of the main electrical quantities and geometric dimensions of the transformer, which are necessary for modeling, was performed according to the methods [5-6]. As high voltage (HV) and low voltage (LV) windings, cylindrical multilayer windings of round wire are adopted.

For the test voltage HV \( U_{HV} = 35 \text{ kV} \), the insulation distances [7] are determined: \( d_{12} = 9 \text{ mm}, \) \( \delta_{12} = 30 \text{ mm}, \) \( a_{22} = 10 \text{ mm}, \) \( \delta_{12} = 3 \text{ mm} \) (Fig. 1).

Table 1. Electrical characteristics of transformer TM 160/10

| Transformer type | TM-160/10 |
|------------------|-----------|
| Power            | 160 kVA   |
| Frequency        | 50 Hz     |
| Number of phases | 3         |
| Primary voltage  | \((10000 \pm 3\times2\%) \text{ V}\) |
| Secondary voltage \( U_2 \) | 3150 V |
| Cooling system   | oil free  |
| Scheme and group of connection of windings | Y/Y |
| Short-circuit voltage | 4.5 % |
| No-load current  | 2.4 %     |
| Loss of idling   | 510 W     |
| Loss of short circuit | 2650 W |

The core design of the transformer with the number 6, \( k_{cr} = 0.913 \) without the pressing plate was chosen. At power of 160 kVA cooling channels in the magnetic circuit are not provided. As the material of the magnetic system of the transformer, cold-rolled electrical steel grade 3404 with a density of 7650 kg/m³ is adopted. Diameter of core rod \( d = 0.150 \text{ mm} \). The average diameter of the channel between the windings \( d_{12} = 0.227 \text{ mm} \).

The winding height is \( l = 0.263 \text{ m} \). The active cross-section of the rod is \( S_r = 0.0153 \text{ m}^2 \). The number of turns of LV windings per one phase is \( w_2 = 327 \). The winding wire is with a diameter of 3.55 mm with a cross-section of 9.895 mm². The number of turns in the layer \( w_{2L} = 65.48 \). The number of layers in the winding \( n_2 = 5 \). The dimensions of the winding LV: internal diameter \( D_{2\text{in}} = 180 \text{ mm}, \) outer diameter \( D_{2\text{out}} = 221 \text{ mm} \). The surface area of the LV winding is \( S_2 = 0.324 \text{ mm}^2 \). Loss of short circuit \( P_{sc} = 382.78 \text{ W} \), weight of wire of winding LV \( G_2 = 18.16 \text{ kg} \). The heat flux density on the surface of the LV winding \( q_2 = 1.18 \text{ kW/m}^2 \). The number of turns of the HV winding at the rated voltage \( wn_2 = 1038 \). The number of turns at one stage of the voltage winding regulation when connecting the HV winding to the star \( wp = 36 \). A multilayer cylindrical winding made of round copper wire of diameter \( d_1 = 1.9 \text{ mm} \), section 3.14 mm². The number of turns in one layer is \( w_{1L} = 109 \). The number of layers is \( n_1 = 9.58 \). The internal diameter of the winding is «before-channel» \( D_{1\text{in}} = 239 \text{ mm}, \) «after-channel» \( D_{1\text{out}} = 269 \text{ mm} \). The outer diameter of the winding is «before-channel» \( D_{1\text{in}} = 261 \text{ mm}, \) «after-channel» \( D_{1\text{out}} = 307 \text{ mm} \). The total cooled surface of the winding HV \( S_1 = 0.888 \text{ mm}^2 \). Short-circuit losses \( P_{sc} = 514.96 \text{ W} \). The wire weight of the «before-channel» part of the winding \( G_{1\text{in}} = 9.522 \text{ kg} \), the weight of the wire «after-channel» part of the winding \( G_{1\text{out}} = 15.27 \text{ kg} \).

Computational experiment

Modeling of heat transfer and hydrodynamics was carried out in the transformer environment in the software package of the free version of Ansys 17.1 (ANSYS Free Student Product Downloads) [8-10].

In view of the fact that the exact calculation of the oil-filled transformer is limited by the computing resources of the computer, a simplified model of the TM-160/10 transformer is used. Cylindrical surfaces that are created in the Ansys 17.1 Design Modeler geometry module are used...
as LV and HV windings, as well as insulation windings. Previously a sketch is created, which is then converted to a 3D shape using the Extrude operation. The models of LV and HV winding of transformer and insulation for one phase, constructed in this way, in accordance with the calculated geometry are shown in Fig. 1.

![Fig. 1. Model of windings of one phase of transformer TM 160/10, created in Design Modeler of the program Ansys 17.1](image1.jpg)

Further, with the help of the Translate tool, two more phases of the transformer are created, and a core is included in the model. After this, the model is placed in the oil-filled tank.

Next, the program specifies the characteristics of the physical model. For this purpose, the characteristics of the materials of windings, rods, yokes, insulation and their environment are specified in the Steady-State Thermal module. As the material of the windings we take copper, core material is steel (Structural Steel), cooling medium is transformer oil (Engineer oil). Then in Ansys Steady-State Thermal the calculated grid area Mesh is defined, which is calculated automatically on the basis of the geometric model (Fig. 2).

![Fig. 2. The calculated grid area of the Mesh transformer (in section) in Ansys Steady-State Thermal](image2.jpg)
Short-circuit mode

The short-circuit mode is specified in Ansys Steady-State Thermal by specifying the specific heat flux \( q \) (Heat Flux). The heat flux density on the surface of the LV winding in the short-circuit mode is \( q_{2sc} = 1183 \text{ W/m}^2 \), from the winding HV - \( q_{2sc} = 580 \text{ W/m}^2 \).

Also for correct modeling, the condition for transferring heat by convection is introduced into the model and we denote all boundaries between the liquid and the solid with the Fluid Solid Interface tool.

From the screenshots shown, it is clear that when the air is cooled, the temperatures at which the transformer operates are significantly higher than the permissible 144…235 °C. The temperature of the hottest points corresponds to approximately 225 °C and is characteristic of the LV winding, and the core temperature \( t = 210 \text{ °C} \) is also high. Due to the presence of insulation, the temperature of the HV windings is significantly lower, but it also exceeds the permissible value. The greatest density of heat fluxes, as expected, is near the windings, as the heat fluxes away from them, the intensity of the heat fluxes decreases rapidly.

Similar simulation of operation in the short-circuit mode with oil filling of the transformer was carried out. The distribution of temperatures and density of heat fluxes is shown in Fig. 3–4.

![Fig. 3](image1.png)

**Fig. 3.** Distribution of temperatures in the transformer in the longitudinal (a) and transverse (b) sections during short-circuit operation. Cooling medium is transformer oil.

The results indicate that the use of transformer oil to fill the transformer significantly reduces the temperature in the active part. The temperature distribution occupies the range of 67…91 °C. This means that the temperature of the most heated part is 91 °C and also corresponds to the winding LV.

![Fig. 4](image2.png)

**Fig. 4.** The distribution of the heat flux density in the transformer in the longitudinal (a) and transverse (b) sections when operating in the short-circuit mode. Cooling medium is transformer oil.

**Dependence of the maximum temperature of the transformer on the operating mode**

The service life of the transformer is determined by the maximum temperature of its windings, depending on the operating mode of the transformer. To study the dependence of the maximum
temperature of the transformer TM-160/10 on the mode of its operation, simulation was performed in the range of losses from idling (510 W) to short circuit (2650 W). The corresponding temperature distribution is shown in Fig. 5.

![Fig. 5. The distribution of temperatures in the oil-filled transformer in the longitudinal (a) and transverse (b) sections with a loss of $P = 2240$ W](image)

Based on the obtained data, the temperatures of the most heated points of the transformer are determined and the dependence of the maximum temperature of the transformer against losses is plotted (Fig. 6). The obtained dependence is well approximated by a straight line described by the equation: $t = 0.0261 \times P + 22.06$, °C.

![Fig. 6. The dependence of the maximum temperature of the transformer on power losses](image)

**Results**

Modeling in Ansys 17.1 environment of thermal operating modes of the transformer was carried out both in the dry and in the oil-filled version. The distribution of temperatures in the active part of the transformer and near it, as well as heat fluxes, is determined. A formula is proposed for the dependence of the maximum temperature (the most heated point) on power losses in the range of idling and short circuit modes that determines its life.

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