Energy efficient heat supply system for electric power facilities

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Abstract. The aim of the work is to confirm the possibility of creating an energy-saving heat supply system for power facilities by using computer modelling, analysis of the potential use of heat losses of electromagnetic energy in magnetic circuits and windings of transformers of substations, as well as the development of schemes for heat recovery losses for heat supply of power facilities. Computer simulation of electromagnetic and thermophysical processes in the power oil-filled transformer is carried out. Energy losses in windings, hysteresis and eddy currents in the magnetic circuit, as well as temperature and heat flux fields in the longitudinal and transverse sections of the oil-filled power transformer in idle and short-circuit modes were determined. The transformer performance in terms of heat recovery losses was evaluated. The possible volumes of heat extraction for heat supply depending on the power of the transformer are determined. The automated oil-water system of heat recovery of the transformer for heating of electric power facilities is proposed. The significance of the obtained results for the construction industry is to confirm the possibility of creating an energy-saving heat supply system for electric power facilities while maintaining the operational characteristics of the transformer based on computer modelling; the significant potential of using the heat loss of power transformers of substations is shown, an automated heat supply system for electric power facilities is proposed.

1 Introduction

In systems of transformation and transportation of the electric power the step up and step down power transformers are used. Their total power according to [1, 2] practically exceeds the established power of all generators of the power system of Russia. During the conversion process in the magnetic circuits and transformer windings, energy is lost and released as heat, which must be removed to avoid overheating of the equipment. In high-power transformers, heat losses can reach hundreds of kilowatts, which can and should be used for heat supply of energy facilities [3]. Selection and utilization of heat of the transformer, including for heating of rooms is one of ways of energy saving. According to JSC "STC FGC UES" [4] the potential of this energy saving direction is about 90 % of power transformers of all voltage classes. The economic effect is achieved by reducing the share of electricity used to remove heat from the transformer equipment in the total cost of electricity for the substation's own needs.

Technical and economic feasibility and the specific method of heat removal and utilization of the transformer is determined by factors such as the need and potential of heat extraction (depends on the power of the substation), the distance of heated rooms from the transformer, the presence and proximity of sources of district heating, the cost of communications, etc., as well as specific conditions for generation and transmission of electricity in the region. Actual use of heat transformers is for the mountainous regions of Vietnam.

Depending on the characteristics of the installed transformers (type, quantity, power), their mode of operation, the required thermal performance, the type of coolant used in the heating system and the distance to the consumers, the scheme with water heating in the oil - water heat exchanger (oil-water system) of heat removal is popular [4 – 7]. The heat exchanger "oil – water", installed next to the transformer receives hot oil from the top of the transformer tank circulating oil pump. In the heat exchanger, the oil gives off heat to the water, which is supplied by a circulation pump to the heating system. At the maximum permissible temperature of transformer oil 60-70 °C, according to GOST R 52719-2007 "power Transformers. General technical conditions" the water temperature in the heat exchanger depending on the heat consumption and can reach 45-50 °C. The greatest implementation of the oil-water system is possible at substations of voltage classes 110-400 kV and transformers of the OFAN type [8]. The preference of this system is due to the fact that it allows using the already existing devices of water heating and transfer heat to 500 - 1000 meters.

Computer simulation of the transformer aims to confirm the preservation of the transformer performance under different loads and to ensure that the steel parts and insulation are not exposed to excessive heat, as well as that no combustible gases are formed inside the tank.

The electromagnetic field of the transformer is simulated in the software environment of ANSYS Workbench [9] using the Maxwell 2D/3D module [10, 11]. ANSYS Maxwell is an interactive computing

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package that uses finite element method which allows to determine the scalar and vector diagrams of flux density, the magnetic and electric fields, current density, and the capacity losses in the windings and the magnetic core based on four of Maxwell's equations with appropriate boundary conditions:

Gauss's law for electric field

$$\nabla \cdot \vec{D} = \rho; \quad (1)$$

Faraday's law of induction

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}; \quad (2)$$

Gauss's law for magnetic field

$$\nabla \cdot \vec{B} = 0; \quad (3)$$

Ampere law for current

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}, \quad (4)$$

where ρ - volume density of electric charge, C/m³; $\vec{J}$ - the density of electric current, A/m²; $\vec{E}$ - electric field strength, V/m; $\vec{H}$ - magnetic field strength, A/m; $\vec{D}$ - electrical induction, C/m²; $\vec{B}$ - magnetic induction, T; t - time, s.

Oil-filled three-phase transformer TM-1600/10, the parameters of which are presented in the table, is used as a source of heat losses for recycling.

Table 1. Electrical characteristics of the transformer TM-1600/10.

Type of transformer	TM-1600/10
Rated power	1600 kVA
Frequency	50 Hz
Number of phases	3
Primary voltage	(10000 ± 3x2%) V
Secondary voltage U ₂	3150 V
Cooling system	natural oil
Circuit and winding connection group	Y/Y
Short-circuit voltage	6.5 %
No-load current	2.4 %
No-load losses	2.35 kW
Short circuit losses	18 kW

The first step in modeling electromagnetic fields is to transfer the geometric model to ANSYS Workbench for preprocessing. Further, the properties of materials for the main components of the transformer, such as magnetic core materials (accepted as solid), winding (copper), insulation and transformer oil, boundary and initial conditions are set. The next step is to instruct the program to solve the problem and control the

convergence of the solution. The final stage is post-processing (processing and analysis of results).

Simulations of electromagnetic characteristics is performed in the range of idle and short-circuit modes. Since the extreme modes are inoperative, it is determined that at a load of 84 % of the short circuit of the nominal frequency of 50 Hz, the main part of the passport losses are Joule-Lenz losses, as well as hysteresis losses and eddy currents in the magnetic circuit. The remaining losses are incremental and account for a few percent of the main losses. According to the model, the loss is 15100 W, which does not exceed the passport values.

In oil transformers heat transfer mainly takes place by conduction and convection. Heat transfer by radiation is negligible, since oil is considered an opaque medium. Then the cooling of the windings and the magnetic circuit of the transformer with an oil coolant is described by the equations [12, 13]:

The energy equation

$$\frac{\partial t}{\partial \tau} + \vec{w} \text{grad} t = a \nabla^2 t + q_v; \quad (5)$$

The Navier-Stokes Equations

$$\rho \frac{D\vec{w}}{d\tau} = \rho g - \nabla p + \mu \nabla^2 \vec{w}; \quad (6)$$

and the equation of continuity

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho \vec{w}) = 0, \quad (7)$$

where t - temperature, K; τ - time, s; w - velocity m/s; a - coefficient of thermal diffusivity, m²/s; q_v - intensity of internal heat sources, W/m³; ρ - density, kg/m³; p - pressure, Pa; μ - coefficient of dynamic viscosity, Pa·s.

For unambiguity of the solution of the system of differential equations, boundary conditions are necessary, i.e. to set the shape and dimensions, properties of the medium and bodies in the transformer and initial conditions – temperature at the time $\tau(0)$. The problem is solved under boundary conditions of the II kind, i.e. the heat flux density is set at the boundary according to the calculated values in the range from the idle mode to the short circuit. The standard k - ε turbulence model was used in the simulation.

For a deep understanding of the process of transformer cooling and heat removal, thermal simulation of oil-filled power transformer TM 1600/10 was carried out. Simulation of heat transfer and hydrodynamics was performed in the transformer environment in the software package of the freely distributed version Ansys 17.1 (ANSYS Free Student Product Downloads) [12]. Due to the fact that the exact calculation of the oil-filled transformer is limited by computer resources, a simplified model of the TM-1600/10 transformer is used.

Fig. 1. Temperature distribution in the transformer in the longitudinal section when operating in idle mode.

The computer simulation of the power transformer in idle mode (Figure 1). The temperature and heat flux fields in the longitudinal and transverse sections of the oil-filled power transformer are determined. A similar simulation of short-circuit operation is also carried out.

As can be seen from the figures, when working in idle mode, the parameters are significantly lower than the nominal ones. The maximum temperature is only 35 °C, and the highest heat flows 90 W/m² with total losses in idle mode 2350 watts. Obviously, this is a non-working mode, although in terms of the service life of the transformer is favorable. Work close to this mode is technically impractical, since in this case the transformer will not effectively perform its main function for the consumer.

When operating in short circuit mode, the temperatures in the active part are in the range of 67-91 °C, which do not exceed the maximum permissible values [14, 15]. Accordingly, the maximum heat flow reaches 620 W/m² with a total short circuit loss of 18000 W. The maximum values of the parameters in this non-working mode also do not exceed the permissible values. The heating system allows you to heat in winter conditions of Central Russia to a comfortable temperature working space built on modern technology area of 120-140 m².

2 Methods

The potential of heat depends on the power substation, mode of operation, the quality of the windings and magnetic cores, transformer design, etc. Assessment of potential volumes of heat for heating, depending on power transformers is carried out according to [16] taking into account the variations of +15 %. The results are presented in logarithmic scale in Figure 2.

Fig. 2 Assessment of possible amounts of heat for heating, depending on the power transformer: P_0 – no-load losses; P_s – short circuit losses; the shaded region is the operating mode.

3 Results

Oil-water scheme of transformer losses utilization is shown in Figure 3. From the top of the transformer tank oil is supplied to the heat exchanger "oil – water", located near the transformer. The heated water in the heat exchanger circulates in the heating system of the building by means of a water pump. Control of the heat supply system is carried out by means of a controller, which, depending on the oil temperature, the operation mode of the transformer and the outside air, turns on or off the drives of the coolers, changes the speed of the circulation pumps in order to create the required heat exchange conditions. In order to take into account, the heat used in the heating system can be installed heat exchanger.

Fig. 3. Oil-water heat recovery system of the transformer for space heating.

4 Conclusions

The method of heat removal and utilization of the transformer depends on the power of the substation, the heat loss of the heated building (architecture) and the temperature of the outside air, the distance of the heated rooms from the transformer. Computer simulation showed a very real possibility of creating an energy-saving heat supply system for power facilities without reducing the operational characteristics of the transformer. There is a significant potential for the use of heat losses of power transformers of substations depending on the power of the transformer. The automated energy-saving oil and water heating system of electric power facilities is proposed. Technical and economic efficiency of the proposed heating system is determined based on specific climatic conditions and schemes of heat supply, generation and transmission of electricity in the region.

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