Modeling and Study of Heat Dissipation of Three-Phase Two-Winding Oil Transformers

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Abstract. This article analyzes the thermal processes of three-phase and two-phase oil-immersed transformers and describes modern modeling methods. The main factors influencing transformer thermal dynamics are examined: load conditions, convective oil flow, magnetic core losses, and the thermal properties of insulating materials. In addition to analytical thermal calculations, the study utilized 3D modeling methods based on CFD (computational fluid dynamics). The results obtained will help improve the reliability of oil-immersed transformers and select the optimal cooling system.

INTRODUCTION

Three-phase oil-immersed transformers are one of the main components of power systems, and their reliability largely depends on the stability of the thermal regime [1]. The heat generated in the transformer is mainly caused by the following sources:

- losses in the magnetic conductor,
- I^2R losses in the first and second coils,
- additional losses due to excitation current,
- insulation aging processes.

In oil-cooled transformers, heat is dissipated primarily through natural or forced convection. Therefore, accurate heat transfer modeling is essential to ensure normal operating temperatures.

THEORETICAL BASIS FOR HEAT TRANSFER CALCULATION

Thermal analysis of oil-immersed transformers typically consists of two main steps:

Waste identification

The total losses in a transformer are expressed as follows:

$$P_{total} = P_{iron} + \mathrm{P}_{winding} + \mathrm{P}_{additional} \tag{1}$$

Here:

P_{iron}- hysteresis and total current losses in the magnetic core,

$\mathrm{P}_{winding}$- losses of active resistance in coils,

$\mathrm{P}_{additional}$- losses caused by surface currents and mechanical vibrations [2].

Heat balance equation. The change in temperature in a transformer is described by the following equation:

$$\mathrm{C}\frac{dT}{dt} = P_{total} - hA(T - T_{atm}) \tag{2}$$

Here:
- C - annual capacity,
- h is the coefficient of convective heat transfer,
- A - heat exchange surface,
- T_{atm}- outside atmosphere air temperature [3].

By solving this equation, we can determine the surface temperature of the transformer oil (the temperature of the top layer of oil) and the maximum winding temperature (the temperature at the hottest point).

MODELING METHODS

Equivalent heat chain method. In equivalent thermal diagrams, transformer elements are represented by thermal resistances and heat capacities similar to those in electrical circuits [4]. This method is fast and suitable for engineering calculations, but has limited accuracy. One of the most effective methods for modeling the thermal behavior of three-phase, two-pipe, oil-immersed transformers in grid-scale and realistic modes is the use of CFD (computational fluid dynamics) technologies. Using programs such as ANSYS Fluent, COMSOL Multiphysics, and OpenFOAM, natural oil convection, heat transfer processes, and temperature distribution in the coil and magnetic core are calculated in 3D [10-15].

Computational fluid dynamics (CFD) modeling. Computational fluid dynamics (CFD) programs (ANSYS Fluent, COMSOL, OpenFOAM, and others) allow 3D convection modeling in oil. CFD models are based on solving hydrodynamic and heat transfer processes using the Navier-Stokes equations. The Navier-Stokes equations are used in the modeling. Structurally, they are expressed as follows:

Equation of conservation of momentum (Nave-Stokes):

$$\rho\left(\frac{\partial v}{\partial t}+(v\cdot\nabla)v\right)=-\nabla p+\mu\nabla^2 v+pg \quad (3)$$

Here:
ρ- oil density,
And- velocity vector,
p- pressure,
μ- dynamic nut (viscosity),
G- gravitational acceleration.

As a result, the following parameters are determined: oil consumption, temperature of insulation and pipes, the hottest spots, heat transfer efficiency in radiators [5-10].

Energy equation:

$$\rho c_p\left(\frac{\partial T}{\partial t}+v\cdot\nabla T\right)=k\nabla^2 T+Q \quad (4)$$

Here:
c_p- heat capacity,
To- thermal conductivity of oil,
IN- heat generated due to losses in the coil and magnetic core.

In CFD modeling, natural convection of oil is calculated based on the Boussines approximation, in which case the change in oil density depending on temperature is written as follows:

$$\rho=\rho_0[1-\beta(T-T_0)] \quad \textit{(5)}$$

where b is the coefficient of thermal expansion of the oil.

Key parameters were determined using CFD modeling. The CFD model allows to determine the following operational and design parameters:

1. Oil consumption. Natural convection flows in oil circuits, velocity in radiator tubes, and gradients along circulation paths are estimated. This information is crucial in pump less (ONAN) and pump less radiator (ONAF) modes [15-22]

2. Temperature distribution in insulation and pipes. Computational fluid dynamics (CFD) results allow us to determine local temperatures in each insulation layer, particularly in hot spots. Temperatures in these areas determine the rate of insulation aging, so their accurate assessment is essential for compliance with technical standards.

3. Location of the hot spot. Determining which part of the transformer structure heats up the fastest is important for design optimization, especially when changing the width and location of the oil channels.

4. Heat transfer efficiency in radiators. The temperature difference in the radiator tubes, oil circulation rates, and heat transfer coefficients are calculated. CFD modeling is used to optimize the radiator design (number of tubes, length, and diameters).

As noted in the literature [5], CFD modeling of oil-cooled transformers provides 15–20% higher accuracy in predicting actual operating temperatures than traditional equivalent circuits and significantly reduces the error in determining temperatures in overheated zones.

RESEARCH RESULTS

As a result of simulation using computational fluid dynamics, the following observations were made:

Increased oil circulation due to load:

In the load range of 80–100%, oil circulation increases and the temperature rise is reduced. This will undoubtedly increase the efficiency of the convection system, as the oil will facilitate more efficient heat distribution.

Figure 1 presents the results obtained based on the modeling of the heat dissipation of a three-phase two-winding oil transformer in a Matlab script.

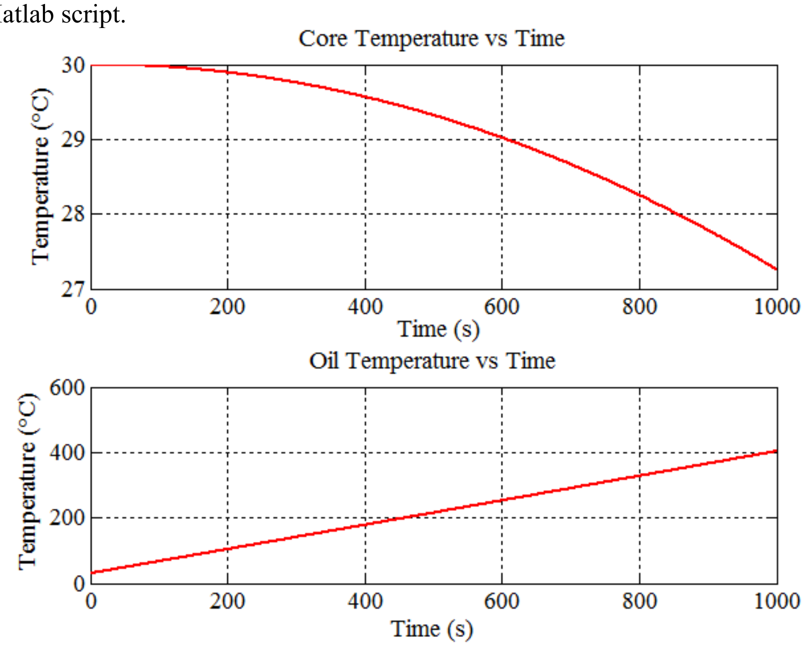

FIGURE 1. Time-varying graphs of core and oil obtained from modeling the heat dissipation of a three-phase, two-winding oil transformer

Thermal gradient on the surface of radiators:

Natural convection n and a high temperature gradient is observed on the radiator surfaces. This can lead to significant temperature differences between radiators, requiring modernization of heat dissipation systems.

Optimization to reduce temperatures in hot spots:

To reduce the temperature at the hottest point by 5–7 °C. It was found that optimizing the oil circulation channel geometry was effective. This, in my opinion, demonstrates that geometry can be improved using CFD modeling, which is essential for temperature control [22-28]

Short-term strong load fluctuations:

Short-term strong load fluctuations increases the risk of rapid aging of the insulation. This demonstrates the importance of a qualified engineering approach (material selection, system design) and the effective use of monitoring systems.

CONCLUSION

Correctly assessing the thermal conditions of three-phase, double-pipe oil-heated transformers is crucial for increasing their reliability and service life. Although equivalent thermal circuits are sufficient for engineering calculations, computational fluid dynamics (CFD) modeling is useful for obtaining accurate temperature distributions. The results obtained have practical implications for optimizing the design of oil-heated transformers and selecting an appropriate cooling system.

CFD modeling plays an important role in the correct assessment of the required thermal conditions for transformers and in the optimization of the design.

Despite some limitations, the use of equivalent thermal circuits in this case allows the use of CFD modeling, which offers new, more accurate and efficient solutions.

CFD simulation results effective optimization of transformer design and its importance when selecting a cooling system.

The obtained results demonstrate the importance of computational fluid dynamics (CFD) modeling in thermal management and design optimization.

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