Effect of the thermal characteristics of dielectric fluids on the loading capacity of a power transformer

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***Abstract*— The use of biodegradable dielectric liquids in power transformers has several advantages, such as increased fire safety or their biodegradability in the event of a leak in the tank. However, they also have a higher viscosity that does not benefit their cooling function within these machines. Although there are many references that analyze the transformers hot-spot temperature for dynamic loading, there are hardly any references that focus on the dynamic evaluation of the hot-spot when the viscosity of the dielectric and cooling fluid changes, with respect to that of the oil of mineral origin. In this work, the algorithms proposed in the bibliography will be combined with the use of computational fluid dynamics software ANSYS-FLUENT, which uses the finite volumes method to solve the equations that govern fluid flow. The software tool will be used to calculate the temperatures of a 100MVA transformer winding. Once these temperatures have been calculated, they can be entered into the hot-spot temperature estimation algorithm when the machine's load regime is varied. This analysis will be repeated using dielectric liquids with different thermal characteristics. Transformer fleet managers may use the results of this study in order to adapt their procedures when the machines they manage do not have conventional mineral oil inside.**

Keywords—power transformer, dielectric fluid, computational fluid dynamics, loading capacity.

I. INTRODUCTION

Power transformers are one of the main and most expensive assets of today's electrical power distribution systems. The technology used in its construction has not changed throughout its history. One of the main components of these electrical machines are the dielectric fluids used to cool and electrically insulate the conductor windings. In recent decades, different types of fluids with characteristics different from those of the traditional oil of mineral origin have been introduced on the market. The need to observe the sustainability of productive activities has also begun to be considered by companies that work in the power sector [1].

Currently, various projects of electric power transmission companies are being promoted for the evaluation of the performance of biodegradable dielectric liquids, natural or synthetic esters, in large power transformers, connected to 400 kV networks [2]. Considering the cost of these large units, it is essential to carry out an adequate design. Thus, it is very important to bear in mind that the useful life of a power transformer is frequently limited by the state of its insulation system. The insulating materials and fluids used in these machines accelerate the speed of their degradation when their temperature is high [3]. As has been shown in multiple scientific tests already published, biodegradable dielectric fluids reduce the aging rate of the solid components of the insulation systems, compared to the behavior of conventional mineral oils [4]. Another advantage to keep in mind is that the combination of biodegradable dielectric fluids and high-temperature solid insulation makes it possible to build large transformers within the weight limits of the trucks used in their transport [5].

At this point, it is necessary to underline that biodegradable dielectric fluids have a higher viscosity than mineral oils. This property does not benefit the cooling function that fluids perform in these machines. In fact, the thermal design of transformers is based on the knowledge of the variation of the fluid properties (viscosity, conductivity, density and specific heat) with temperature [6]. Numerous authors have analyzed the performance of dielectric esters in power transformer windings, comparing it with that of mineral oils. To implement these studies, Computational Fluid Dynamics (CFD) analysis tools have been used in most cases. With the results of these works, the temperatures in the different parts of the transformer windings can be known. This information is vital to using the proper type of solid insulation [7, 8].

In this proposal, the effect of the thermal characteristics of dielectric fluids on the loading capacity of a 100 MVA power transformer will be studied. In this topic there are two reference standards, the IEC 60076-7-2018 [9] and the IEEE standard C57.91:2011 [10], which offer procedures for estimating hot-spot and oil temperatures under a regime of variable load. The algorithm proposed in the standard published by IEEE allows considering the characteristics of the fluid, specific heat, density, and viscosity. In this way, the data of two commercial fluids will be considered; one corresponds to a common mineral oil and the other one to an ester of natural origin. It will also be necessary to know the temperature rises with respect to ambient in the machine windings: top, bottom, average and hot-spot. This information will be determined by means of a CFD simulation of the winding of the considered transformer.

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From the review of the articles that were previously published on this topic, it is worth highlighting [11]. This presents an analysis of a high-temperature insulation system, aramid-enhanced cellulose in natural ester, on a prototype transformer. The results show that this combination can improve the overload capability of a transformer.

Another relevant reference would be [12], in which data obtained by the working group that is revising the IEEE C57.154 standard [13] is offered. Its objective is to quantitatively define an operating temperature limit for new brands and types of alternative liquids, and thus improve the accuracy of thermal class ratings.

On the other hand, the article presented here considers the performance of a Kraft and thermally upgraded Kraft insulation system combined with a natural ester in a real 100 MVA transformer. The temperatures necessary for the analysis were obtained from a CFD model that was validated with the measurements of fiber optic sensors in the tests performed in this machine.

In the next section of this article, the model developed for the calculation of winding temperatures will be explained. Later, in the third section results and discussion will be included. Finally, the conclusions obtained during the development of this paper will be summarized.

II. MODEL DESCRIPTION

This section describes the model used for the CFD simulations carried out in this study. The model corresponds to a 100 MVA power transformer Low-Voltage Winding (LVW) working under heat-run test conditions.

A. Geometry

The power transformer used for CFD modelling and numerical studies is presented in Figure 1. This device, which is manufactured by BEST Transformers, is a 100 MVA, 170/36 kV power transformer working under ONAN/ONAF mode although the assumed cooling mode is ONAN. Regarding the windings, the LV winding consists of a layer winding with axial ducts for the oil flow. It consists on an internal cardboard cylinder of 3 mm thick and 792 mm inner diameter, surrounded by 5 concentric conductor layers with 25 copper turns by layer. Each turn has 4 parallel plates (15.95 mm x 14.95 mm) that are wrapped with a dielectric paper of 0.8 mm width. The copper layers are separated by means of 80 wooden sticks of 6 mm thick. The total winding height is 1634 mm.

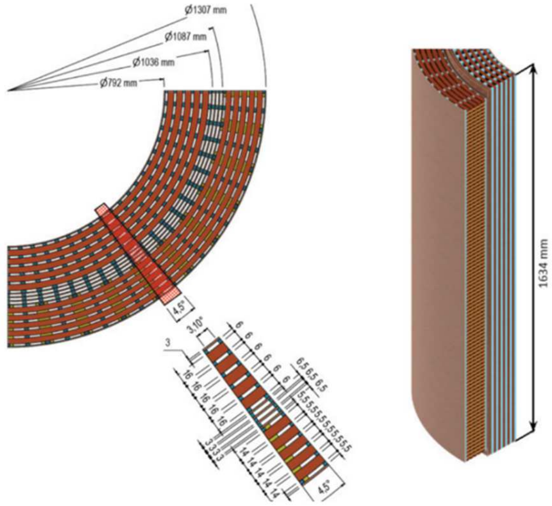

Fig. 1. 3-D model and geometrical information of low voltage winding.

B. Governng equations

Regarding the CFD simulations, the solid and fluid interfaces inside the transformer winding are modelled using the Conjugate Heat Transfer model. Thus, different equations are considered for the fluid and solid domains.

In the fluid domain, mass, momentum and energy conservation equations represent the proposed model behaviour. To model the buoyancy forces, the Boussinesq approach has been used in the model. For this approach, fluid properties are considered constant and calculated at the reference temperature. This model leads to the equations (1-3).

$$\nabla u = 0 \tag{1}$$

$$\begin{aligned} \rho \cdot \frac{\partial u}{\partial t} + \rho \cdot (u \cdot \nabla) u \\ = -\nabla p + \mu(\nabla^2 u) + \rho_{ref} \cdot g \\ \cdot \beta \cdot (T - T_{ref}) \end{aligned} \tag{2}$$

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} + \rho \cdot c_p \cdot \nabla \cdot (u\, T) = k \cdot \nabla^2 T \tag{3}$$

Where ρ is the fluid density, u is the velocity field, p is the pressure field, μ is the fluid viscosity, g is the gravity vector, β is the thermal expansion coefficient, c_p is the specific heat of the fluid, k is the thermal conductivity of the fluid and T is the temperature field.

Equations (1-3) describe a non-isothermal incompressible flow for a Newtonian fluid, where the viscous friction and pressure contribution to the energy equation are negligible. In this case, these equations describe the oil flow through the winding channels. Since the flow is thermally driven and the fluid viscosity is high, no Reynolds number representing turbulent flow are expected, so laminar flow model is chosen for the case.

In the solid domain, the temperature follows a diffusion equation. Equation (4) describes the behavior of the temperature field inside the solid domain.

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = k \cdot \nabla^2 T + q_s \tag{4}$$

Equation (4) represents the equation of a transient 3D diffusion process with a source term that represents the power losses on the conductor layers of the winding.

The governing equations are solved using the Finite Volume Method (FVM) using the commercial software ANSYS Fluent and considering a steady-state study. For this problem, a structured hexahedral mesh is used for the FVM. Second Order Linear Upwind scheme is selected for the derivatives approach in a pressure-velocity coupled scheme of a pressure-based solver. The normalized residuals are set to be lower than 10^{-5}, except for the energy equation residuals, that is set to be lower than 10^{-8}. The model uses a structured hexahedral mesh of 14 M elements for the CFD analysis. Mesh independence test and validation of the CFD model have been carried out a previous work of the authors [7].

C. Boundary conditions

The boundary conditions selected for this case are a uniform velocity and uniform temperature at the inlet, that represents the mass flow rate through each section and the bottom oil temperature of the transformer, which is the inlet temperature of the winding. These values are obtained from the geometrical aspects of the transformer and from the heat run test results, by performing a thermal and hydraulic balance of the transformer cooling circuit and are presented in Table I. At the outlet, a zero-gauge pressure condition was set. External walls of the domain are considered as static walls with no-slip condition and adiabatic, since the thermal conductivity of the insulation cylinder is very low. Solid-fluid interface boundaries, such as disc walls, are considered as no-slip walls with thermal coupling (considered in the CHT model). For the heat losses, a volumetric heat source is considered in the conductor domain, which represents the losses under heat-run test conditions.

D. *Materials*

The oils considered for this work are a mineral oil and a natural ester as cooling fluids. Since Boussinesq approach is considered, properties of the oil are calculated at a reference temperature, which is the bottom oil temperature. The properties from these fluids are shown in Table II. The conductor material is considered as a uniform material with cylindrical orthotropic thermal conductivity that represents the combination of materials in a CTC conductor.

E. *Loading guide model*

The results obtained from CFD will be used as inputs for the model proposed in [10] to estimate the hot spot temperatures under a load cycle. This model needs from data of the described transformer, especially the losses distribution that is shown in Table III. These losses are obtained considering 75 ºC for a 100 MVA load. Apart from the losses, rated temperature rises are needed for the model, which are obtained from heat run test and CFD simulations. Those are the average winding temperature rise, hot spot temperature rise, bottom oil temperature rise and top oil temperature rise. Those values were obtained from the CFD simulations of the transformer working under heat run test conditions and are shown in Table IV, considering the ambient temperature is 28.85 ºC. The proposed load cycle is described in [10] and corresponds to a 24 h period, it can be observed in Fig. 1 and Fig. 2 (yellow line).

In the case of the natural ester filled transformer, the input values have been calculated through CFD simulations and the fluid properties have been modified in the model proposed.

III. RESULTS AND DISCUSSION

In this section, the results obtained from the calculations proposed in this work are presented. A first approach is considering that the dielectric fluid is a conventional mineral oil. Secondly, a natural ester-based oil is considered as the cooling fluid. Finally, cooling from both studied cases is compared.

A. *Mineral oil*

Fig. 2 shows the evolution of hot-spot, top-oil and bottom-oil temperatures under the load cycle, considering the mineral oil. The proposed load cycle varies from a minimum of 0.56 at 6h to a maximum of 1.1 at 16h. At the minimum load time, the hot-spot to top-oil temperature difference and hot spot to bottom oil temperature difference observed are 7.2ºC and 20ºC, respectively. Under these conditions, the observed hot spot temperature is the minimum, being this value of 71.2ºC. The maximum hot-spot to top-oil and hot-spot to bottom-oil temperature differences are observed at 15h, being those values of 20.4ºC and 35.8ºC, respectively. The maximum hot spot temperature is observed at 16h, with a value of 109.7ºC.

TABLE I. INPUT VALUES FOR CFD SIMULATIONS

	Mineral oil		**Natural ester**	
	Mass flow (kg/s)	***Temperature (K)***	***Mass flow (kg/s)***	***Temperature (K)***
CFD input	8.94e-3	337.9	4.87e-3	329

TABLE II. THERMAL PROPERTIES OF DIELECTRIC FLUIDS

	Mineral oil	**Natural ester**
Ref T (K)	337.9	329
Density (kg/m3)	832.1	894.4
Viscosity (Pa·s)	3.98e-3	1.93e-2
Specific heat (J/kgK)	2392	1915
Thermal Conductivity (W/mK)	0.129	0.172
Thermal expansion coefficient (1/K)	6.26e-4	5.89e-4

TABLE III. DATA CONSIDERED IN THE LOAD CYCLE ANALYSIS

Ohmic losses (W)	63,345
Winding eddy losses (W)	98,255
Stray losses (W)	16,000
Core losses (°C)	47,600
Type cooling for load cycle	ONAN

TABLE IV. TEMPERATURES OBTAINED FROM CFD ANALYSIS

	Mineral oil	**Natural ester**
Average winding rise over ambient (°C)	56.4	58.3
Hot-spot rise over ambient (°C)	68.5	83.7
Top-oil rise over ambient (°C)	52.4	65.5
Bottom oil rise over ambient (°C)	35.9	27.3
Ambient temperature (°C)	28.85	28.85

B. *Natural ester*

Considering the natural ester case, a different temperature distribution is observed. Fig. 3 shows the evolution of hot-spot, top-oil and bottom-oil temperatures under the load cycle, considering the natural ester. The minimum hot spot to top oil and hot spot to bottom oil temperature differences are observed at 6h, with values of 9ºC and 38ºC respectively. The maximum values of these temperature differences are 29.8ºC and 66.3ºC, observed at 15h. The minimum hot spot temperature is observed at 6h with a value of 83.2ºC whereas the maximum hotspot temperature is observed at 17h with a value of 132.3ºC.

C. *Comparison between Mineral Oil and Natural Ester*

As can be appreciated in Fig.4, the three calculated temperatures for the proposed load cycle are higher when the cooling fluid is a natural ester-based oil. The oil temperature rise is also different for both proposed oils, with an average temperature variation of 14.6ºC for mineral oil and 33.9ºC for natural ester. The observed hot spot temperature is higher for natural ester, with an average value of 17.3ºC and a maximum of 22.6ºC higher than mineral oil.

IV. CONCLUSIONS

In this work, the impact of the thermal characteristics of dielectric fluids on the loading capacity of 100MVA power transformer has been studied. The main conclusion obtained from this work are the following:

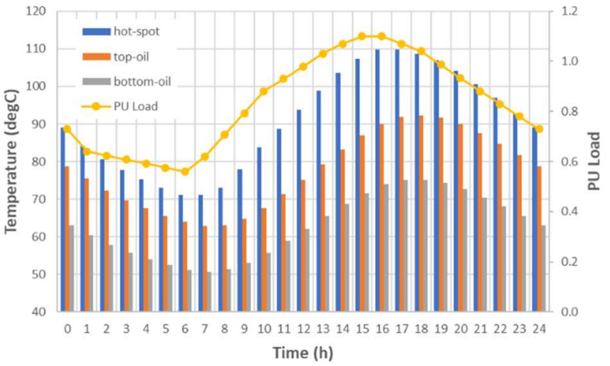

Fig. 2. Evolution of oil and hot-spot temperatures under a load cycle, considering the mineral oil.

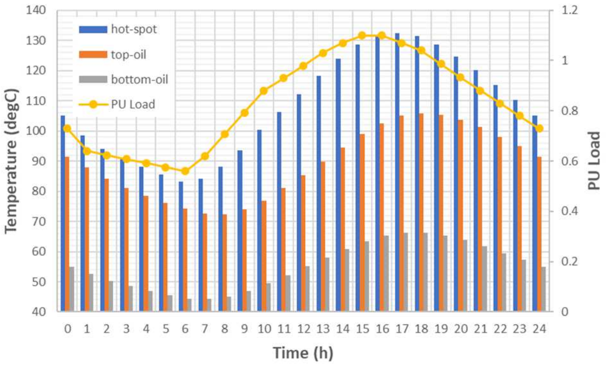

Fig. 3. Evolution of oil and hot-spot temperatures under a load cycle, considering the natural ester.

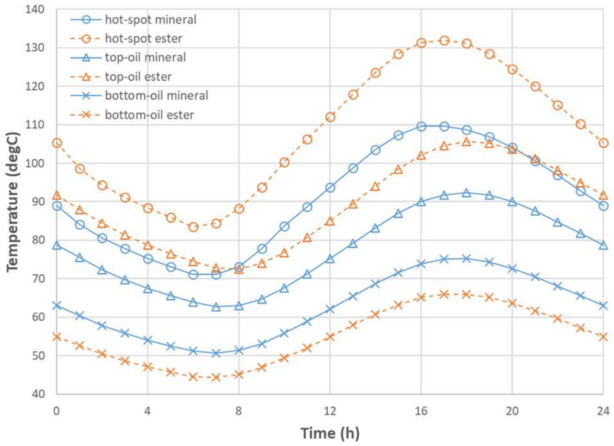

Fig. 4. Evolution of oil and hot-spot temperatures under a load cycle, considering the mineral oil and the natural ester.

First, the hot spot temperature has a considerable increase when considering natural ester as cooling fluid, during the whole loading cycle. Moreover, the maximum hot spot temperature appears with a higher delay from the maximum load time in the case of natural ester.

From this study, is observed that the same transformer working under the same proposed load cycle, shows an increase of the observed bottom-oil, top-oil and hot-spot temperature during all the load cycle.

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