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CFD EVALUATION OF THE OIL COOLING SYSTEM IN A MOBILE POWER TRANSFORMER

Luciene Martins Moura*
Rudolf Huebner
Paulo Vinicius Trevizoli

Department of Mechanical Engineering, Federal University of Minas Gerais (UFMG), Belo Horizonte 31270-901, MG, Brazil
**Corresponding author:* lumoura@cemig.com.br

Abstract.
Power transformers represent an important part of the capital investment in transmission and distribution substations. The cooling of the windings (electrical coil) depends on the convection of heat, enhanced by the forced circulation of oil in the windings, as well in heat exchangers. Forced circulation of oil combined with forced circulation or air in the heat exchanger is usually found in mobile transformers, whose compact structure is a challenge in terms of heat transfer rates. An improper design or fabrication problems associated with the assembling of the cooling system may result in an inefficient exchange of heat, result in transformer failure from overheating. This way, the present work proposes a CFD study of the winding cooling system in a 138X69-13.8 kV 25 MVA mobile power transformer, with the objective of evaluating the thermal performance of the transformer operating under nominal conditions. It is considered nominal inputs of flow rates of oil, temperatures, power dissipated. In a second evaluation, some constraints are artificially imposed to the transformer, which may impact the velocity and temperature fields, in order to understand the formation of "hot spots" and the transformer failure.

Keywords: *power transformer, oil cooling system, overheating, CFD.*

1. INTRODUCTION

Transformers immersed in naphthenic mineral oil represent the most common types in power distribution and transmission substations. This fluid has the function of dielectric and cooling at the same time (Cheim *et al*,2009). Interruptions in the power transformers have an important technical and economic impact on the operation of the transmission and distribution electrical system, due to repair costs, non-transmitted energy and all the inconveniences associated with industries and society.

One of the most important parameters that govern the life expectancy of a transformer is its operating condition under load (kA-kiloampères), that is, the power supplied to the power utility loads (Hamza e Herskind,2019), which directly affects the temperature of the oil, windings and consequently the insulating materials that make up its active part.

This paper analyzes, throughout CDF simulations, the thermal behavior of a mobile transformer, with an ODAF-type cooling system, which takes place internally by Directed Oil – OD – by using of centrifugal pumps associated with directing in ducts in the interior of the windings; and externally by Forced Air – AF, throughout heat exchangers or aerothermals. These mobile transformers are generally compact units, mounted on carts and made of insulating materials that have an operating temperature limit for high temperatures and therefore provide a demand for high power density. They are normally applied for emergency assistance on the electrical system, in case of failure of fixed transformers, given their mobility.

The cooling process depends on heat convection, promoted by liquid circulation between the windings and heat exchangers, either by natural action or by forced oil circulation using pumps. Improper sizing or cooling system assembly problems can lead to insufficient heat exchange and, consequently, transformer burnout. Overheating for a given power to be supplied is one of the main factors causing the so-called "hot spots", which can appear inside the windings or in the magnetic core (Daghrah, *et al*, 2020). In high power transformers, such as those above 15 MVA, the temperature rise is a fundamental parameter in the control of the useful life of the equipment.

In this direction, this work focus in understanding the causes of thermal inefficiency of the ODAF-type cooling system and its association with early transformer failures, which consequently affect its operational availability and capital return. In addition to the simulations performed under normal operating conditions of a mobile transformer at 138 - 13.8 kV, 25MVA, it is artificially imposed some structural irregularities that can lead to failures related to ineffective thermal exchanges. Under these conditions, the occurrence of temperatures (hot spots) higher than those temperature limits are evaluated.

2. MATHEMATICAL APPROACH AND DIMENSIONAL ANALYSIS

Fluid flow and heat transfer in the transformer winding cooling ducts are governed by conservation of mass, momentum and energy equations. In directed oil cooling, the effect of the buoyant force is negligible (Zhang *et al*, 2020) and, therefore, fluid flow can be decoupled from heat transfer. First, it is necessary to consider the conservation equations of mass, momentum and energy for a constant 2D flow of an incompressible fluid, with constant properties, in cylindrical coordinates that can be expressed by the equations below:

- Continuity:

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{\partial u_z}{\partial z}=0 \tag{1}$$

- Momentum in r:

$$\rho\left(u_r\frac{\partial u_r}{\partial r}+u_z\frac{\partial u_r}{\partial z}\right)=\frac{\partial p}{\partial r}+\mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial(ru_r)}{\partial z}\right)+\frac{\partial^2 u_r}{\partial z^2}\right) \tag{2}$$

- Momentum in z:

$$\rho\left(u_r\frac{\partial u_z}{\partial r}+u_z\frac{\partial u_z}{\partial z}\right)=\frac{\partial p}{\partial z}+\mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{\partial^2 u_z}{\partial z^2}\right) \tag{3}$$

- Energy- for the fluid phase:

$$\left(u_r\frac{\partial T}{\partial r}+u_z\frac{\partial T}{\partial z}\right)=\frac{k}{\rho c_p}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}\right) \tag{4}$$

where, $\boldsymbol{r}$ (m) is denoted for the radial coordinate, $\boldsymbol{u_r}$ (m/s) velocity radial component, $\boldsymbol{z}$ (m) axial coordinate, $\boldsymbol{u_z}$ (m/s) velocity axial component, ρ (kg/m^3) liquid density, $\boldsymbol{p}$ (Pa) static pressure, $\boldsymbol{\mu}$ (Pa·s) kinematic viscosity, $\boldsymbol{T}$ (K) liquid temperature, $\boldsymbol{k}$ (W/(m·K)) liquid thermal conductivity, $\boldsymbol{c_p}$ (J/(kg·K)) liquid specific heat. It is important to note that the viscous dissipation term for energy conservation is neglected because the oil velocity is small and, therefore, it can be considered negligible in relation to advection and conduction. As proposed in (Zhang *et al*, 2017), it is considered the following dimensionless variables:

$$r^*=\frac{r}{Dh}e\ z^*=\frac{z}{Dh} \tag{5}$$

$$u_r{}^*=\frac{u_r}{u_m}e\ \ u_z{}^*=\frac{u_z}{u_m} \tag{6}$$

$$p^*=\frac{p}{\rho u^2{}_m} \tag{7}$$

$$T^*=\frac{T-T_{to}}{T_{am}-(T_{to}+T_{oi})/2}=\frac{T-T_{to}}{g} \tag{8}$$

where, $\boldsymbol{Dh}$ is the hydraulic diameter ($\boldsymbol{Dh}=\frac{4\mathrm{A}}{\mathrm{L}}$, (m)), $\boldsymbol{A}$ is the cross sectional area of the vertical oil passage (m^2), $\boldsymbol{L}$ is perimeter of the inlet vertical duct (m), $\boldsymbol{g}$ is the mean temperature gradient ($\boldsymbol{g}=T_{am}-\frac{(T_{to}+T_{bo})}{2}$, (K)), $\boldsymbol{T^*}$ is the dimensionless temperature, $\boldsymbol{T_{to}}$ is the top oil temperature (K), $\boldsymbol{T_{am}}$ is the average winding temperature (K), $\boldsymbol{T_{bo}}$ is the bottom oil temperature do oil (K) and $\boldsymbol{u_m}$ is average winding pass input speed (m/s).

Replacing (5) - (8) into (1) - (4) and considering that the hydraulic diameter of the system, the average oil speed at the inlet passage (one) and the concentrated temperatures ($\boldsymbol{T_{am}}$, $\boldsymbol{T_{to}}$, $\boldsymbol{T_{bo}}$) are not in functions of coordinates, we can obtain the following dimensionless forms of the governing equations:

- Continuity:

$$\frac{1}{r*}\frac{\partial(r^{*}{u_r}^{*})}{\partial r*}+\frac{\partial {u_z}^{*}}{\partial z^{*}}=0 \tag{9}$$

- Momentum in r:

$$\left({u_r}^{*}\frac{\partial {u_r}^{*}}{\partial r^{*}}+{u_z}^{*}\frac{\partial {u_r}^{*}}{\partial z^{*}}\right)=-\frac{\partial p^{*}}{\partial r^{*}}+\frac{1}{Re}\left(\frac{\partial}{\partial r^{*}}\left(\frac{1}{r^{*}}\frac{\partial(r^{*}{u_r}^{*})}{\partial z^{*}}\right)+\frac{\partial^{2}{u_r}^{*}}{\partial {z^{*}}^{2}}\right) \tag{10}$$

- Momentum in z:

$$\left({u_r}^{*}\frac{\partial {u_z}^{*}}{\partial r^{*}}+{u_z}^{*}\frac{\partial {u_z}^{*}}{\partial z^{*}}\right)=-\frac{\partial p^{*}}{\partial z^{*}}+\frac{1}{Re}\left(\frac{1}{r^{*}}\frac{\partial}{\partial r^{*}}\left(r^{*}\frac{\partial {u_z}^{*}}{\partial r^{*}}\right)+\frac{\partial^{2}{u_z}^{*}}{\partial {z^{*}}^{2}}\right) \tag{11}$$

- Energy- for the fluid phase:

$$\left({u_r}^{*}\frac{\partial T^{*}}{\partial r}+{u_z}^{*}\frac{\partial T^{*}}{\partial z^{*}}\right)=\frac{1}{RePr}\left(\frac{1}{r^{*}}\frac{\partial}{\partial r^{*}}\left(r^{*}\frac{\partial T^{*}}{\partial r^{*}}\right)+\frac{\partial^{2}T^{*}}{\partial {z^{*}}^{2}}\right) \tag{12}$$

where, ***Pr*** is Prandtl number and ***Re*** is Reynolds number based on the hydraulic diametes, calculated by:

$$Pr=\frac{\mu c_p}{k} \tag{13}$$

$$Re=\rho\frac{u_m Dh}{\mu} \tag{14}$$

Since the coordinates are normalized in relation to hydraulic diameter, winding entry velocity and pressure in relation to twice the dynamic winding inlet pressure, it is possible to confirm that, for a given winding geometry, the distribution of the volumetric flow rate is dictated by the Reynolds (*Re*) number. The dimensionless temperature distribution at the hot-spot, is actually the convective componente of the so-called hot-spot factor - ***H_{ve}*** (Zhang *et al*, 2017), therefore, the *Hve* is a funciton of the Reynolds and Prandlt Number. Previous studies (Jarman *et al*, 2018), have shown that ***Re*** has in fact a greater influence on the cooling conditions of OD-type transformers than the ***Pr.***

3. COMPUTATIONAL APROACH

In the CFD approach, using the Ansys-Fluent®, modeling is performed on 2D axisymmetric geometries to reduce computational requirements. The study focuses in the investigation of the relationship between a type of early failure in the windings, in which there is a short circuit in the turns due to the probable degradation of insulating materials, with the dynamic behavior of the ODAF refrigeration system, .

In addition to the windings, the following are considered: the number of discs, diameters, number, thickness and width of spacers, number of oil conductors, conductor dimensions, type of insulating oil, conductor insulation. After this modeling, the input data is configured, as heat exchange capacities, pressure drops, axial and radial speeds for each set of windings. heat exchange capacities, pressure drops, axial and radial velocity. Figure 1 represents the oil cooling for a mobile transformer. The indicated control volume delimits the computational domain to be simulated:

Simulations of oil flow distribution and pressure drop for type OD transformers are generally conducted adopting dimensional analyzes as in (Nordman and Lahtinen, 2013) and (Zhang *et al*, 2017). From that oil flow distribution and pressure drop are transformed into dimensionless parameters of flow distribution in each cooling duct and the coefficient of pressure drop over the winding, respectively. The control parameters can finally be related to the Reynolds numberfor a givens winding flow velocity. These speeds naturally influence both the thermal exchanges and the electrostatic charging behavior, so it is one of the main control parameters in this type of equipment.

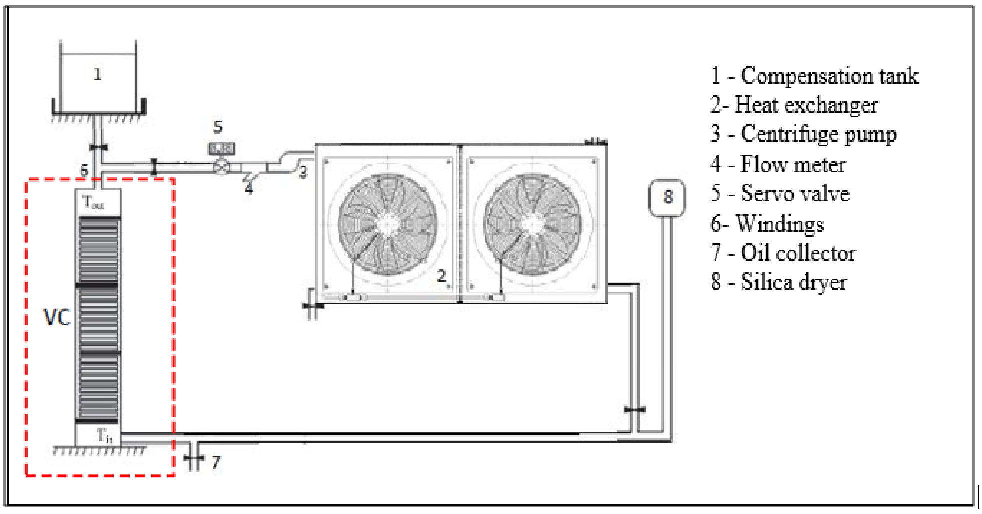


Figure 1. ODAF cooling system for mobile transformer.

Previous studies (Torriano *et al*, 2010) and (Jarman *et al*, 2018) were developed for equipment of different capacities. In this work, as a computational validation strategy, the same configurations of a standard geometry for a 60MVA transformer were reproduced, with the same voltages of primary and secondary windings, studied by (Torriano *et al*, 2010). In this way, the corresponding power, input speeds, and input temperature are applied according to the model verification.

From the construction of the mesh and from the known boundary conditions, in this case it was observated a maximum difference, considering the avarege temperature on the discs, of 5º C on disk number 5 (second pass of the winding) ,as can be seen in Figure 2, which was considered a satisfactory result, given the limitations of the presented preliminary results. In future studies, we intend to perform a more accurate mesh independency analysis.

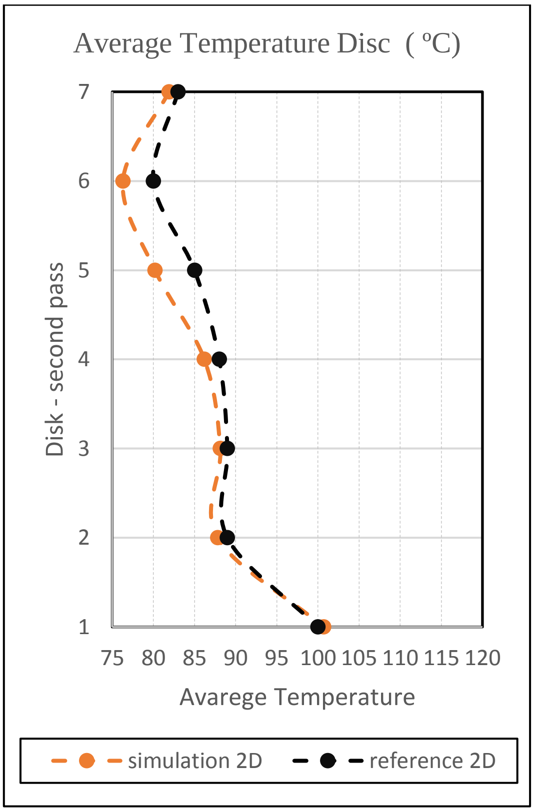


Figure 2. Model Verification

Once the mathematical model and numerical implementation presented satisfactory reproduction of a previously published result, a new set of simulations are performed, now inserting the parameters design of the 25MVA transformer adapting the flux density characteristics in the windings, temperatures and input speeds.

3.1 25 MVA POWER TRANSFORMER WIDING GEOMETRY

A large core type power transformer comprises a magnetic iron core surrounded by co-axial cylindrical windings being the most common disc type. In this model, there are 16 discs, axially separated by spacers, originating radial ducts, where the cooling oil can flows. As a way to direct the flow throughout the radial ducts, washers are inserted periodically along the axial direction to impose a zigzag flow pattern through the winding. The power transformer operating in ODAF cooling has 3 windings located, with increasing diameter, as it follows: Low Voltage (LV), High Voltage (HV) and Regulation (Reg). The 2-D geometry represents a cutting plane along the axial direction as in Figure 3.

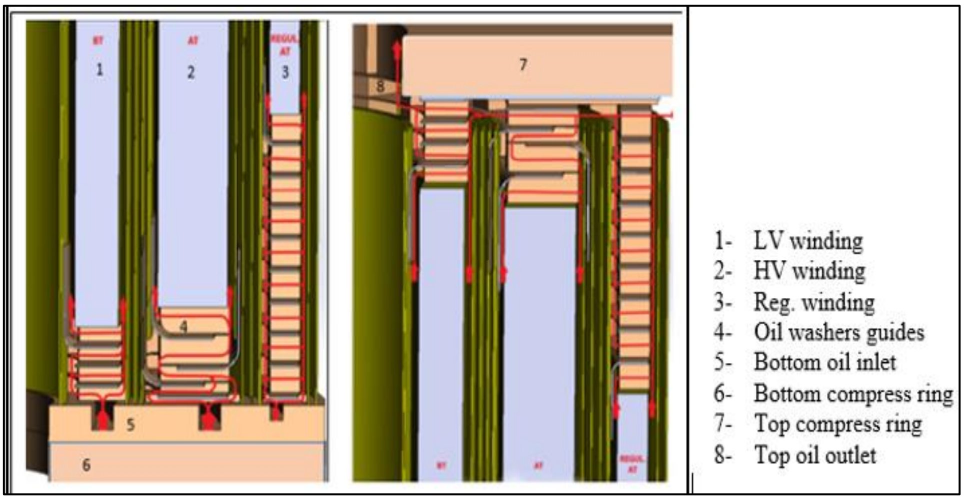


Figure 3. Details of the considered control volume.

Although the windings have a cylindrical shape which is nearly axis-symmetric, the hydrodynamic and thermal effects of radial spacers (especially by reduction of cooling area) are not taken into account in the 2D model. As in the fault domain of interest, the LV winding will be represented in 2 blocks, one with 9 disks and the other with 7 disks (in the direction of the upper compression ring).

3.2 COMPUTATIONAL GRID AND CONVERGENCE CRITERIA

Following the numerical solution, an important step is the definition of the mesh: type, number of elements or volumes, and the mesh domain. As in Figure 4, different types of mesh are considered to the solid and fluid domains: structured mesh in the fluid; and nonstructured mesh (triangular) in the solid domain, including winding and guides. The overall 2D domain was then subdivided into 92637 elements of various sizes (in this preliminary study), noticing smaller elements (more refined mesh) in critical zones. The smallest element size was 0.7 mm.

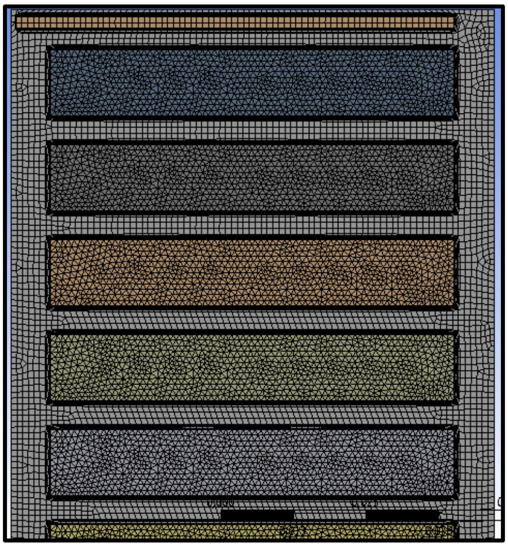


Figure 4. Solid and liquid domain meshes.

Once this step is completed, the conservation equations are solved through an iterative process, until the convergence, criteria of 10^{-6}, to all variables, are verified. A larger number of volumes can imply a more precise solution, on the other hand, a dense mesh can result in a relevant computational cost and longer processing time. Therefore, with this number of iterations, this criterion was considered satisfactory.

3.3 MATERIAL PROPERTIES AND OPERATING CONDITIONS

The oil thermal conductivity and heat capacity were assumed constant. Density and viscosity are temperature dependent. Table 1 presents the fixed value or equation to evaluate these properties.

Table 1. Naphthenic oil properties.

Physical Properties	**Reference Value**
ρ (kg/m^3)	868*(1-0,00064*(T(ºC)-20))
μ (Pa·s)	5.73101 - 0.0612751·T(ºC) + 0.000246719·T^2(ºC) - 4.42934E-07·T^3(ºC) + 2.98939E-10·T^4(ºC)
k (W/(m·K))	0,1278
c_p (J/(kg·K))	2030

The power transformer discs are composed by a group of copper conductors wrapped in Nomex410®. Here, it is assumed the copper properties for the discs (copper wrapped in paper), as shown in Table 2.

Table 2. Cooper properties.

Physical Properties	**Reference Value**
ρ (kg/m^3)	8978
$\boldsymbol{k}$ (W/(m·K))	388.5
$\boldsymbol{c_p}$ (J/(kg·K))	381

Regarding the operating conditions they are shown in Table 3:

Table 3. Operating conditions.

	Unit	**OD (25MVA)**
Mass flow rate	kg/s	3,62
Dissipated power per disc	W/m^3	165197
Velocity inlet	cm/s	24.5
Oil inlet temperature	ºC	77.1

In this model the source terms allow the specification of volumetric energy sources (dissipated power per disc), so it is necessary to define these values for the solid domain, referring to the disks. Given the low flow speeds (Re < 2100), the regime is considered laminar.

4 RESULTS

4.1 NORMAL OPERATING CONDITION

As previously mentioned, the first simulation results are regarded to normal operating conditions for a 25 MVA transformer, considering that the assembly of the power transformer was flawless and the final product is exact the designed one. Figure 5 below shows the location of the hot spot and the maximum temperature reached in the windings for the imposed power of 25 MVA.

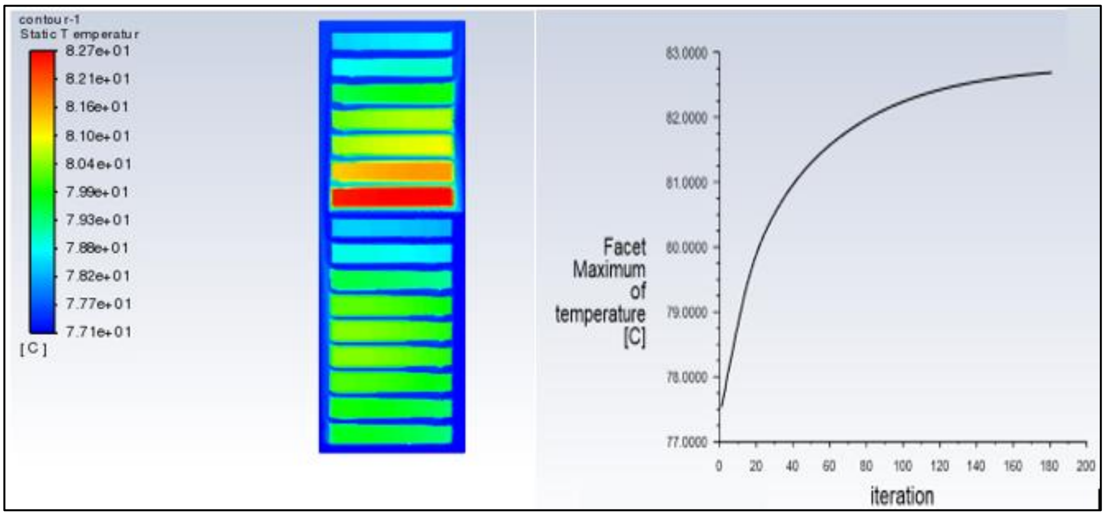


Figure 5. Temperature contours and maximum disc temperatures predicted by the CFD simulation.

In Figure 5, it is observed that the maximum temperature in the windings is approximately 83ºC, on the first disc of the second block (i.e, 10º disc, from bottom to top). It is known that the hot spot limit at 25 MVA must be 85ºC. The presented result will be revised after a mesh refinement analysis.

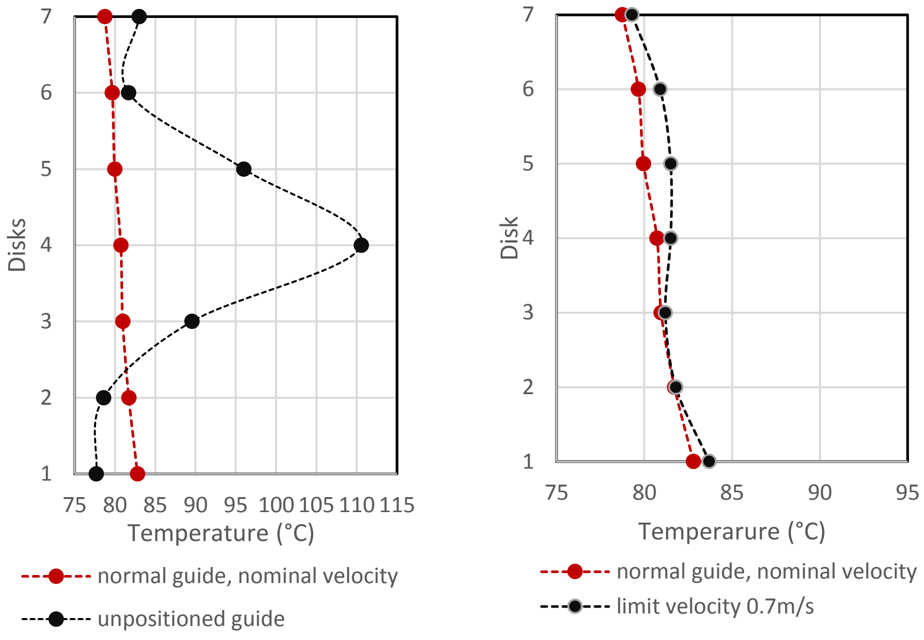
4.2 DISTURBANCE SIMULATIONS

In this section, some constraints are artificially imposed to the transformer, which may impact the velocity and temperature fields, in order to understand the formation of hot spots (with temperatures above the standard limit), and, as a result, the power transformer failure. It is proposed two different cases: i) the deformation of one flow guide; ii) increase of the flow velocity.

The first case refers to the variation or deformation of the flow guides. These guides are barriers strategically placed within the windings to guide oil, thus improving the flow distribution and consequently, the cooling efficiency. This evaluation is justified because during the manufacturing process, it is essential to ensure that the guides do not bend or are moved along the spools. Hence, some simulations were performed after changing the original geometry: reducing the length of the guide that directs the oil to the center of the coil. In order to assess the impact of this issue on the oil flow and temperature distribution.

In the second case, the changes to the guides were kept and the flow velocity was increased to the limit of 0,7 m/s. The oil flow system, including pump and ducts, is designed to provide adequate cooling rates to ensure operating temperatures that are within the allowable limits. However, there is a velocity limit that must be respected in order to avoid incorrect actuation of the gas relay by directed flow or the concentration of electrostatic charges in the windings. The formation of vortices in the cooling channels can lead to the circulation of bubbles or the phenomenon of electrostatic charges (Nantes, 2016). Therefore, a fundamental parameter in the simulations is the monitoring of the electrostatic charging trend (ECT), which imposes a speed limit of up to 0.7 m/s for the designer in question (CIGRÈ, 2002) and (CIGRÈ, 2013).

Figure 6 presents the result of both types of restrictions imposed in the simulation. Since the first indication of hot spot location is in the second block of the shaped winding, between disk 1 to 7 (towards the upper compression ring), it is important to emphasize that this region of interest is then delimited to evaluate the temperature distribution, in order to simplify the analyses.



(a) (b)

Figure 6. Average temperature evaluated at each disk: (a) compares the normal transformer conditions with case (i) including a deformation at one flow guide; (b) compares the normal transformer conditions with case (ii) increasing the flow velocity.

In the profile of Figure 6(a) there is a displacement of the hot spot from disk 1 to disk 4, with an important increase in the temperature. Furthermore, it is verified that in fact the hot spot point exceeds the admissible limits in the norm for that power, ranging from 82ºC to 110ºC. In the profile of Figure 6(b) it is observed that, with the limit condition of 0.7m/s at the entrance of the pipeline, it is possible to recover the initial cooling condition, even if the guides are deformed, thus obtaining a hot spot level within the admissible limits for the class.

5 CONCLUSIONS

This study presented an evaluation of the temperature distribution fields for a 25 MVA ODAF transformer, in perfect operating conditions and imposing some geometric or flow imperfections that, adding geometric imperfections that may arise in the manufacturing process. The study demonstrated that such geometric problems can interfere with the profiles and location of the winding hot spot, causing local overheating above the admissible limits for the materials used in the insulation. This work will allow future transformer designs to be better structured, so that the critical points of the ODAF project are not neglected, ensuring the expected thermal exchanges for the imposed operating conditions. As future stages of the research it is intended to expand the analysis for the geometry of the 3 superimposed windings, Low Voltage (LV), High Voltage (HV) and Regulation (Reg), relating the results to a failure case study real.

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