Numerical Investigation on the Influence of Clack-bands on Lifetime of Disc-type Windings

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Abstract- **This study is aimed at investigating the significant influences of using clack-bands in a disc-type winding in an attempt to determine the effects on the lifetime of power transformers. The excessive heat generated inside the winding must be dissipated without allowing the core, winding, and structural parts to reach a temperature that will cause deterioration of insulation. If the insulation is subjected to temperatures higher than the maximum allowable value for a long time, it loses insulating properties, i.e., the insulation gets aged, severely affecting the transformer life. A clack-band can be defined as the gap between two turns in a disc, where the solid insulation has been moved to allow oil flow through the gap. In this manuscript, non-uniform heat loss distribution in the winding has been considered to investigate the influence of flux leakages within the winding on the average temperature and the location of the hot-spot (HSL). This study includes the accurate numerical 3D CFD (Computational Fluid Dynamics) simulations of the force cooled type at the flow rate of 9 kg/s and inlet temperature of 80 °C. The presented results provided an insight into the thermal aspects of the disc-type windings enabling to identify the influence of using the clack-band at different operating conditions; specially to consider the non-uniform heat loss distribution.**

Keywords—Thermal Modelling, Biodegradable Oil, Clack-band, Non-uniform Heat Losses Distribution

I. INTRODUCTION

In the last decade, rapid advancement and developments have taken place in the design, analysis, manufacturing and monitoring technology of transformers. To maintain the reliability and efficiency of power transformers, the insulation characteristics have to examined regularly. Since the power transformers experience different mechanical and thermal stresses during their lifetime, it is very important to investigate the influence of different designs to decrease the rate of ageing. If the insulation is subjected to temperatures higher than the allowed value for a long time, it loses insulating properties, i.e., the insulation gets aged. The values of maximum oil and winding temperatures depend on the ambient temperature, transformer design, loading conditions, and cooling provided [1]. The degradation of materials sets a limitation on the lifetime of the winding insulation to avoid overheated domains within the windings; therefore, the accurate determination of the highest temperature of the winding and its location inside the winding has to be considered at the design or manufacturing stage. Traditional methods of transformer winding thermal design have utilized simple models based on hot-spot factors [2] and thermo-hydraulic networks [3], which are corroborated with measurements on winding models, to simulate the effect of winding losses [4]. Tenbohlen et al. [5] used 2D and 3D numerical simulations with experimental validation to evaluate the thermal behavior of the oil-directed (OD) cooling method in power transformer windings. In [6], the oil speed in horizontal ducts of an OD cooled winding model was measured in comparison to a 3D CFD model to give an insight of flow behaviors in the OD cooling method. Since the temperature distribution is not uniform in transformers, the part which is operating at the highest temperature will be exposed to the greatest deterioration. Therefore, ageing studies that include the effect of thermal stresses and transformer loading on the lifetime of insulated transformers are considered in recent studies [7].

Furthermore, due to the well-known advantages of biodegradable oils in transformers such as higher fire point, environmental friendliness, and slower insulation ageing rate over mineral oil [8], thermal aspects of the new generation of power transformers filled with biodegradable oils are highly interested. Recent studies are determined the detailed flow patterns and thermal degradation of insulation using natural esters and other types of biodegradable oils [9]. Apart from the cooling oil materials, the effects of operational conditions, including initial conditions of oil flow and heat loss distribution, are investigated [10]. Additionally, geometrical parameters have been studied to figure out the affecting parameters during the design steps of windings [11,12]. In addition to our previous work [13], this paper aimed to study an oil-directed cooling method to investigate the influence of using clack-band in winding filled with two different oil materials.

In sections II in the present study, a description of the main design and the numerical model with appropriated boundary conditions are explained. In section III, the source of non-uniform heat loss distribution is discussed, and the reasons for higher thermal stresses at the top section of the winding are shown. Finally, the accurate 3D CFD results are represented to show the influence of new design on thermal behavior and the ageing process of the disc-type winding model.

It should be noted that the highlighted achievements of this study are defined in the last section of the contribution. Firstly, the combination of the operational conditions with two different geometrical winding models leads to evaluate the thermal aspects. The effects of using clack-band are illustrated at the oil flow rate of 9 kg/s. Following up, the comparison of mineral oil with ester oil at different boundary conditions shows the main influences of cooling oil materials on the ageing rate of insulation. Consequently, in this manuscript, the perdition of the effects of different parameters on temperature distribution is accomplished.

II. Numerical Method

A. Disc-type Winding Model

The construction of disc-type windings in power transformer shows a considerable symmetrical thermal behavior in the circumferential direction [6]. Accordingly, to take advantage of geometrical symmetry for the heat and mass transfer analysis, only a segment between two adjacent cardboards is considered. The entire winding model consists of three passes. A pass is defined as the number of discs between two successive washers. In this model, each pass consists of 6 discs, 8 conductors and 6 cooling channels, which is equipped with washers to obtain a zig-zag cooling mode. Each conductor has fully covered with an insulating sub-layer with a thickness of 0.6 mm; therefore, the thickness of the insulation between two conductors nearby is 1.2 mm. Fig. 1 shows the selected segment between two spacers (8° of the entire of the disc-type winding) including highlighted main passes with the location of the washers.

Fig. 2 shows the detailed front view of the dimensions and the width of vertical channels. The lengths of gaps with clack-band are selected the same as the vertical channels. In the design without clack-band, the gaps are built with a thick layer of isolations, which are the same size as the gaps to keep the winding's dimensions similar. For the comparison between two designs that are equipped with clack-band and without clack-band, Fig. 3 shows the position of gaps and the fluid flow directions to identify the geometrical differences.

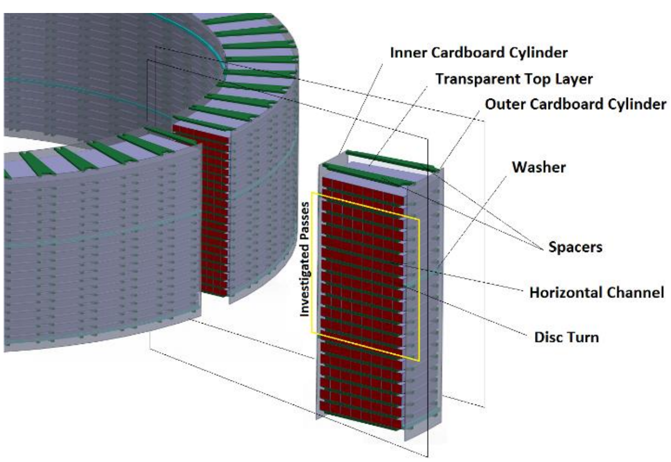


Fig. 1. Details of the disc-type winding model including horizontal and vertical channels at the segment of 8°

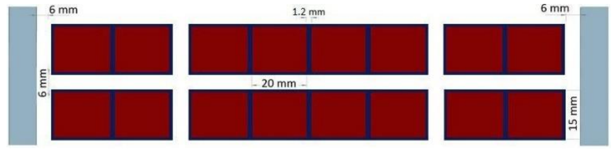
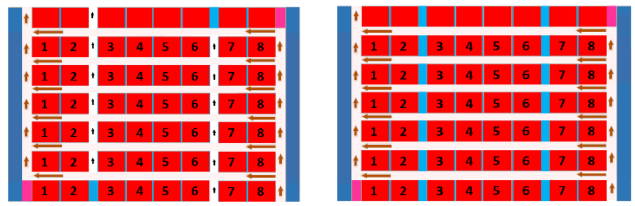


Fig. 2. Cross-section of the winding model with given channel dimensions and insulation thickness applied surround conductors



a. With clack-band b. Without clack-band

Fig. 3. Detailed view of two different designs at the top pass, including the numbering of conductors and flow directions, 6 discs per pass

B. Modelling Approach

Numerical CFD investigation of the winding models requires a proper discretization of the respective domains. To apply the numerical accuracy, three different mesh sizes are created, and the results are acquired with a fine mesh consisting of approx. 400×10^6 cells. The model consists of a narrow sub-layer of 0.6 mm, which is used to simulate the insulating paper surround the conductors. All the CFD investigations carried out in this manuscript are conducted using the proprietary software "ANSYS CFX", which is based on the finite volume method. Due to the complexity of the investigated winding models, "ANSYS Workbench" is employed to create the mesh domain depending on the respective modelling designs.

Thermal boundaries are set equally for both designs in other to obtain the geometrical designs in oil-directed conditions. The numerical model allows changing the oil flow properties with temperature, which has enough flexibility to investigate different boundaries. Considering the operational parameters, it can be concluded that the analyzed flow condition with the oil flow rate of 9 kg/s shows a turbulent flow regime which corresponds to the Reynolds number (Re) of 2000. The validation of the numerical model is defined in [6].

Inlet oil temperature is set to 80 °C and the uniform heat loss 64 W is mounted to each disc. Because of having 8 turns at each disc, 8 W/turn is integrated for each conductor in a uniform heat loss distribution. In order to figure out the influence of non-uniform heat loss distribution with different geometrical conditions. In section III, the source of non-uniform distribution is mentioned, and the rates of loss are given in Fig. 4.

III. Power Losses

Losses within the power transformers are divided into no-load and load losses [14]. No-load losses depend primarily upon the voltage and frequency and often are small and consequently often neglected under operational conditions. Load losses are varied by a load of power transformers and classified as I^2R losses and as stray losses. I^2R losses contribute the largest part of heat within the winding. Apart from the ohmic losses, leakage flux dominantly affects the stray losses that can be led to excessive heat losses in the metal parts around leads. Local overheating due to the extra heat losses by the influence of leakage flux at the bottom and the top of windings at design steps are not neglectable. Fig. 4 shows the heat loss distribution per turn in the winding. It can be seen that the top disc has more rate of heat losses and the outer turns in radial direction experience less rate of flux leakages in comparison to inner turns.

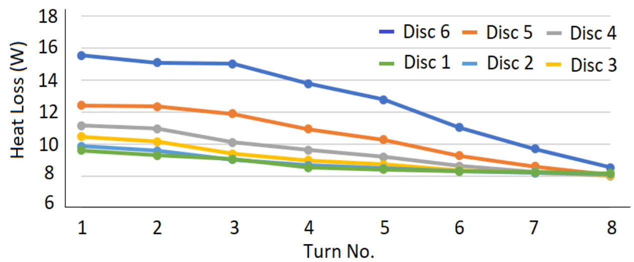


Fig. 4. Loss distributions within conductors at the non-uniform condition

IV. Results and Discussions

By using CFD simulations that are set with the specified boundary conditions, the detailed insight into the thermal behavior of the winding in power transformer can be determined. At the first prior, this section proposes to discuss the effect of using clack-band in the winding model.

Afterwards, the effects of considering the non-uniform heat loss distribution are mentioned. Fig. 5 and Fig. 6 represent the temperature distribution and the velocity distribution within the pass at the winding. Uniform heat loss distribution at 8 W is used for both designs in the figures. Streamlines are also illustrated in these figures to show the fluid flow behavior. As seen, the hot-spot temperature of the winding equipped with clack-band at the same flow rate is less than 10 Kelvin lower than the winding design without clack-band.

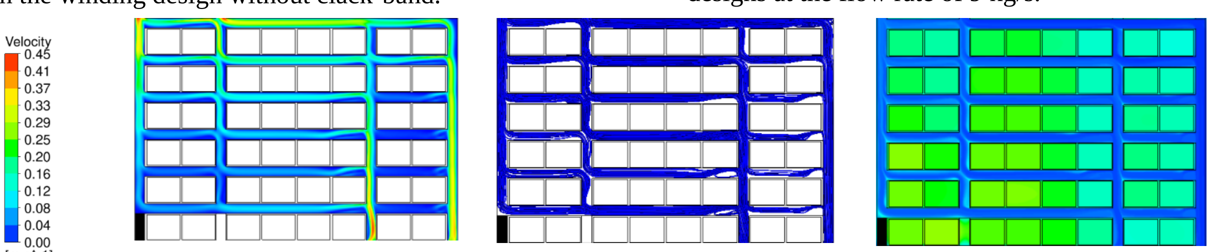
Furthermore, average temperature of the winding is lower, and the temperatures are distributed with a lower gradient between the conductors. Due to the more homogenous oil distribution, there is no local overheating which is emerged in the design without clack-band.

Notably, the entrance section of the bottom horizontal channels experiences fewer eddies that are led to flow the oil more smoothly. In contrast to the design equipped with clack-band, the other design has more eddies and reversed flow at the inlets of the horizontal channels. Apart from the thermal point of view, the maximum magnitude of the velocity is lower in the winding model with clack-band. Apparently, the lower velocity due to the extra second oil path at the inlet of the pass results in a lower pressure difference between the top and the bottom of the pass at the same rate of the fluid flow.

Table 1. is summarized the effect of using ester oil and mineral oil in the winding models. As shown, the hot-spot temperature and the average temperature of the ester oil is lower than the winding filled with mineral oil. As a result, in both designs, the cooling condition of the models with ester oil is better at oil-directed cooling mode.

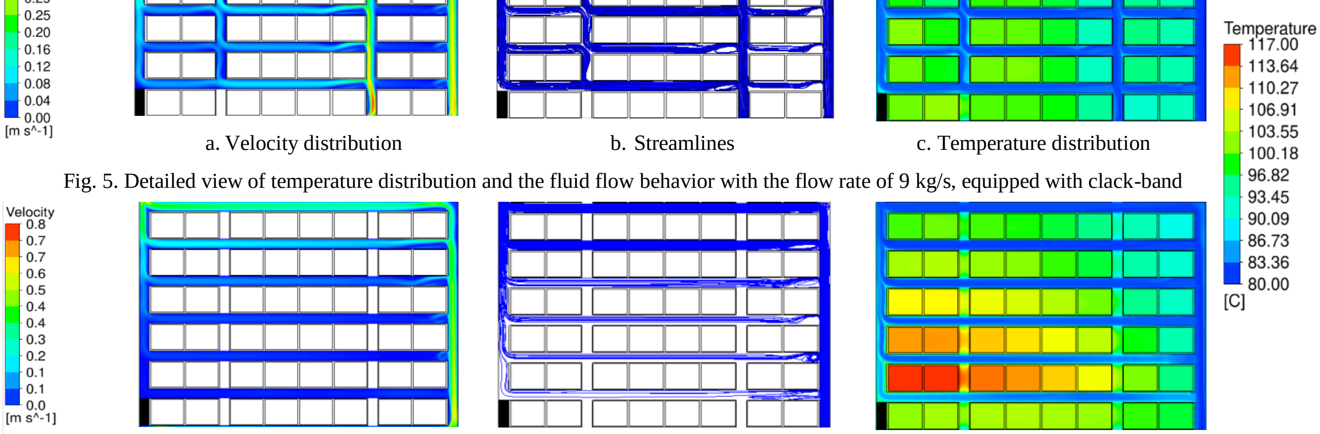
The location of the hot-spot is not changed at various oil materials. Although the ester oil condition has lower hot-spot temperature, the overheated local section is also not neglectable. It should be noted that the additional path which is created because of the gap used clack-band in the winding model creates a new interface.

The interface of oil with the surface of insulation leads to obtain better heat transfer using convection along the new vertical channels. Moreover, the designed models have been built with fully-isolated conductors that make it possible to compare the effects of coupled convection and conduction heat transfer at the same study. It is worthful to discuss that the non-uniform heat loss distribution has affected the location of the hot-spot and the average temperature of both winding designs at the flow rate of 9 kg/s.



a. Velocity distribution b. Streamlines c. Temperature distribution

Fig. 5. Detailed view of temperature distribution and the fluid flow behavior with the flow rate of 9 kg/s, equipped with clack-band



d. Velocity distribution e. Streamlines f. Temperature distribution

Fig. 6. Detailed view of temperature distribution and the fluid flow behavior with the flow rate of 9 kg/s, equipped without clack-band

TABLE I

OVERVIEW OF THE NUMERICAL THERMAL CONDITION OF THE WINDING MODEL WITH THE DIFFERENT OPERATING CONDITIONS AND AT THE MASS FLOW RATE OF 9 KG/S. "HST" REPRESENTS HOT-SPOT TEMPERATURE; WHEREAS "AT" REPRESENTS THE AVERAGE TEMPERATURE OF THE INVESTIGATED PASS. "L" SHOWS THE NUMBER OF TURNS AND "D" DEFINES THE DISC NUMBER.

Oil Materials		Mineral Oil			Ester Oil		
Operating Condition		HST (°C)	AT (°C)	HSL	HST (°C)	AT (°C)	HSL
Non-uniform Heat Loss	With clack-band	109	102	D. 6 /L.5	106	99	D. 6 /L.5
	Without clack-band	122	112	D. 6 /L.4	118	110	D. 6 /L.4
Uniform Heat Loss	With clack-band	103	98	D. 2 /L.4	99.2	92	D. 2 /L.4
	Without clack-band	115	106	D. 2 /L.2	113	106	D. 2 /L.2

The location of the hot-spot is not changed at various oil materials. Although the ester oil condition has lower hot-spot temperature, the overheated local section is also not neglectable. It should be noted that the additional path which is created because of the gap used clack-band in the winding model creates a new interface. The interface of oil with the surface of insulation leads to obtain better heat transfer using convection along the new vertical channels. Moreover, the designed models have been built with fully-isolated conductors that make it possible to compare the effects of coupled convection and conduction heat transfer at the same study. Although the cooling condition is similar by using the same oil material at the same flow rate, the higher temperature has been experienced within the winding model. Despite the higher flow rate of the oil at the top channels, the hot-spot temperature is located at the top disc of the winding. It shows that the influence of the higher losses of heat is dominated in comparison to the oil flow rate. Therefore, the effect of the non-uniform heat loss distribution is not neglectable.

V. CONCLUSION

In this contribution, the thermal behavior of two different disc-type winding designs of the power transformers has been investigated. The influence of the non-uniform heat losses on the temperature distributions, the hot-spot locations and, the fluid flow have been calculated. Accurate 3D CFD simulations have been used to investigate the fluid and solid domains at different operational and geometrical conditions. The investigation indicated the increment of the average temperature and the hot-spot temperature by considering the non-uniform heat loss distribution. Although the oil-directed cooling mode provides a higher share of oil at the top of the winding, additional heat losses at the top discs lead to change in the location of the hot-spot to the top discs. Local overheating has emerged in the design without clack-band. Moreover, the winding model equipped with the clack-band had a lower average temperature and the oil distributed more smoothly within channels. It was observed that the design with clack-band had fewer eddies which were better to avoid any stagnation of the fluid flow through the horizontal channels. Consequently, the effects of using ester oil have been explained. As it has been shown, at the same flow rate by the oil-directed cooling mode, ester oil has a lower hot-spot temperature over mineral oil, and the heat transfer process cooled down the surfaces more effectively. To sum up, by the oil-directed cooling mode, from the thermal point of view, the best scenario represented by the winding model equipped with clack-band and filled with ester oil. Apparently, the effects of flux leakages have to be considered for further designs or manufacturing stages to avoid early ageing of the winding.

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