21, rue d’Artois, F-75008 PARIS
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New prospects for power transformer winding thermal design optimisation using THNM and CFD simulations

J. Coddé, T. Baelmans
KU Leuven
Belgium

W. Van der Veken
CG PS Belgium
Belgium

S. B. Paramane, V. Chandak
CG Ltd
India

SUMMARY

Insulation ageing is a major risk in transformer failure. Assessing this risk and proper handling of subsequent Life Cycle Decisions requires detailed knowledge of the thermal state of the transformer windings. In this paper a detailed thermal evaluation of both the Thermo-Hydraulic Network Model approach and Computational Fluid Dynamics (CFD) simulations are assessed. The capabilities of both thermal models are demonstrated on an ON-cooled LV-winding with a relatively flat additional loss profile. In this case the hot-spot temperature is outspoken compared to the rest of the winding. Therefore, a thermal redesign is warranted. The resulting arrangement is shown to lower the hot-spot temperature by 12 °C, equivalent to a life-time extension by a factor 4. It is shown that both techniques have the potential to improve life cycle management and lower insulation ageing risk during design phase, the latter with minimal increase in manufacturing cost.

KEYWORDS

Insulation ageing, Risk assessment, Life cycle decisions, Design optimization, Thermo-hydraulic network model, Computational Fluid Dynamics

Introduction

In the asset management of transformers, insulation ageing is an important parameter to take into account. More specifically, in ranking the risk of transformer failure, insulation age proves to be one of the highest contestants [1]. Therefore this paper focusses on the capability of current techniques to assess this risk and/or to achieve optimal design with respect to reduced ageing risk.

Since the insulation ageing speed is proportional to a temperature-dependent exponential, the so-called hot-spot determines the place at which the insulation is most susceptible to breakdown. Thus, knowledge of the temperature at this spot gives rise to a formal parameter for risk analysis. The challenge now becomes to determine both hot-spot location and temperature. Fiber optic cables deliver only a partial solution, as their location is pre-determined and fixed. This advocates for model based prediction of hot spots. Such a prediction can be based on thermal modeling, using the winding design and the electrical losses as input. This has been the subject of the Cigre A2.38 working group on thermal modelling. An overview of the available techniques can be found in Amoiralis et al. [2].

Next to risk analysis, the thermal model can aid in Life Cycle Decisions. Technically, the hot-spot temperature is calculated as the product of the so-called 'gradient' and the hot-spot factor. While the winding gradient is dependent on average winding temperature and thus on average winding losses and total oil flow through the winding, the hot-spot factor is dependent on local oil flow properties as well as local heat losses. Detailed calculation of the local oil flow and heat losses with thermal models contributes to identifying problem areas and provides solutions to reduce this hotspot temperature.

This paper focuses on the capabilities of the two types of thermal modeling, namely thermo-hydraulic network modeling and Computational Fluids Dynamics (CFD) simulations. In a next section, the application to a LV-winding is described. The subsequent two sections are dedicated to each of these techniques. They explain the set-up of the model and explore its relevance in risk assessment and life cycle decisions. The two subjects are weaved together by a case study. This case study is an extreme case showing the capabilities of both techniques in identifying and solving possible insulation ageing problems.

Application to LV-Winding

Every technique in this paper is applied to the LV winding of a 40 MVA-rated power transformer. This winding is a zig-zag cooled layer winding in the oil natural cooling (ON) regime, composed of CTC netting cables with spacers between turns. Washers and seals separate the passes; each pass consists of 11 turns. The radial channels between the turns are 3 mm high, while the top channel between last turn and stress ring is 6 mm high.

The loss distribution of the winding is presented in figure 1. As can be seen from this graph the loss distribution has a very moderate shape. The proportion of the losses in the top disk over the average disk losses = 326/291 = 1.12.

Based on the IEC 60076-7 formulas for recalculating of the gradients we would expect a hot-spot factor of:

$$\frac{g_{ave}\cdot\left(\frac{326}{291}\right)^{1.3/2}}{g_{ave}}=1.08$$

So at first sight a very moderate hot-spot factor is expected for this winding.

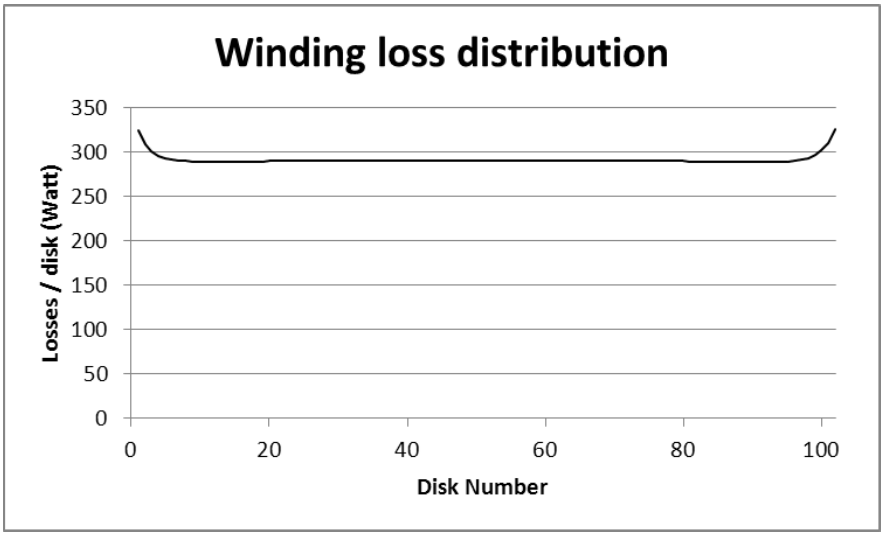


Figure 1: Electrical losses in the studied LV-winding

Thermo-hydraulic network model

Methodology

A thermo-hydraulic network model (THNM) is essentially a lumped model, similar to a resistive network for an electric circuit. The oil flow inside a channel, possibly heated or cooled, comprises a first (the flow) network. The insulator-conductor structure of the windings leads to a second (the thermal) network, coupled to the oil loop via surface temperature and heat flux.

The advantages of the THNM approach are its low calculation time – one or two minutes – and ease to parameterize. Its disadvantage is that it is based on custom-built software; the latest models include Zhang and Li's model [3], TEFLOW [4]. Further, its accuracy largely depends on proper calibration of the various pressure drop and heat transfer correlations. Because not all pressure drop and heat transfer geometries as present in a transformer are described in literature, these correlations are most often calibrated with (numerical) experiments [5], [6].

Results

An updated version of Radakovic' THNM is run [7]. As this model comprises the full transformer, all data relevant for transformer design on different levels is accessible, namely:

- transformer level: top and bottom oil temperature, total oil flow;
- winding level: average winding temperature, average winding gradient, oil flow through the winding;
- local level: oil temperature inside channel, oil mass flow through channel, temperature of wires.

In the context of risk assessment and design optimisation, we are particularly interested in temperatures on a local level, as this includes the hot-spot temperature. Furthermore, averaging the conductor temperature per turn indicates how to mitigate the hot-spot temperature: the oil flow can be redistributed according to this temperature profile, keeping in mind the inverse relationship between mass flow through the adjoining radial channels and average turn temperature. This data is presented below, together with the results from the CFD simulation.

The data at higher levels (winding & transformer level) can provide help in life cycle decisions. For example, changes in the external circuit can be assessed: changes in e.g. radiators, fans or pumps. Furthermore, changes to the overall winding design can be taken into account.

CFD simulation

Methodology

Computational Fluid Dynamics (CFD) simulations solve the Navier-Stokes and energy equations on a discretized domain. When properly used, it is very accurate and can be very detailed. Nevertheless, a simulation requires multiple hours, both in preparation and effective simulation time. Therefore, an affordable simulation is limited to one winding.

As is the case for THNM, CFD simulations require electrical losses – which can be calculated with electromagnetic simulation software – . Further, as the CFD model only covers one specific winding, it needs an appropriate inlet mass flow and temperature. For our case, this data is extracted from the THNM.

Geometry and mesh

Because of both meshing and computational time requirements, three simplifications are applied: 1) only the top two passes are considered; 2) the simulation is a modified axisymmetric model and 3) the internals of the CTC cable are homogenized. These simplifications will be elaborated in detail next.

First of all, only the top two passes are simulated. This is justified because the hot-spot is expected to reside in the top pass. Further, the penultimate pass will ensure to generate a correct ‘flow history’.

Secondly, the full 3D rotationally periodic geometry is simplified to an axisymmetric model. Since the spacers cover part of the bottom or top of a cable, both the flow section of the oil and the cooled surface area of the cables are reduced. The losses below or above a spacer have to be conducted away tangentially to a nearby radial channel. Since axisymmetric conditions suppose no spacers are present, the flow through the winding is divided over 360° and the losses are evacuated over 360°. Therefore, the axisymmetric case is modified to mimic a radial channel by multiplying the mass flow, the losses and the radial conduction of the insulation by a factor f containing the coverage of the spacers:

$$c = 2\pi\, r_{mid}$$

$$f = \frac{c}{c - n_{sticks} * w_{spacer}}$$

With r_{mid} being the radius from the centre of the core to the middle of the cable; f proves to be 1.3356 for the LV winding under investigation. Although, this axisymmetric model does not exactly capture reality, a similar approach was successfully taken in [8].

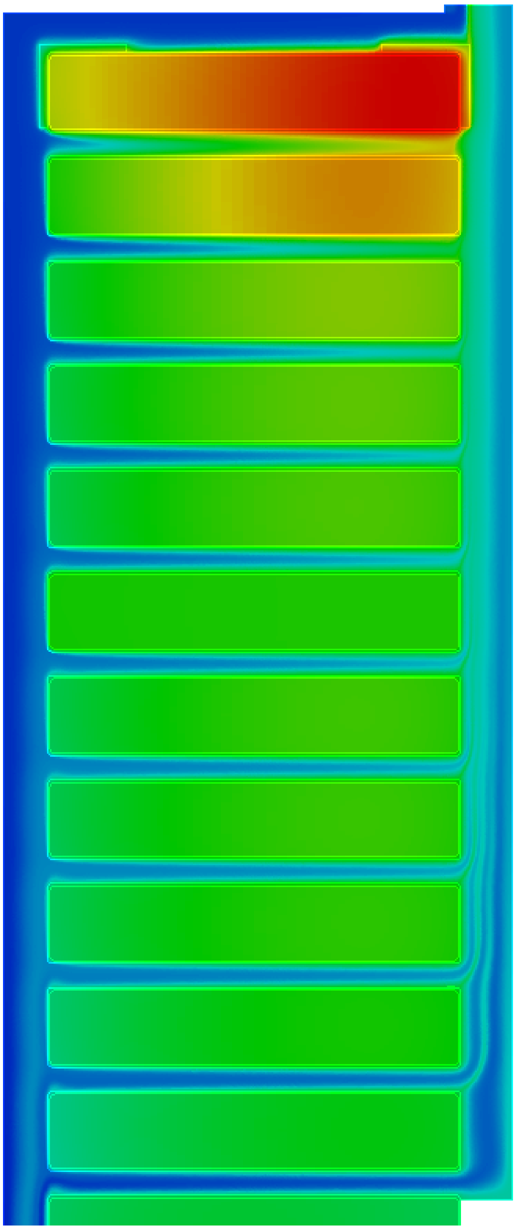
The third simplification is proposed on the level of a turn. Instead of composing the CTC cable from numerous smaller wires, the internal part of the cable is replaced by an anisotropic material. This is similar to approach 3 in [9], with the major difference being that the outer insulation (i.e. netting and the enamel between netting and copper conductor), is maintained. This way, the large temperature drop is withheld in a separate layer, being adequately resolved and not influencing the copper temperature. Another advantage is that the problem of a 2D-representation of the CTC cable is alleviated. Instead of 55 wires – with the ‘top’ wire constantly changing position -, the CTC cable is virtually composed of 56 wires, resulting in a rounded rectangle. Of course, the losses will only equal those of the 55 wires. This way, the CTC cable is represented as shell of a blended insulation material and an anisotropic heat source material.

The mesh is prepared in Ansys Icem v14.5 and is assembled from two separate meshes, one for the fluid and one for the solid part. They are coupled with a non-conformal mesh interface. The fluid mesh is a mixed triangular-rectangular mesh, having 1.5 million elements. Each cable in the solid mesh is composed of 10,000 elements; the insulation layer is 10 cells thick.

Solution

The problem is solved with Ansys Fluent v14.5. Only the energy and the buoyancy models are activated; the Reynolds number is very low, not necessitating a turbulence model. The inlet boundary conditions are extracted from the THNM simulation: the mass flow is 0.2797 kg/s (to be multiplied by f) and the inlet temperature 68.1 °C. The outlet is a pressure outlet. The other boundaries are considered insulated. Second order discretization schemes are applied for all variables.

The problem is initialized as a standstill flow with a temperature of 335 K. The solution is iterated until the scaled residuals for momentum and energy reach 10^{-6} and 10^{-10}, respectively. The relative error on the global mass and heat balance is respectively 10^{-8} and 10^{-7}. The mesh is refined, having 1.6 times the number of elements. This gives a negligible difference. A simulation with the precursory pass included – for a better resolved inlet profile – also gives a negligible influence on the hot-spot temperature.



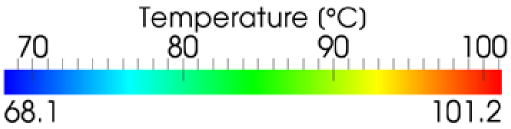


Figure 2 : Temperature distribution of the top pass according to the CFD simulation.

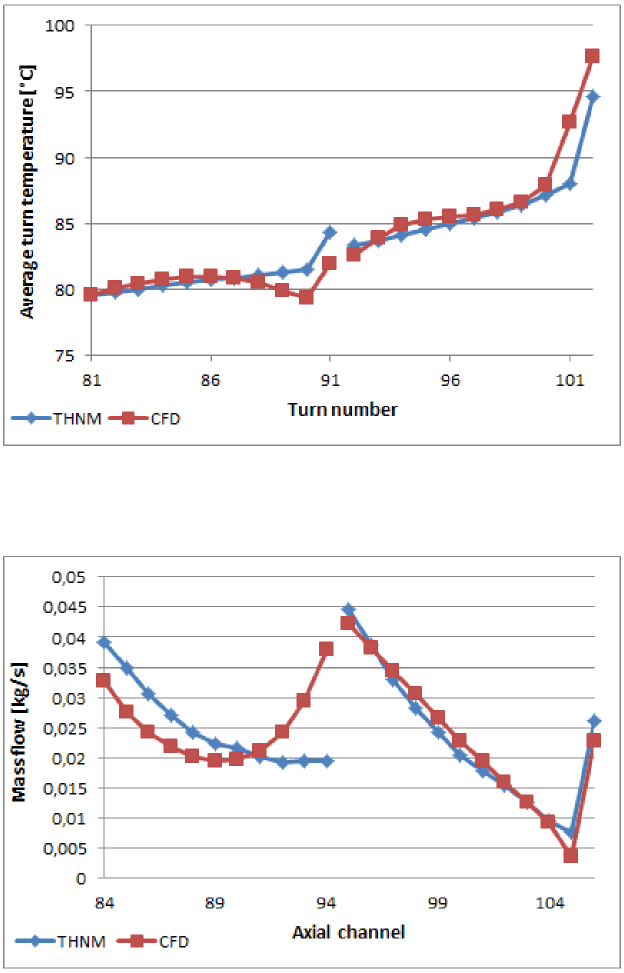


Figure 3 : Average temperature per turn and mass flow distribution along the height. A gap in the graph denotes the pass boundaries.

The results are displayed in figures 2 and 3. Figure 2 depicts the temperature distribution of the top pass, with the temperature scale at the right. Figure 3 presents the average turn temperature and the mass flow distribution along the height of the top two passes, both for CFD and THNM simulations. The results agree very well, despite the fact that the THNM calculates a low mass flow through the top radial channels of the penultimate pass. This can be corrected by proper calibration of the pressure drop correlations for the ON-situation.

Although that based on the heat loss distribution a very low hotspot temperature was expected, both calculation methods reveal a very high hot-spot factor: 1.55 per THNM and 1.76 per CFD. This is due to the very low oil flow through the penultimate radial channel. Therefore, design changes will be explored in order to alleviate this problem.

Winding design optimization

The main reason for the high hotspot factor is the low oil velocity around the top disks. To increase the oil velocity at these locations, the following actions are taken:

1. A washer is placed such that the top five cables form a separate pass; of course, the outlet of the winding is now present at the inner axial channel.
   This measure splits the top pass in two passes and will result in higher oil velocities in this section. However, also the total oil pressure drop will increase due to the extra pass. Both effects can be taken into account and will be checked in a THNM calculation.

2. The channel between top disk and stress ring was reduced from 6 mm to 4 mm. This reduction results in a more even oil flow distribution in the top section.

Another measure which is taken, is to remove the edge protection at the inner side of the winding. Note that it is far better to remove the edge protection at this side, because of the build-up of the thermal boundary layers.

The relative ageing speed for non-thermally upgraded paper is defined in IEC 60076-7 as

$$V = 2^{(\theta_h - 98)/6}$$

Since above measures reduced the hotspot temperature with 12 K an increase of the lifetime of the paper insulation with a factor 4 can be achieved with these measures. All measures introduced had no effect on cost price of the transformer. This shows how thermal models are adequate design tools giving room for optimising the winding design and increasing transformer lifetime without increasing transformer cost price.

Conclusion

In the present study an ON cooled LV-winding provides an extreme case for ageing risk assessment by means of thermal models. It clearly shows the benefits and possibilities of the latest developments in thermal winding modelling. The improved calculation methods can be used in different aspects of transformer asset management. Some examples are listed below:

1. Existing transformers can be recalculated with the latest thermal design software to assess the risk of transformer failure.
2. During refurbishment, these techniques can be used to optimise the winding cooling and reduce hotspot temperatures, resulting in a refurbished winding with higher expected lifetime as the original one.
3. For new transformers, these techniques can be applied to optimise the winding design, so that transformer lifetime can be increased without increasing transformer cost.

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