THERMAL-HYDRAULIC INVESTIGATION OF A LARGE POWER STEP UP TRANSFORMER

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Abstract: The topic of this article is the calculation of the oil flow and temperature distribution within the windings of a large power step-up transformer with the help of CFD (Computational Fluid Dynamics). The cooling mode of the investigated transformer is ODWF (Oil Direct - Water Forced), where both windings (generator and high voltage windings) are fed with oil by one common DOF (Directed Oil Flow) channel. Such a design raises the question if the delivered oil flow at different operating states is distributed appropriately into each winding. Accordingly, because of the strong interdependencies between the oil flow distribution and the resulting winding temperatures, a coupled approach had to be developed. For that purpose, first the characteristic hydraulic curves of each winding, depending on the applied oil flow rate and chosen inlet temperature, were determined by a set of CFD simulations. The comparison of the obtained results concerning the pressure drop in each winding then provided the so-called working points, describing the resulting flow ratio at given total oil flow rates and inlet temperatures. Given specific working points, the corresponding temperature distributions in both windings were determined in detail and the hot spots were identified by temperature and well located. Finally, the results of these calculations were compared with those results of the measurements from the heat run test on a real transformer.

1 INTRODUCTION

The lifetime of a power transformer is mostly limited by the lifetime of its paper insulation. Furthermore, the latter depends on the depolymerisation of the cellulose which accelerates with increasing thermal load. An increase in temperature of 6 to 8 K leads to a duplication of the ageing (depolymerisation) rate of the cellulose. The specifications of a new transformer before commission typically comprise a statement regarding the minimum service lifetime. Only an accurate calculation of the temperature distribution within the windings can ensure that locations with exceeding temperatures will not appear and therefore the minimum service lifetime can be kept reliably. On the other hand, an accurate temperature calculation helps to avoid waste of materials

2 DESCRIPTION OF THE INVESTIGATED TRANSFORMER

The transformer, which was investigated, is a large power transformer. The cooling mode is ODWF, which means that the winding is directly fed with oil by a pump through piping and oil tight leads. The oil is forced into the bottom of the windings and flows to its upper end where it escapes freely into the vessel. Then it is pumped back to the cooling unit where the cooling circuit is closed. The high voltage (HV) winding is a disc type winding with horizontal oil ducts between the discs. Zigzag oil flow in the horizontal ducts is formed by frequently placed oil flow washers while the discs are intermitted in radial direction by clack band so that oil can also flow vertically though the discs. The discs are made of Continuous Transposed Conductors (CTC) and the connection to the 400 kV line terminal is made from the middle of the winding. The conductors are insulated with thermally upgraded paper. The low voltage (LV) winding is a helical winding type with transposed conductors in parallel. The conductors are separated from each other by radial spacers, which form radial cooling ducts and the vertical oil channels are intermitted by oil flow washers to enforce oil flow in zigzag manner. The conductors are without paper insulation but wrapped with perforated Nomex tape for thermal and technological reasons. Temperatures at expected locations of hot spots are measured via fibre optic sensors, placed in the spacers between the winding discs.

3 APPROACHES FOR MODELLING

3.1 General procedure for modelling

To limit the computational efforts within reasonable boundaries, it is necessary to simplify and disassemble the concerning arrangement inside the transformer in a proper way. Therefore some short cuts have to be taken to implement the given technical circumstances efficiently. One of them is that the cooing unit, the pumps and the oil pipes can be easily cut out of the scope of the detailed analysis since they can be characterized by curves, or values delivered by its manufacturers. Another useful element for simplification of the model is the strong periodicity of the winding, especially in circumferential direction. Neglecting small irregularities, the geometry of the winding is repetitive (sub-divided by spacers). Therefore it is only necessary to model a single section, the winding is composed of. Similar simplifications were also applied in axial direction (Figure 1).

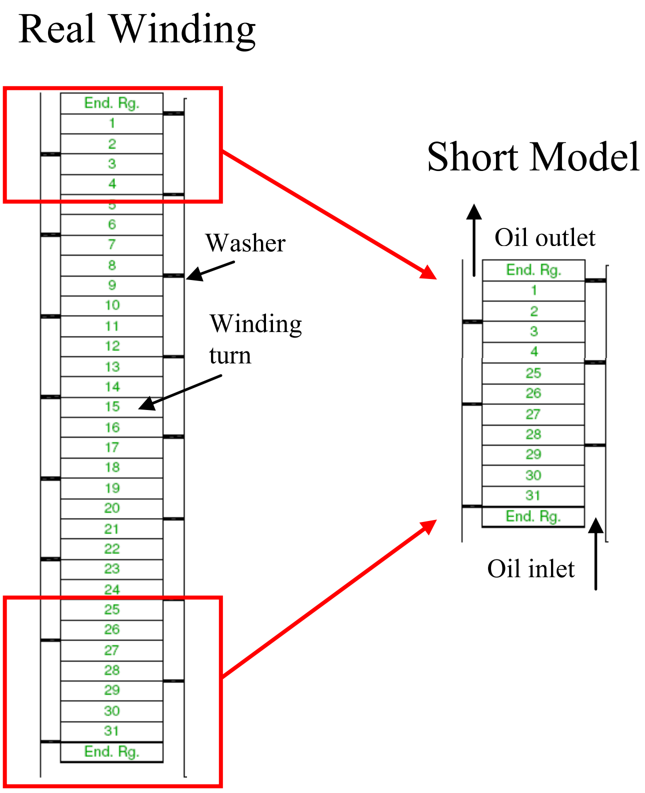

Figure 1: Modelled sections in axial direction

These partial elements are now eligible to be investigated by CFD. After post processing of the simulation results, each individual element can be characterized by its hydraulic curves or maps and thermal characteristics. After that, all the partial elements can be reassembled in parallel and serial manners to restore the entire assembly. The behaviour of the complete system can then conveniently be investigated.

3.2 Modelling of the windings

In order to save computational effort, some simplifications had to be made or were justified because of their negligible influence on the results. An essential simplification is that the impact of the spacers, bounding the horizontal channels in circumferential direction, was neglected. Therefore, a 2D axis-symmetric modelling was sufficient. The sticks in the vertical channels were simplified to a reduced circumferential width of the intermediate channels. In Figure 2, the top view on a periodic section of the HV winding is displayed and the neglected area is marked.

The 2D axis-symmetric modelling leads to a huge reduction of computational and modelling efforts. By consequence of neglecting the spacer region, all losses of the conductors were concentrated on modelled conductor lengths. There is no problem for this simplification since the heat transfer from solid to oil within the neglected spacer region is negligible. All types of passes (sections between washers) contained in the real windings are also presented in the models. At the inlet of the windings an oil mass flow of variable magnitude and temperature was impressed. The loss power was impressed volumetrically into each single conductor according to the calculation results of a software used to predict the eddy losses in CTC conductors. During the simulation the coupled thermal-hydraulic equations were solved. Winding sections, which are geometrically identical to each other are mostly modelled only once. When there were slight differences in the loss distributions, always the highest losses were impressed into the conductors of the modelled section to represent the “Worst Case”. The resulting model for the HV winding comprises approximately 2 million cells while the model for the LV winding consists of about 1 million cells per modelled layer. To model the material properties of the oil, a Newtonian fluid model was chosen, implying an exponential or linear temperature-dependency of the viscosity and density. Since the Reynolds number was relatively low, no turbulence model was used. Since the washers in the vertical channels are not completely tight, a leakage gap had to be modelled. As a first approximation a gap width of 1 mm was chosen. In Figure 3 a section of the model for the LV winding is shown with the details of the mesh and cognisable gap between winding cylinder and washer. In Figure 4 the velocity distribution within this geometry at a medium flow rate is shown. The leakage flow due to the gap of the washer is clearly visible.

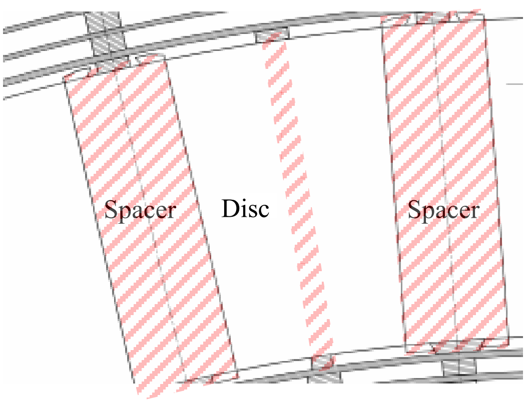

Figure 2: A winding disc with neglected parts marked

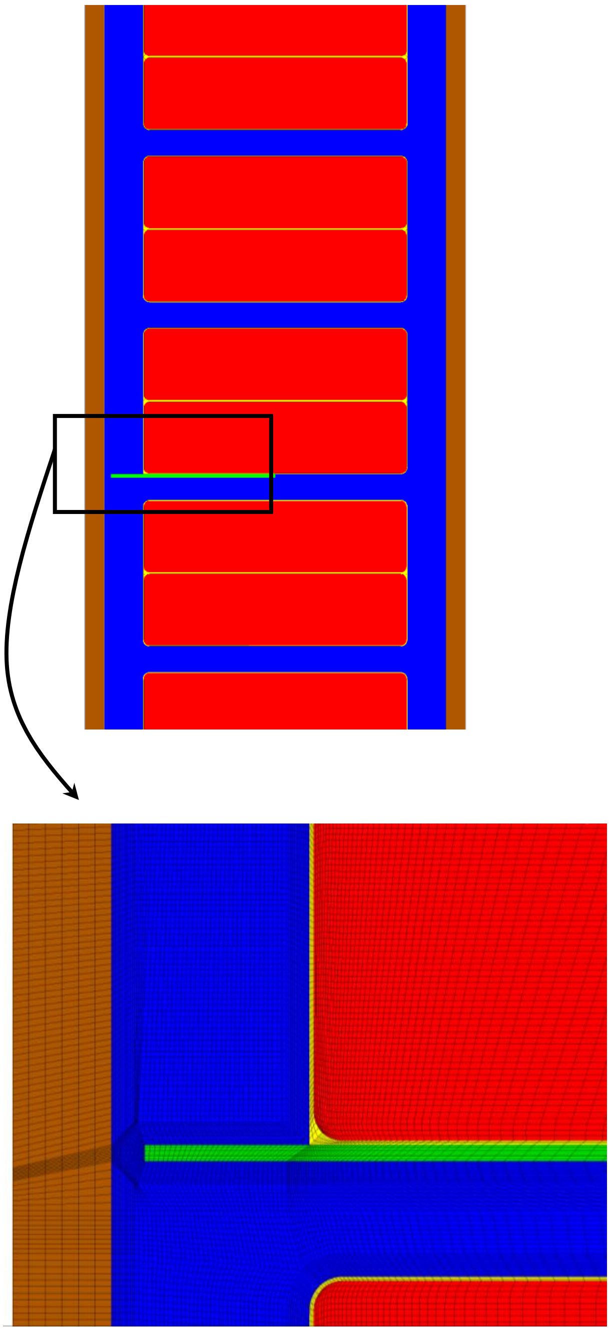

Figure 3: Section of the geometry of the LV winding and meshes for conductor (red), insulation (yellow), washer (green), fluid (blue) and boundary winding cylinder (brown)

4 POSTPROCESSING OF THE SIMULATION RESULTS

Since each repeating section (pass) of the windings was modelled only once, some post processing had to be done, before the data of interest considering the entire windings were available. The simplified CFD models were therefore fed with three different inlet temperatures and oil flow rates resulting in nine simulations for each model. Each winding pass could be characterised by data points e.g. the pressure drop between its washers, the conductor temperatures etc. resulting from a specific inlet temperature and inlet flow rate. These data points were interpolated by polynomial functions showing the dependency of the pressure drop with respect to the inlet temperature and flow rate for each concerned winding pass. The dependency of each disc temperature and also of the resulting hot spot temperatures were displayed in the same way. To evaluate a specific value for the whole winding e.g. the pressure drop, at first the emerging inlet temperature at each pass with the respective flow rate was calculated using the energy balance equation. Then the single values could be added up to the pressure drop along the entire winding. The results are the characteristic curves for the pressure drop over the complete winding, the averaged winding temperature and the hot spot temperature as shown in Figure 5, 6, 7 and 9.

It is necessary to mention that especially at the connection between the feeding oil pipe and the winding inlet an oil leakage can be anticipated. The strong impact of the unknown amount of leakage can be reviewed especially in the characteristic curves in Figure 7 and 9. There is a rough estimation about the actual amount of leakage in use. It values the amount of leaking oil not entering the windings as significant. However, there is no solid argument for such a rough estimation and this uncertainty will remain until measurements of oil leakage on real transformers can be carried out.

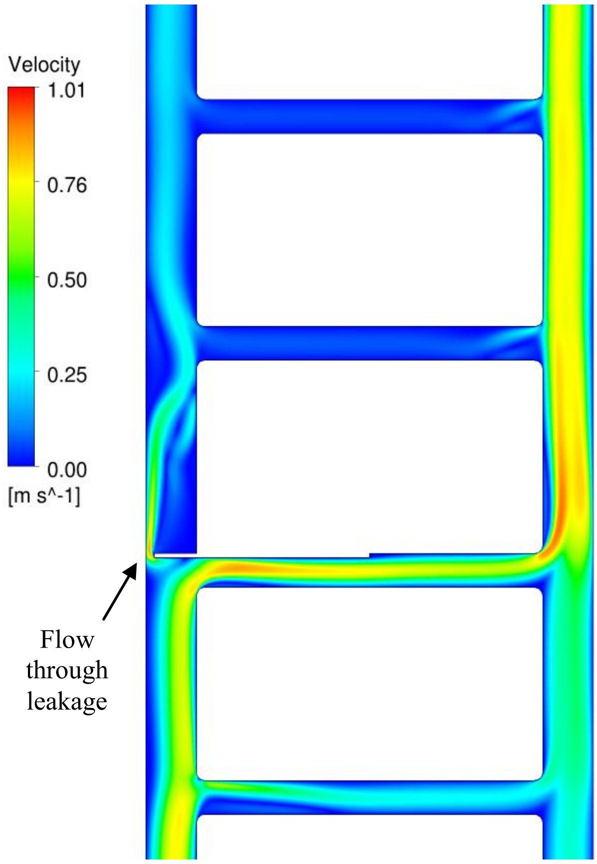

Figure 4: Section of the velocity distribution in the LV winding

5 DETERMINATION OF THE WORKING POINT

An exact knowledge about the flow rate actually entering a specific winding is a premise to evaluate the temperature distribution within this winding reliably. Accordingly, this flow rate needs to be determined and -if necessary- adjusted. Before the oil flow rate at the entrance of a specific winding can be ascertained, the total oil flow coming from the pumps needs to be assessed. Since the pressure drop at the oil-water heat exchanger is usually much larger than the pressure drop over the winding, it is reasonable to assume this total oil flow rate of the pump given by the cooler supplier to be impressed into the tank and to be independent from the hydraulic resistance of the winding. Subsequently, the total oil flow delivered by the pumps distributes between the windings according to their hydraulic resistance. Since both windings are fed by one common channel, the pressure at their inlets is always identical. Consequently, a matching pressure drop in both windings is caused by a total oil flow rate, that can be calculated as the sum of the oil flow rates entering both windings.

As an example we can assume a common pressure drop of 5000 Pa at an inlet temperature of 40 °C. Given the characteristic hydraulic curves for this oil inlet temperature for both windings (Figure 5 and 6), a total flow rate of 24,2 kg/s = 9,8 kg/s + 14,4 kg/s can be determined. Now the flow distribution into both windings for this inlet conditions is ascertained, the characteristic thermal curves permit the evaluation of the average winding temperature in each winding and the resulting hotspot temperature. Accordingly, the arising average winding temperature in the HV winding at the previously defined working point is 61,9 °C, as shown in Figure 7. The corresponding hot spot temperature of 79 °C (T3) can be determined in the same way, using the characteristic curves for the individual conductor temperatures in the hot spot region (Figure 9).

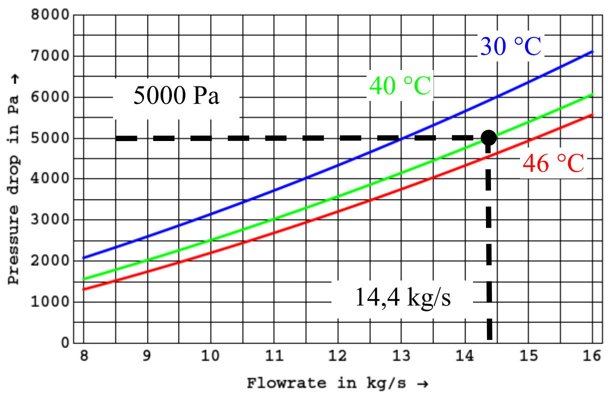

Figure 5: Pressure drop of HV winding

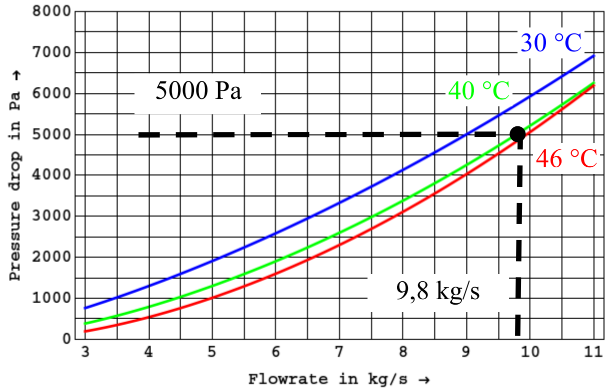

Figure 6: Pressure drop of LV winding

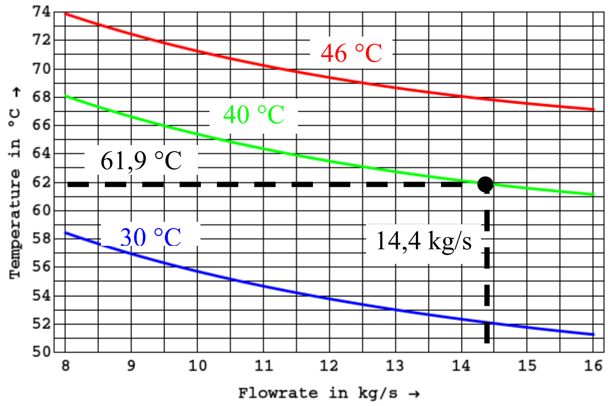

Figure 7: Average temperature of HV Winding

The other temperatures in Figure 9 (T1, T2, T4 and T5) represent the temperatures on the insulation surfaces and in the adjacent oil channels, as shown in Figure 8. Since additional solid insulation is applied at the top of the conductor, the temperature gradient within the solid insulation of that region is much more important than at the bottom side of the conductor.

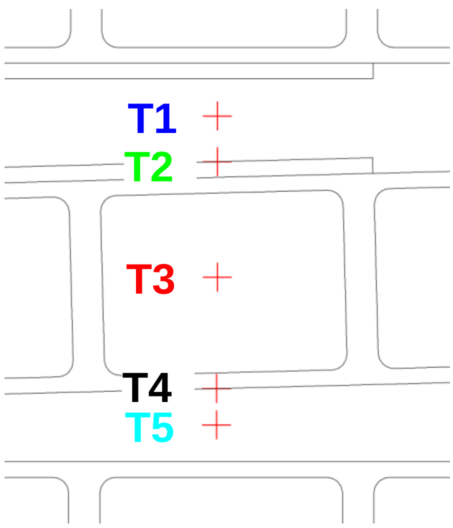

Figure 8: Hot spot region

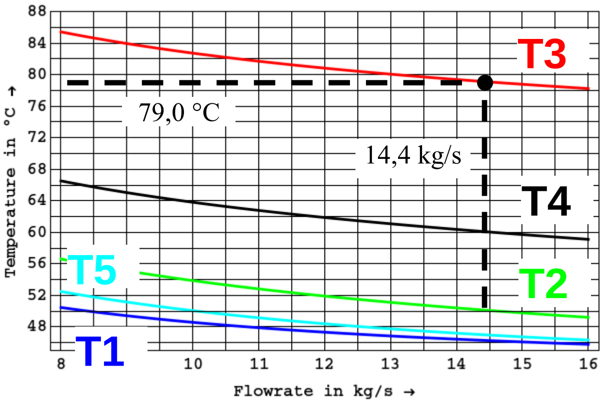

Figure 9: Temperatures in and around hot spot, as an example for 40 °C at oil inlet

6 COMPARISON WITH THE TEMPERATURES MEASURED IN TEST FIELD

Since the investigated transformer was actually built, during the heat-run test hot spot measurements by means of fibre optic sensors were performed in order to compare the numerically determined results with the measured values. In Table 1, the deviations between measured and calculated values are listed. Positive deviations mean that the measured values were higher.

Table 1: Deviations between measured and calculated temperatures

Deviation of average temperature of HV winding	+0,6 K
Deviation of average temperature of HV winding	+4,3 K
Deviation of average temperature of LV winding	+8,2 K

This comparison shows some significant deviations between measurements and simulations, especially for the LV winding, while the values for the HV winding are more or less acceptable. However, experience shows that quite large deviations could even occur for measured temperatures between transformers of identical design under the same test conditions. Deviations of +- 3 K are not unusual. The causes seem to be most likely the tolerance in manufacturing process and measurement errors. In addition, in CFD simulations, the real leakage at the oil washers as well as at the connection between oil pipe and winding entry is a big uncertainty, which could also be a cause of deviations.

7 CONCLUSION

The thermal-hydraulic investigation of power transformers by means of CFD is a promising way to improve the reliability of thermal design. Though a number of simplifications should be applied to keep the use of computational resources within reasonable boundaries, this approach gives a much more detailed model than traditional network models. Unfortunately, big deviations between measurements and calculation could result from tolerances in material, manufacturing process and measurements and also uncertainty of the assumed boundary conditions for simulation, especially the flow rate of the oil at the inlet, reduced by an unknown leakage rate.

8 ACKNOWLEDGMENTS

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9 LITERATURE

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