Hot Spot Determination in Transformer Windings through CFD Analysis

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SUMMARY

This document presents general aspects and main results of a method to determine the hot spot location and its magnitude inside a winding using CFD (Computational Fluid Dynamics). The presented analysis and results reflects ABB’s effort regarding combined development and application of modern methods dedicated to Power Transformers and High Voltage Reactors reliability and performance regarding thermal aspects. The CFD analysis shows that the winding hot spot location is not necessarily determined by the location of maximum losses; the design example reveals that the hot spot may be positioned at a different location where locally reduced cooling occurs. This implies then that hot spot factors need to be based on the design details regarding both cooling and losses, and therefore that the default hot spot factor value of 1.3 should be avoided. A sensitivity analysis is performed showing that detailed spacer data and detailed loss distribution are required to correctly determine the magnitude and location of the hot spot. Fiber optic measurements of a transformer unit are presented that support the conclusions.

PALAVRAS CHAVE
Power Transformer, CFD, Hot spot, Winding, Temperature

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1.0 INTRODUCTION

Power transformers and high voltage shunt reactors should be designed to limit the temperature of the hottest spot inside the transformer because the aging of the insulation material is exponentially related to the temperature level and it will therefore directly affect the expected lifetime of the transformer.

Given the ever increasing computational processing power, numerical simulations are contributing increasingly with consistent results and processing time acceptable for industry application. As a consequence, the modern CFD application offers a powerful tool to analyze the thermal behavior of power transformer and high voltage reactor windings, with publications now emerging (for example, see [1], [2], [3] and [4]).

National and International Thermal Standards such as ABNT [5], IEEE [6] and IEC [7] describe how a hot spot temperature in a winding can be obtained from measurement of oil and winding temperature rise. Their simple models based on a hot spot factor depend on the knowledge of oil and winding temperature gradients ratio considering the average and the hot spot locations. Often this hot spot factor is taken as a default value of 1.3 (as suggested by the standards in case no further information on the actual design is known), or estimated by calculating the ratio of losses between the top disc and the average loss per disc. Alternatively, fiber-optic measurement can be used to obtain a value for the hot spot.

A default hot spot factor can create a false sense of security since there is no simple way to determine a realistic hot spot factor without taking into account the hydrodynamic effects inside the winding. The hot spot will not necessarily be located in the disc with the highest losses but could be in another disc where flow conditions do not provide sufficient cooling. The default hot spot factor can therefore not be used as a substitute for detailed thermal analysis. Instead, an actual hot spot value should be based on a detailed analysis based on modern tools and a thorough understanding of the physical processes and local winding design effects on the formation of the hot spot temperature.

Direct measurements by fiber-optic sensors of local temperature inside a transformer are useful but for the same reason described above cannot be considered to represent the true hot spot temperature unless the measurement position coincides with the hottest spot. Detailed knowledge about location of the hottest spot requires sophisticated analysis of the thermal behavior of the power transformer or high voltage reactor evaluated.

2.0 STANDARDS

The proper determination of the hot spot temperature in paper-based insulation material has been an important challenge throughout the more than 100 years of power transformer design and diagnostics. The focus has been – and is expected to remain - on winding hot spot temperature determination since a significant part of the losses-related heat is generated in the windings.

The winding hot spot temperature determination during a heat run test has for a long time been built on agreed, design-independent hot spot factors, and the following well-known IEC model is generally applied to determine a hot spot temperature based on measured quantities and the hot spot factor H according to

$$T_{hotspot} = T_{top} + g \cdot H \tag{1}$$

where g is the winding-to-average oil temperature gradient. In this formulation all of the local winding design details that affect the hot spot temperature are contained in H. According to technical standards such as ABNT [5] and IEEE [6], H should be obtained through detailed information provided by the manufacturer, but the standards do not offer a method to calculate it. Although not recommended, the only explicitly mentioned alternative is the default value of 1.3.

It is only since the last few decades that the techniques and routines for predicting and measuring temperatures have been refined to such extent that is at least potentially possible to directly determine a hot spot location and level (without relying on a predefined hot spot factor) in very much detail. Examples of such techniques for predicting are simulation approaches like THNM (Thermo-hydrodynamic Network Modeling) and – very recently – CFD (Computational Fluid Dynamics), and the possibilities and limitations of these approaches are expected to be described in detail in the forthcoming CIGRE WG A2.38 brochure. Complementary to simulation methods, accurate measurement opportunities are available by the use of optical fiber sensors. The hot spot factor still remains an important concept though, since it can be used to relate measured quantities (average winding temperature rise as well as top – and bottom oil temperature rise) to a hot spot temperature in case optical fiber measurements are not available. Furthermore, the hot spot factor is used in dynamic loading models. The results obtained from the before mentioned advanced simulation methods applied on a final design can then be used to define a design-specific hot spot factor with high accuracy.

From the experience gained with modern modeling methods it has become clear that the relation between losses, cooling, local winding design details and the resulting hot spot temperature is complex and not necessarily dominated by the winding losses distribution alone. Whilst earlier versions of the temperature rise standard IEC 60076-2 only described a single formulation for the hot spot factor, the latest version [7] recognizes the separate contribution of losses and cooling by defining the hot spot factor in more detail using the following formulation:

$$H = Q \cdot S \tag{2}$$

where Q is the losses contribution and S is a design factor representing the effect of cooling in the hot spot area. This is certainly an improvement recognizing the complex nature of hot spot generation, but this still requires an assessment of the cooling factor S as a function of winding height and its contribution to the hot spot factor as a whole (in IEC 60076-2 values for the S-factor are proposed for a number of winding design configurations but these appear not to be based on a thorough model analysis). Modern methods like CFD can be useful to define the contribution of the cooling factor and to show that this factor can become important enough to result in a hot spot on a different location than where the maximum winding losses occur.

3.0 CFD ANALYSIS APPROACH AND MODEL EQUATIONS

In CFD (Computational Fluid Dynamics) analysis, the equations representing conservation of mass, momentum and energy are discretized and solved numerically. Instead of depending on empirical relations for heat transfer and fluid flow, the CFD approach allows complex geometries to be modeled in great detail. Although in principle the accuracy of a CFD model is only limited by the available computational resources, there are several factors such as numerical discretization schemes, convergence criterion, formulation of physical models, etc., that affect the quality of the computed results and calculation time consumption.

In this study the CFD approach was used to investigate oil flow velocity and temperature distribution in transformer windings. The fluid flow is solved by the incompressible Navier-Stokes equations representing conservation of mass:

$$\frac{\partial}{\partial t}\rho + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{3}$$

conservation of momentum:

$$\frac{\partial}{\partial t}\ (\rho \boldsymbol{u}) + \rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nabla \cdot \tau + \rho g \beta (T - T_{\mathrm{ref}}) \tag{4}$$

and conservation of energy:

$$\frac{\partial}{\partial t}\ (\rho c_p T) + \nabla \cdot\ (\rho \boldsymbol{u} c_p T) = \nabla \cdot (\boldsymbol{k} \nabla T) \tag{5}$$

The buoyancy term is included in the right side of the equation number (4) to consider the mass displacement caused by density variation of the transformer oil.

The governing equations are solved using the commercial CFD software Ansys Fluent [8]. Since the flow velocities in the cooling channels are quite low and the oil viscosity is high, the flow is laminar and no turbulence model is required.

4.0 WINDING MODEL DESCRIPTION

A disc type winding, which is a common type of winding in power transformers, is being described in the present modeling approach as a 2D axisymmetric vertical cross section of the winding. The inlet oil flow is adjusted to compensate the spacers between the discs which are not modeled since it's a 2D model. The approach is also valid for helical windings.

All the discs and spaces between the discs from the bottom to the top of the winding are included in the CFD model. The full height of the winding is divided into a number of sections defined by the number of oil guides, and the spaces between the discs varies according to the winding design definition. Axial duct height of radial cooling ducts due to spacers, cooling mode, cooling fluid material properties are all examples of important parameters that will affect the magnitude and location of the hot spot and are taken into consideration in the present modeling approach.

The cross section of the winding disc is modeled to consist of one homogeneous inner section of copper with equivalent thermal conductivities and loss density. A quantity of insulation paper layers are wrapped around this inner section of the disc.

The cooling fluid is a mineral oil. Its properties such as density, specific heat, heat conductivity, kinematic viscosity, dynamic viscosity are taken into consideration. Except for the oil viscosity which is taken as temperature dependent, the other oil properties are considered constant with values valid at the average oil temperature. The fluid is considered incompressible but with buoyance taken into account through the Boussinesq approximation for density.

In order to determine the heat loss generation inside the copper of the winding, the in-house electromagnetic solver Ace based on finite element analysis was used to calculate ohmic losses and winding eddy losses due to the leakage flux. For the CFD model presented here the losses are considered as a constant volume heat source for each disc but is allowed to vary between different discs.

The top section of the winding CFD model with the mesh is shown in Figure 1.

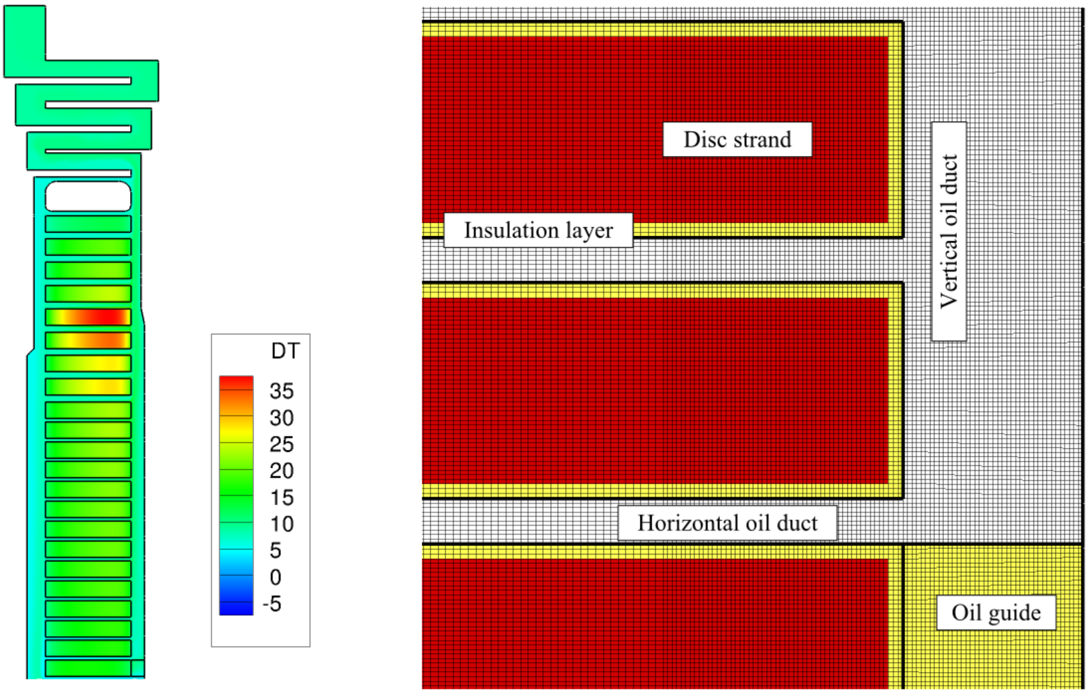

Figure 1 : The winding CFD model.

5.0 CASE STUDY

Detailed fiber optic measurements were performed on the High Voltage (HV) zig-zag cooled winding of a 200 MVA transformer. The winding is a continuous disc winding with 150 discs. The spacers in the winding have a uniform height except at the top of the winding which has a spacer height of double the nominal height to provide better dielectric performance. A number of disks on top and bottom of the winding are manufactured from thicker but shorter cables to lower winding eddy losses due to radial stray flux in winding ends. Detailed loss distribution in the top discs is shown in Figure 2.

The cooling mode for the winding is OFAF.

Fiber optic sensors were positioned measuring temperature in several discs throughout the winding. The positions are plotted in the resulting temperature profiles (Figures 3 and 4).

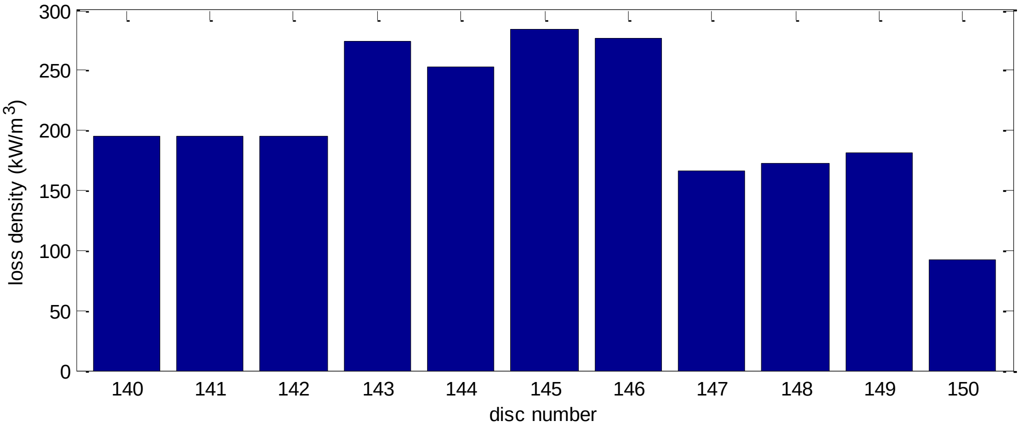

Figure 2 : Detailed loss distribution in the top discs of the winding.

5.1 Influence of flow rate

CFD simulation is performed with two different flow rates: a high flow rate which is calculated using a thermal network model taking into account all the windings as well as the cooling equipment, and a low flow rate computed to agree with oil temperature measurements performed in the top and bottom collar system of the winding under investigation. Results are plotted together with fiber optic measurement data in Figure 3 for the 1.00 times the rated current and in Figure 4 for 1.35 times the rated current. It can be seen that for the higher flow rate, the hot spot occurs as expected in the discs with the highest loss density at the top of the winding. However, for the lower flow rate, hot spots occur at lower locations in the winding where there are no fiber optic measurements. These hot spots will also not be predicted by the rules given in the technical standards.

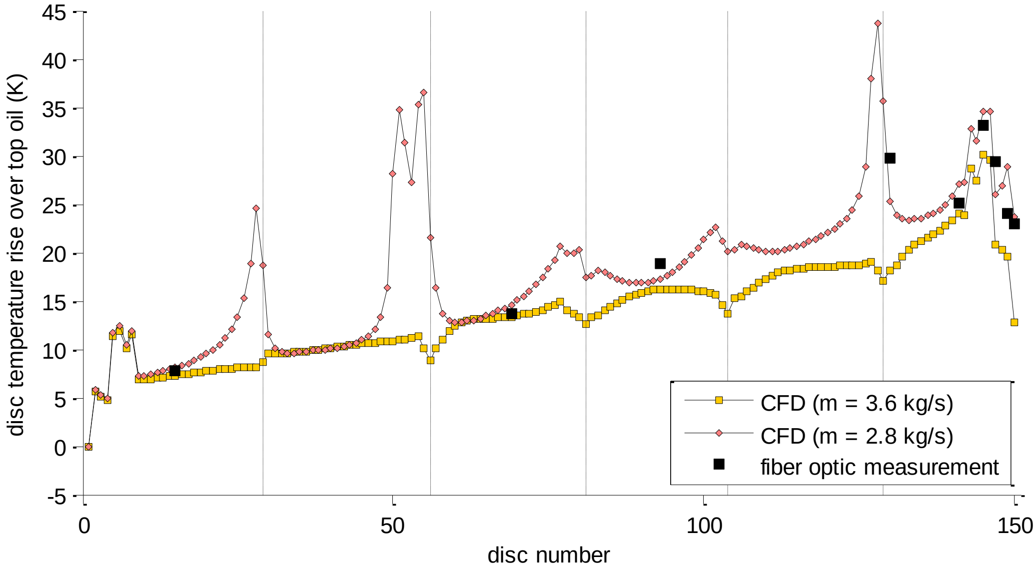

Figure 3: Comparison of winding temperatures for the rated current case at high oil flow (calculated with a thermal network model) and low oil flow (computed from measured values of winding bottom oil and winding top oil temperatures).

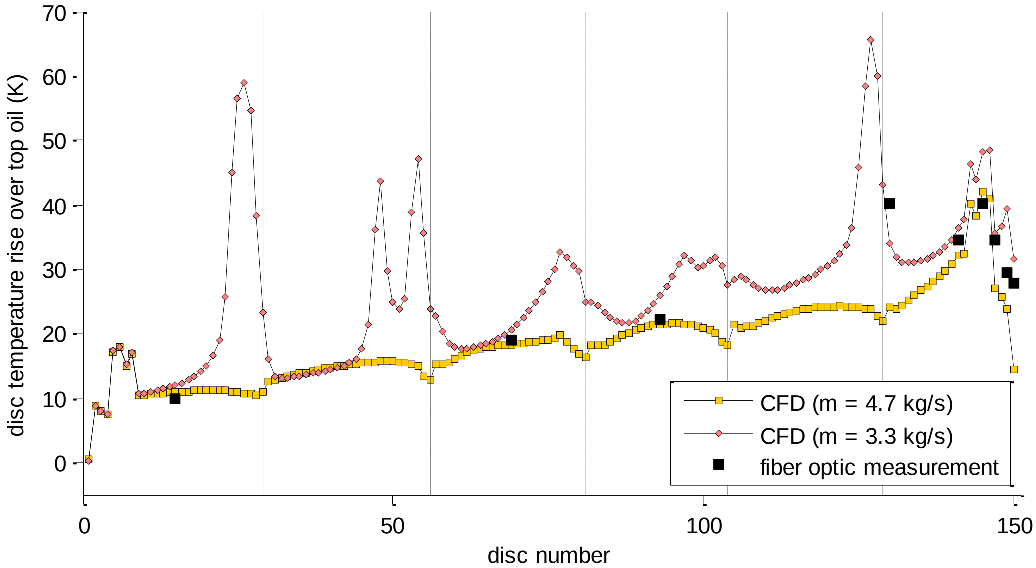

Figure 4 : Comparison of winding temperatures at 1.35 times the rated current at high oil flow (calculated with a thermal network model) and low oil flow (computed from measured values of winding bottom oil and winding top oil temperatures).

Table 1 shows the hot spot factor computed according to the international standards as well as calculated in reverse from fiber optic measurements and CFD analysis. For IEC the hot spot factor is computed based on a *Q* factor of 1.44 given by the ratio of highest specific losses to average specific losses. The *S* factor is assumed 1 as per the recommendation in Section B.3.1. It can be seen that the actual hot spot factor is much larger than the one suggested by the standard. Furthermore, the CFD calculation predicts a hot spot location that is not in the top disc of the winding, neither in the disc with the highest losses but actually further down.

Table 1 : Comparison of hot spot factor computed according to the standards, calculated according to fiber optic measurements, and calculated according to the low oil flow rate CFD computation.

	ABNT/IEEE	IEC	fiber optic measurement	CFD (disc 145)	CFD (disc 128)
Hot spot factor (1.00 rated current)	1.3	1.44	2.70	2.80	3.48
Hot spot factor (1.35 rated current)	1.3	1.44	1.94	2.29	2.80

5.2 Influence of modeling detail

The influence of the level of modeling detail is investigated by performing additional CFD simulations with permutations of two basic simplifications: Firstly, replacing the detailed loss distribution with uniform losses throughout the winding, and secondly replacing the detailed spacer data distribution with uniform spacers throughout the winding. The results for the top section for the case of 1.00 times rated current are plotted in Figure 5.

The temperature distributions are quite different for the various simplifications. For the uniform losses and spacers, the temperature distribution is also almost uniform. For uniform losses but detailed spacer distribution, the hot spot appears at the top of the winding, showing the importance of accurately resolving the cooling liquid flow field. However, it is not obvious that this behavior can be captured by defining a simple *S*-factor as defined in the IEC standard. For detailed loss distribution the hot spot of the top section occurs as can be expected in the discs with the largest losses, but again the detailed geometry data has a significant effect on the absolute value.

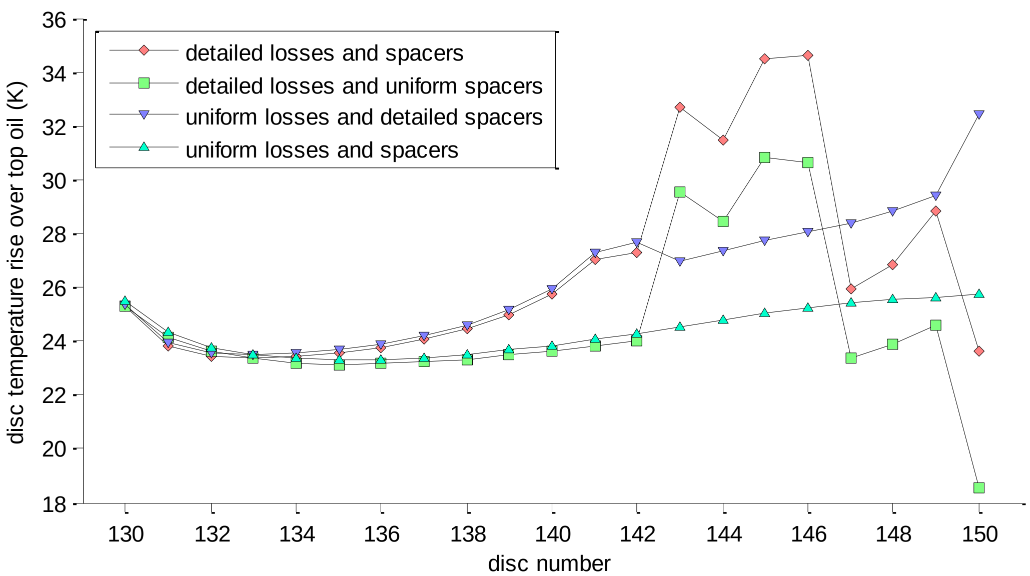

Figure 5 : Comparison of winding temperature in top section for different levels of modeling detail

Table 2 shows the hot spot factors that would be obtained from the simplified calculations, either in the top disc (for the cases with uniform losses) or in disc 145 (for the cases with detailed loss description). The simplifications cause a large variation in the hot spot factor, indicating the importance of detailed description of both geometry and distribution of losses. Furthermore, the *S*-factor is significantly larger than the value prescribed by the IEC standard, and clearly not independent of the loss distribution. Consequently, the methods suggested by the standards are insufficient to predict the magnitude and location of hot spot, and more powerful tools such as CFD should be used for this purpose.

Table 2 : Q and S factors calculated in reverse from the CFD results for the different level of modeling simplification.

	1	2	3	4
losses	detailed	uniform	detailed	uniform
spacers	detailed	detailed	uniform	uniform
Q	1.44	1.00	1.44	1.00
S	1.94	2.65	1.76	2.15
H	2.80	2.65	2.53	2.15

6.0 CONCLUSIONS

Modern approaches like CFD-based simulation studies reveal the complex interplay between the losses distribution and the cooling oil flow which together determine both the position and level of the winding hot spot temperature. These studies show that local winding design details as well as the winding oil flow rate may have a significant influence on the local cooling efficiency and may dominate the hot spot factor for the particular design. The cases investigated in this paper reveal that the position of the hot spot does not need to coincide with the position of maximum losses. Furthermore, the design-dependent hot spot factor that is derived from the CFD results can be strongly different from the widely applied hot spot factor value of 1.3, which shows that a detailed analysis based on a final design is to be used for estimating a realistic hot spot temperature and location and corresponding hot spot factor. Consequently, a thorough CFD analysis on a final design can play a very useful role in a design review in determining the position of optical fiber measurement sensors as well as deriving an accurate hot spot factor that can be used for heat run tests and other applications.

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