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NEW DEVELOPMENTS IN TRANSFORMER COOLING CALCULATIONS

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Summary

Thermal aspects affect transformer design. Therefore precise temperature calculations ensure good quality and long life expectancy of transformers.

The temperature gradient between conductor and oil consists of a gradient inside the solid winding insulation and a gradient inside the boundary layer at the winding surface. The gradient inside the solid insulation depends on the thickness of the enamel, paper insulation and oil pockets between conductor and paper wrapping. The heat transfer at the winding surface is determined by the cooling conditions. Two general approaches are in use: the forced convective cooling (OD) and the natural convective cooling (ON).

Another important thermal design aspect is the longitudinal temperature gradient inside ON-cooled windings. This value results from a balance of the natural convective oil driving forces accelerating the oil flow and hydraulic resistances in the oil circuit slowing down the oil flow. Further hydraulic resistances outside the winding are able to reduce the oil flow through ON-cooled windings additionally. Longitudinal temperature gradients measured in heat run tests with variable hydraulic resistances inside the winding were evaluated.

Heat transfer coefficients at the winding surface were calculated using heat run test results of various ON- and OD-cooled winding types. Two different general approaches were made for ON- and OD-cooled windings. The characteristic of the heat transfer coefficients were calculated for each winding type.

Further temperature rise experiments with an ON-cooled disc winding operated with variable heat flux densities were performed in order to investigate the influence of the heat flux density on the cooling efficiency of the boundary layer.

Keywords: *Power Transformers, cooling, heat transfer, winding temperature rise*

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1 Introduction

Transformers are valuable assets in power systems. It appears worthwhile to pay special attention to this key component to ensure stability in power systems. Cellulose insulation is used in most power transformers until yet. The ageing rate of the paper-oil insulation in transformers strongly depends on the temperature. There is a strong interest to determine the winding hottest spot temperature which is also the limiting factor for transformer loading. This temperature can be determined by the load conditions, the winding design and the ambient oil temperature given by the cooling equipment. The heat transfer phenomena inside transformer windings are complex and presently there is no universal thermal winding model available. Changing boundary conditions and manufacturing tolerances influence analytic and numeric heat transfer calculations strongly. Many winding types, each with different cooling duct designs, are in use to meet customer requirements and to reach competitive design solutions. Uncertainties in thermal design calculations appear as safety margins and lead to additional material costs. The origin of deviations between measured and calculated temperatures are manufacturing tolerances in the final assembly, tolerances in parts procured from sub-suppliers, measuring tolerances and uncertainties in calculation algorithms and safety margins.

The goal of the experiments carried out is to minimize the deviations between measured and calculated temperatures in transformer windings

2 Winding types and cooling modes

A large variety of winding and cooling duct arrangements are used in power transformers. Generally the windings can be divided into disc type windings and layer windings. Table 1 shows all winding types which were considered separately to evaluate a function for the heat transfer coefficient of the boundary layer. All winding types were evaluated for natural convective cooling (ON) and forced directed cooling (OD).

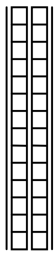
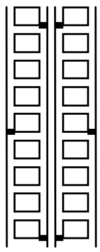
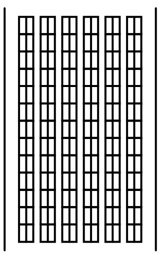
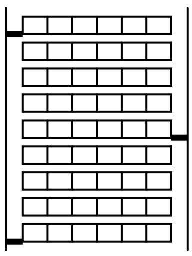
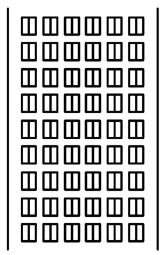
	axial	radial	axial+radial
layer windings			not considered
disc windings			

Table 1: Winding types and cooling duct arrangements

A general approach for all heat transfer calculations between winding and oil independent on the cooling mode and winding type is:

$$\Theta_{Cu\_Oil} = q_{th} \cdot \left(\frac{\delta}{\lambda} + \frac{1}{\alpha} \right) \tag{1}$$

q_{th} describes the effective heat flux density at the winding surface, δ is the thickness of the solid conductor insulation, λ is the specific thermal conductivity of the solid conductor insulation and α is the convective heat transfer coefficient (HTC) of the winding surface. The parameters q_{th}, δ and λ can be determined easily and with a high confidence. The HTC depends on the specific oil values like viscosity, density and expansion coefficient which are also temperature dependent.

3 HEAT TRANSFER COEFFICIENT

3.1. Variation with the heat density

A general theory dealing with the determination of natural convective heat transfer coefficients (HTC) between surface and fluid is given in the boundary layer similarity theory. Fundamental differences can be found between natural and forced convective heat transfer. The experimental research was mainly focused on the natural convective case. An application of this theory to forced convective cooling is described in [1].

The fundamental approach is the correlation between the convection HTC (α) and the Nusselt number (Nu), [2].

$$\alpha = \frac{\lambda\, Nu}{L_c} \tag{2}$$

L_c denotes a characteristic length which depends on the geometry of the surface. In case of natural convection the Nusselt number is expressed as a function of the Rayleigh number. For practical problems it is applied as:

$$Nu = C_0 \cdot Ra^m . \tag{3}$$

The coefficients C_0 and m depend on the geometry and are defined based on experimental results measured in a “similar” configuration. In transformer windings it is assumed that the surfaces are loaded with a constant heat flux density q_{th}. In this case the Raleigh number can be modified.

$$Ra = \frac{g\, \beta\, q_s\, L_c{}^4}{\lambda\, \nu\, a} . \tag{4}$$

ν	kinematic viscosity (m^2 / s)
a	thermal diffusivity (m^2 / s)
g	gravity acceleration constant (9.81 m / s^2)
β	volumetric thermal expansion coefficient (K^{-1})
λ	thermal conductivity (W / (m K))

Table 2: Fluid parameters.

All fluid parameters are calculated for the mean value of the surface temperature and the oil temperature inside the cooling duct. The best comparable geometry for windings which is described in the general heat transfer theory is a configuration with vertical ducts. The characteristic size of a cooling duct is its width (w) [3]. Equation (3) can be written as:

$$Nu = C_0 \cdot Ra^{m} \cdot \left(\frac{w}{L}\right)^{m} \qquad (5)$$

L represents the radial length of the cooling duct. The ratio w/L can be considered as a correction factor taking into account different geometrical proportions of the investigated winding type.

For HTC calculations in this clause a simplified approach is used:

$$\alpha(q_S) = C \cdot q_S{}^{n} \qquad (6)$$

The coefficients C and n were evaluated from measured HTC using a least square method. The experiments were made on an ON-cooled disc winding with oil guiding elements and radial cooling ducts. Fig. 1 shows the cross section of the investigated winding and the winding equipped with a number of PT100 sensors in order to measure local temperatures. The design data are listed in Table 3.

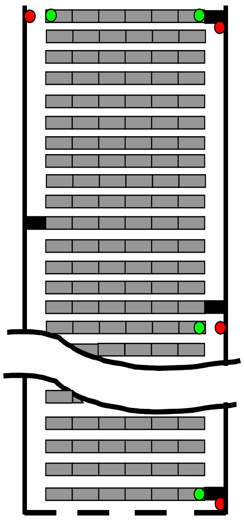


Fig. 1a: Schematic cross section of the investigated winding

Fig. 1b: Winding equipped with sensors for local temperature measurements.

conductor dimensions axial x radial	6 mm x 3 mm
number of turns per disk (disk dimensions 31 mm x 8.05 mm with paper insulation)	6
inner diameter of the disk	322 mm
axial distance between the disks (height of the radial cooling duct)	5 mm
number of disks	62
height of the winding	827 mm
oil guiding elements at the inner axial duct (discs numbered from bottom to top)	12, 32, 42, 52
oil guiding elements at the outer axial duct	1, 22, 38, 48, 62
axial cooling ducts inside the winding	0

Table 3: Design data of the investigated winding.

The HTC results for four heat flux densities are shown in Fig. 2. The values of the coefficients in equation (6) are calculated to C = 8.202 and n = 0.458.

Fig. 2 shows a strong dependency of the HTC on the heat flux density. This result is based on the temperature dependency of the oil driving force responsible for the convective heat transfer expressed by the Rayleigh number.

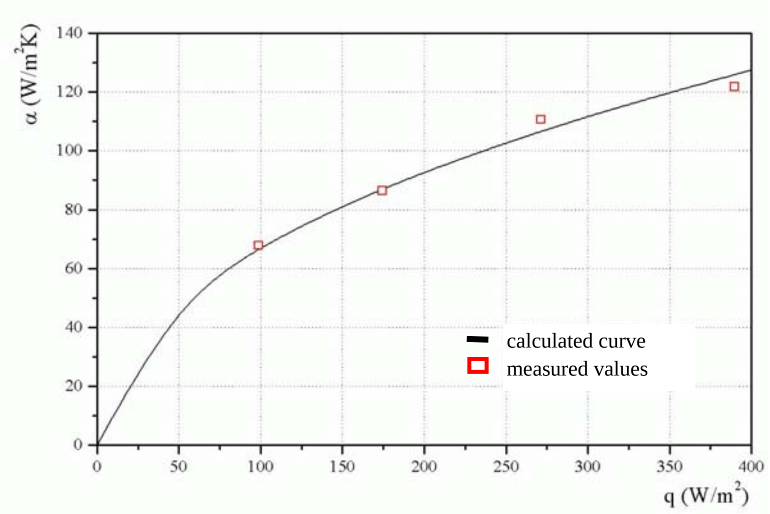


Fig. 2: HTC as a function of heat flux density for maximum oil entrance cross sectional area of S_0 = 3927 mm^2

3.2. Influence of the hydraulic resistance on the HTC

It is known from design and manufacturing practice that the thermal behaviour of similar windings installed in different transformers may be different. This phenomenon appears in ON-cooled EHV windings. One reason is the difference in the windings insulation level. A series of experiments have been carried out on the same winding described in the previous section reducing the cross sectional area for the oil entrance. By this way a variable hydraulic resistance of the winding support was simulated.

In Fig. 3 the HTC values for different oil entrance cross sectional areas are shown. The cross section for the oil entrance has been reduced down to approximately 10 %, 20 % and 30 % of the original cross section of 3927 mm^2 (S_0). It is obvious that for the same heat flux density but increased hydraulic resistance the HTC is reduced. This result is caused by a minor oil velocity in the cooling ducts due to an increased hydraulic resistance leading to reduced oil mass and heat transfer through the entire winding.

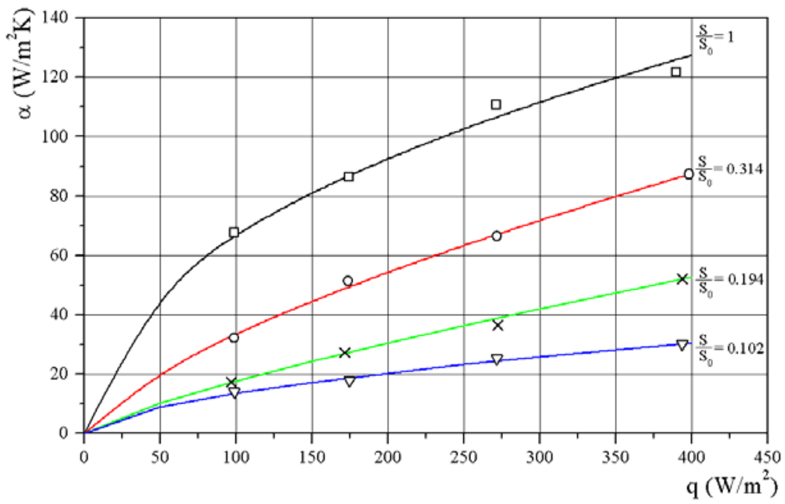


Fig. 3: HTC for oil entrance cross sectional areas of 10.2%, 19.4% and 31.4% of the maximum oil entrance cross sectional area of 3927 mm^2.

Another evaluation of the HTC is shown in Fig. 4. On the abscissa the oil entrance cross sectional area in per cent of the maximum value of 3927 mm^2 is given. On the ordinate the ratio of the measured HTC for the reduced oil entrance and the related HTC obtained from the measurements depicted in Fig. 3 is shown for each of the four examined heat flux densities.

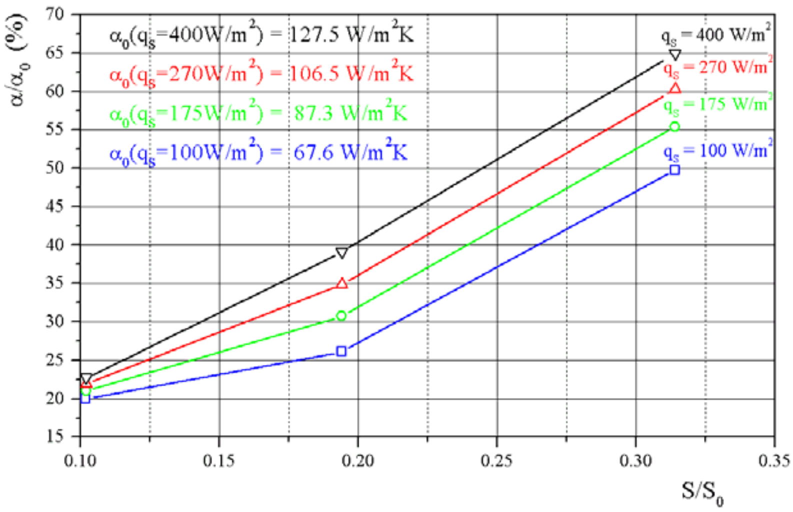


Fig. 4: Relative HTC depending on the oil entrance cross sectional area and the heat flux density.

In Table 4 the values of the coefficients *C* and *n*, stated in equation (6), for all four oil entrance cross sections are given.

S/S_0	1.0	0.314	0.194	0.102
C	8.202	1.439	0.477	0.922
n	0.458	0.686	0.785	0.585

Table 4: Calculated coefficients *C* and *n*.

4. AXIAL OIL TEMPERATURE GRADIENT

Another important design value is the axial temperature gradient of the oil inside the winding. The importance of this temperature gradient is clear since the average copper temperature is equal to the sum of average oil temperature plus the gradient copper to oil influenced by the HTC.

In Fig. 5 the top oil temperature is represented by the temperature of the measured top oil temperature in the tank. In Fig. 6 instead of the directly measured top oil temperature the vertical oil temperature gradient is calculated using the temperature gradient of the oil at the middle position of the winding.

The curves depicted in Fig. 5 show that the analysis with the directly measured top oil temperature delivers only vague conclusions whereas the results with the measured oil temperature in the middle of the winding, shown in Fig. 6, provide a clear significance between an increased longitudinal oil temperature gradient and an increased hydraulic resistance, i.e. reduced oil flow through the winding. The differences between the results obtained from the different top oil temperature determination are obvious since the directly measured one represents a mixed temperature of the hot oil streaming out of the winding and the surrounding top tank oil of lower temperature.

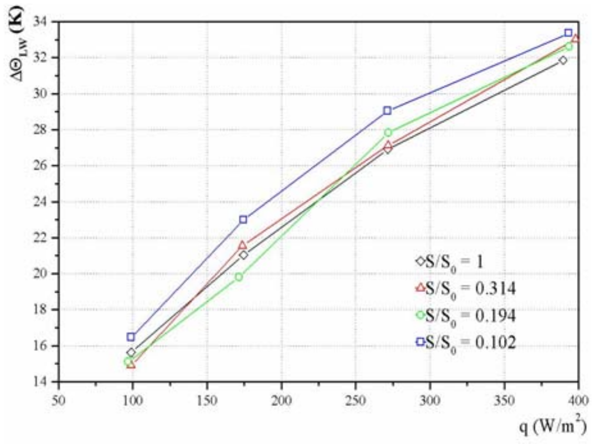


Fig. 5: Vertical oil temperature gradient inside the winding, calculated with the top oil temperature in the tank.

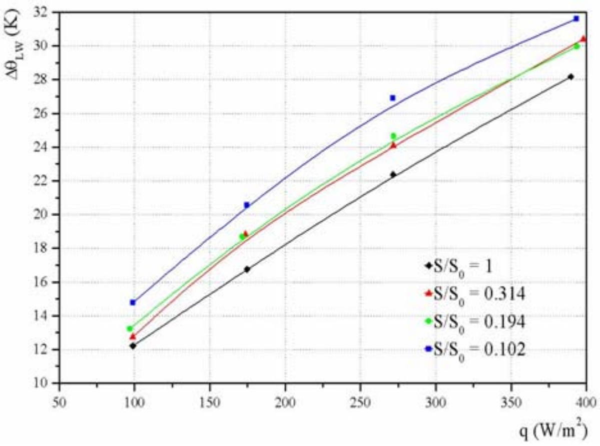


Fig. 6: Vertical oil temperature gradient inside the winding, calculated through the oil temperature in the middle of the winding.

In [4] this problem is pointed out and consequently the procedure evaluating the oil temperature in the middle of the winding seems to be more credible as validated in Fig. 6.

5. HEAT TRANSFER COEFFICIENT FUNCTIONS

For the variety of the winding geometries shown in Table 1 HTC functions were extracted from a number of heat run tests. More general approaches were used in order to get similar equations for all winding types.

5.1 General approach

Two different approaches are necessary for forced convective and natural convective cooling.

natural convective cooling (ON)

$$Nu = C \cdot (Gr \cdot \mathrm{Pr})^m \cdot k$$

forced convective cooling (OD)

$$Nu = C \cdot (\mathrm{Re} \cdot \mathrm{Pr})^m \cdot k$$

The parameters C and m are evaluated from a data set of temperature measurements in windings of different geometries but of the same winding and cooling type. The correction factor *k* takes into account additional dimensions of the winding geometry. It is necessary if more than one geometrical length is influencing the winding HTC.

winding type	forced convective cooling		natural convective cooling	
	C	m	C	m
Layer winding, axial	0,834	0,213	9,05	0,61
layer winding, radial	0,834	0,213	8,152	0,191
disc winding, radial	0,834	0,213	8,152	0,191
disc winding axial	0,61	0,210	9,05	0,61
disc winding axial + radial	0,0148	0,47	0,262	0,346

Table 5: Parameters for HTC functions

The total uncertainty caused by all the influences mentioned above is in the range of 3-5 K depending on the winding and cooling type. Experiences with heat run tests at identical transformers of one series or comparisons between the phases of three phase units show that this is a sufficient calculation accuracy compared to the remaining tolerances.

6. CONCLUSIONS

The related theory and procedure to establish a function for HTC calculation is shown. One of the major factors for the universal application of the functional dependencies is the hydraulic resistance of the whole oil circulation path. Therefore, the experimental research takes into account variable hydraulic resistances, simulated by changing the cross sectional area of the oil entrance to the winding. Both important factors are analysed: HTC and vertical oil temperature gradient inside the winding. The experimental results are discussed and the applicability in design practice of windings is emphasised.

Various winding types are used in power transformer design. Each winding type has a typical cooling duct arrangement. The thermal characteristic of each winding type needs to be considered separately for each cooling mode. Based on heat run test evaluations HTC functions for all different winding types and cooling modes were extracted.

8. LITERATURE:

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