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An Efficient Procedure for Temperature Calculation of High Current Leads in Large Power Transformers

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ABSTRACT This article presents an efficient methodology for calculating the steady-state temperature of high current busbar leads (HCBL) oil-immersed in large power transformers. The temperature at the surface of the copper HCBL is mainly affected by the Joule effect caused by the passing current, the paper insulation, the top oil temperature rise, and the ambient temperature. The Power Transformer Manufacturers usually follow their proprietary technical specifications for HCBL design in the absence of normalization, and customers would request guidance for temperature calculations independently of proprietary techniques. To date, there is a lack in the literature for this purpose. The method allows calculating the temperature on the HCBL as a function of the parameters already mentioned being flexible because it allows change of the parameters. The method is based on calculating the convection heat transfer coefficient (h), which in turn depends on the geometry factors and cooling system characteristics. The parameter (h) is of major importance and play the primary role during temperature calculation, once the desired temperatures are susceptible to its value and accuracy. Other relevant factors such as the skin and proximity effect are determined by the Finite Element Method (FEM). To validate the proposed method's accuracy, we did measurements using the T2TM Fiber Optic Temperature Sensor from NEOPTIX on a 460 MVA Transformer, running the heating test at 100% of load during 72 hours, yielding satisfactory results. The method is also compared with the winding gradient, which is usually used to estimate the top's conductor temperature.

INDEX TERMS Power transformers, busbar leads dimension, temperature analysis, transformer design.

I. INTRODUCTION

This article presents a method to determine the temperature of HCBL in Power Transformers. These HCBLs are widespread in Generate Step-Up (GSU) and Industrial Transformers.

The correct temperature calculation allows customers to verify the design under different conditions and to monitory possible heat sources to avoid undesired hot-spot region and, consequently, thermal failures.

There are several works developing methods for thermal models in power transformers. Most of those methodologies focus on calculating and controlling the hot-spot temperature since it is considered crucial in determining the power transformer lifetime. Besides, an accurate thermal model allows a compact size design, defines its nominal rate and life expectancy [1]–[18].

Besides that, there are standards for hot spot predictions as well, reflected in the ANSI IEEE Std C57 series [19] and IEC 60076-7 Loading Guide [20].

However, although several techniques have been proposed in the literature, there is little information on oil immersed HCBL design. Overlooking the importance of HCBL is letting out of monitoring a possible and difficult to detect heat point. Internal hidden heat points have been related to HCBL due to bad contact or bad dimension. However, In the case of a hidden heat point on the HCBL, it would not be easy to

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detect it, neither with standard tests nor gas analysis, because this temperature would be high but not high enough to create gases.

Available literature is related to external leads. For instance, in [21], the thermal model for not oil-immersed cooper leads has been addressed. Another extensive guide for external busbar design can be found in [22]. In [23] a cylindrical leads is designed based on heat transfer theory, but skin and proximity effect as well as rectangular sections are not addressed. In [24], the minimization of induced losses by optimizing the leads routing is proposed, while in [25], a method for eddy current losses minimization caused by high current leads is presented.

Usually, to know the conductor temperature at the top of the transformer, the calculation is simplified by calculating the gradient. That is the rise of average winding temperature above average oil temperature. This value is added to the winding's top oil temperature to know the temperature at the surface of the leads [13].

Manufacturers usually follow their own technical standards. However, checking these standards from a local manufacturer, several factors such as the skin and proximity are not taken into account, and empirical convection heat transfer (h) is employed for design. For instance, for vertical leads, a coefficient around $h = 100$ and $h = 50$ for horizontal leads. This study expands the bus-bar temperature calculation in [23], and heat transfer theory [26].

The contribution of this work is the proposal of a method for the HCBL temperature calculation, based on the computation of the convection heat transfer coefficient of the oil-immersed conductor.

To find the HCBL temperature, the calculation of the dimensionless numbers are proposed, such as the Prandtl, Rayleigh, Grashof, and Nusselt numbers considering natural convection. To get an estimate of the HCBL temperature, we did measurement by installing robust Fiber optic temperature probes.

The experimental results show the validity of the proposed method. We also compare the proposed method with the temperature estimated using empirical convection heat transfer and adding the top oil temperature to the average winding temperature.

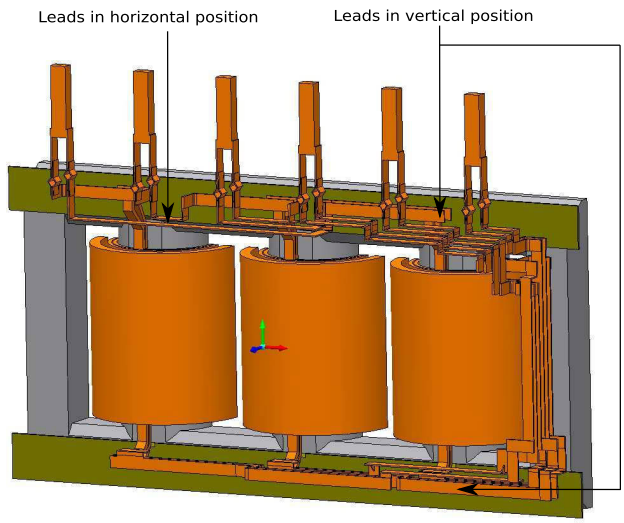

FIGURE 1. Low voltage internal cooper HCBLs.

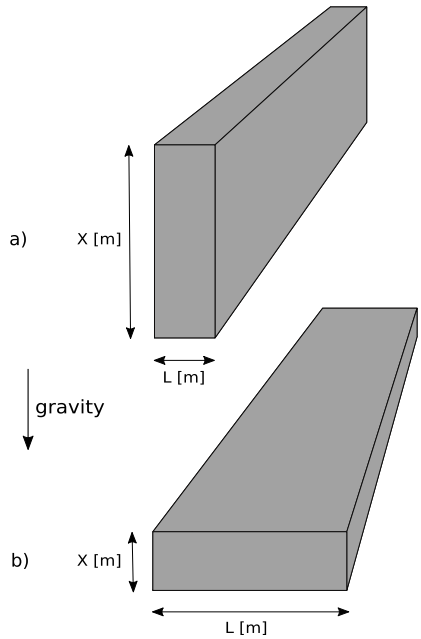

FIGURE 2. Dimension of the high current leads in a) Vertical and b) Horizontal Position.

II. ANALYSIS AND METHODOLOGY

This work aims to calculate the temperature at the surface of the HCBL for large power transformers. The methodology can also be used to calculate the conductor section thickness ($X[m]$) of the HCBL cross-section as a function of a final objective steady-state temperature of the leads for rated passing current. It could be calculated as a function of the section length (L) as well, but it will depend on whether the thickness or length is standardized as a copper provision for manufacturers. Fig 1 shows the internal HCBL leads that are in both vertical and horizontal positions, while Fig 2 shows the section of the HCBL leads for both positions.

The final absolute temperature of the conductor leads is the sum of the rises temperatures of the conductor itself, dissipating heat (ΔT_{cu}), the paper cover (ΔT_{pc}), the top oil (ΔT_{to}), and finally, the ambient air temperature (T_a). That is:

$$T_{cu} = \Delta T_{cu} + \Delta T_{to} + \Delta T_{pc} + T_a \tag{1}$$

The steady-state temperature is defined as the stabilized temperature after reaching thermal equilibrium. The steady-state temperature rise of the HCBL due to the passing current ($\frac{dI}{dt} = 0$) is:

$$\Delta T = \frac{Q}{Ah} = \frac{I^2 R_{cu}}{Ah} \tag{2}$$

where:

- h: Convective heat transfer coefficient $[W/(m^2K)]$
- Q: Losses by Joule effect $[W]$
- A: Cross section area of cthe conductor leads $[m^2]$
- I: Rated current$[A]$
- R_{cu}: Cooper Resistance $[\Omega]$

The convective heat transfer h can be found by the Nusselt number (Nu) related to the convection and conduction heat transfer across the boundary. Both convection and conduction transfer must be measured under the same conditions.It should be noted that despite the transformer has ODAF, this system is only for the core and winding, so the HCBL is outside the hydraulic circuit and has to be treated as natural convection. The Nusselt number for natural convection is:

$$Nu = \frac{hL}{k_f} \therefore h = \frac{k_f Nu}{L} \tag{3}$$

where:

- k_f: Thermal conductivity of the fluid (oil) $[W/(mK)]$
- L: Characteristic length (perpendicular to the fluid) $[m]$

On the other hand, the Nusselt number can be found as a function of the Rayleigh (Ra) and Prandtl number (Pr).

For vertical isotherm surfaces, applicable to Busbars ($Ra < 10^9$), according to [26], [27], the Nusselt number is:

$$Nu = 0.68 + \frac{0.67Ra^{\frac{1}{4}}}{\left(1 + (\frac{0.492}{Pr})^{\frac{9}{16}}\right)^{\frac{4}{9}}} \tag{4}$$

For calculating the Rayleigh number and Prandtl numbers, the following formulas can be used:

$$Ra = GrPr = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{5}$$

$$Pr = \frac{c_p\mu}{k_f} = \frac{c_p\sigma\nu}{k_f} \tag{6}$$

where:

- Gr: Grashof number $[m/s^2]$
- g: Gravity of earth $[m/s^2]$
- α: Thermal diffusivity $[m^2/s]$
- ν: Kinematic viscosity $[m^2/s]$
- β: Volumetric thermal expansion coefficient $[°C^{-1}]$
- L: Length $[m]$
- μ: Dynamic viscosity $[N \cdot s/m^2]$
- cp: Specific heat $[J/kg \cdot° K]$
- σ: Oil density $[kg/m^3]$
- T_{cu}: Temperature of the cooper lead surface $[°C]$
- T_∞: Quiescent temperature $[°C]$

A. INFLUENCE OF PAPER COVER

When the HCBL is under high voltage, electrical insulation should be needed by wrapping some kraft paper layers around the bars. The insulation is a significant factor because of the thicker the insulation layer, the lower the heat dissipation. The steady-state temperature rise due to the paper layer covering the HCBL is:

$$\Delta T_{pc} = \frac{Q \cdot e}{A \cdot k_p}$$

$$A = 2(X + L) \tag{7}$$

where:

- Q: Losses $[W]$
- A: Cooling area (Perimeter x 1 meter long) $[m]$
- e: Paper thickness $[m]$
- X: Busbar Thickness $[m]$
- k_p: Paper thermal conductivity $[W/(m \cdot° K)]$

The cooling area of the HCBL A is standardized for 1 meter long.

B. TEMPERATURE DEPENDENT PARAMETERS

Some parameters are temperature dependent, as listed below:

$$R_{cu} = \frac{\rho_{cu}[1 + [\alpha_{cu}(T_{cu} - 20°C)]]}{LX} f_s f_p f_d \tag{8}$$

where:

- α_{cu}: Correction resistivity coefficient $[°C^{-1}]$
- ρ_{cu}: Cooper resistivity at $20°C$ $[\omega/m]$
- fs: Skin factor
- fp: Proximity factor
- fd: Leakage flux factor

The physical properties of mineral oil, such as the density (σ), specific heat (cp), thermal conductivity (k_f), and kinematic viscosity (ν), were fitted as a function of temperature according to the tables taken from [28]. See Fig 3 and 4.

$$\sigma = -1E^{-10}T^6 + 2E^{-8}T^5 - 1E^{-6}T^4 - 1E^{-5}T^3 + \ldots\ldots 0.0016T^2 - 0.5873T + 892.93 \tag{9}$$

$$c_p = 8E^{-10}T^6 - 2E^{-7}T^5 + 2E^{-5}T^4 - 5E^{-4}T^3 + \ldots\ldots 2E^{-4}T^2 + 4.352T + 1762.7 \tag{10}$$

$$k_f = 6E^{-15}T^6 - 1E^{-12}T^5 + 8E^{-11}T^4 - 3E^{-10}T^3 - \ldots\ldots 8E^{-8}T^2 - 8E^{-5}T + 0.133 \tag{11}$$

$$\nu = 7847.5T^{-1.7147}10^6 \tag{12}$$

C. SKIN, PROXIMITY AND LEAKAGE FLUX FACTORS

The three factors play an essential role in calculating the copper resistance (R_{cu}) as a function of temperature. The calculation of these three factors was done using a Finite Element Method (FEM) based program. For the skin factor (f_s), we did a linear regression for various possible thicknesses ($X[mm]$) of the HCBL at 50 and 60 Hz, as shown in Fig. 5. For 60 Hz, the linear regression yields:

$$f_s = 0.97 + 0.029643X \tag{13}$$

The proximity (f_p) and the winding leakage factors remain constant since it is the same separation between HCBLs. Fig. 6 and 7 show the current density calculation influenced by the skin and proximity factors for a HCBL section of $L = 154mm * X = 16mm$.

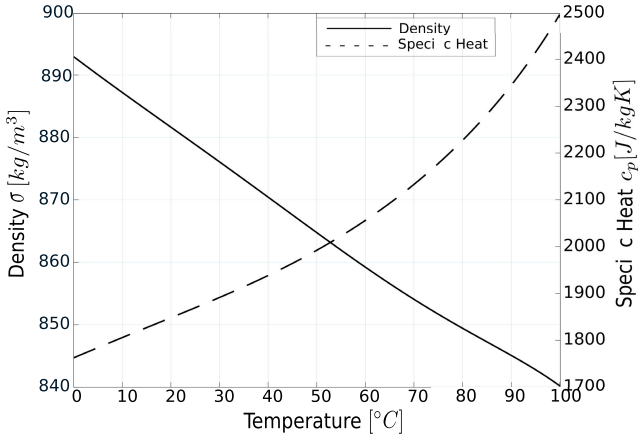

FIGURE 3. Density and specific heat as a function of Temperature.

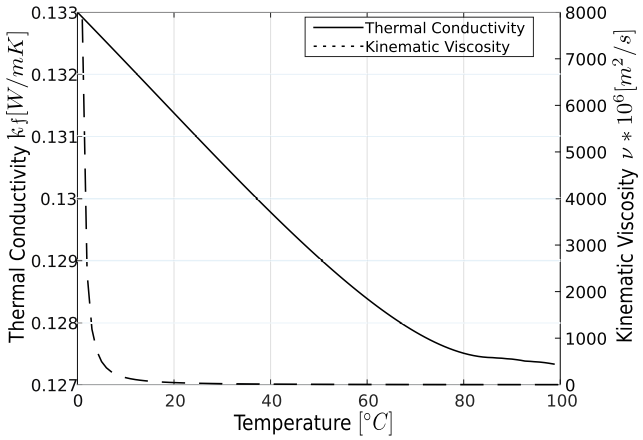

FIGURE 4. Thermal conductivity and kinematic viscosity as a function of temperature.

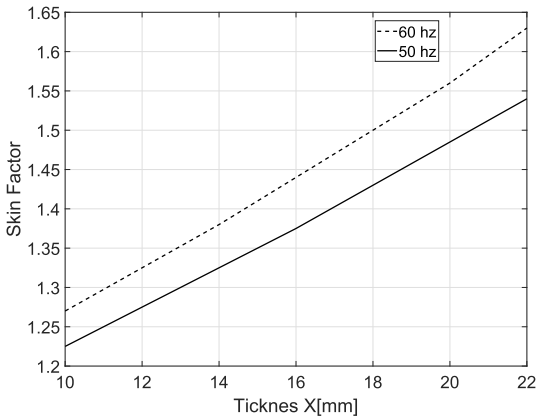

FIGURE 5. Skin factor in function of thickness and frequency.

D. SOLVING MODEL

The system of equations are sort as follows:

$$\begin{cases} \dfrac{hL}{k_f} - \left(Nu = 0.68 + \dfrac{0.67\, Ra^{\frac{1}{4}}}{\left(1 + (\frac{0.492}{Pr})^{\frac{9}{16}}\right)^{\frac{4}{9}}} \right) = 0 \\ x_1 + x_2 - \dfrac{Q}{Ah} - \dfrac{Qe}{Ak_p} = 0 \end{cases} \tag{14}$$

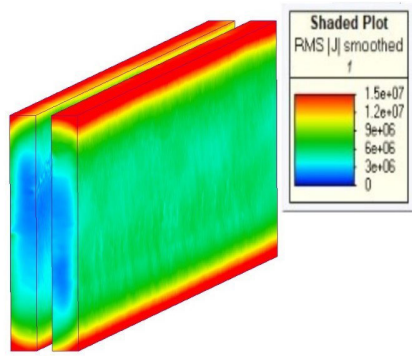

FIGURE 6. Current density in the HCBL lead due to the skin and proximity effect.

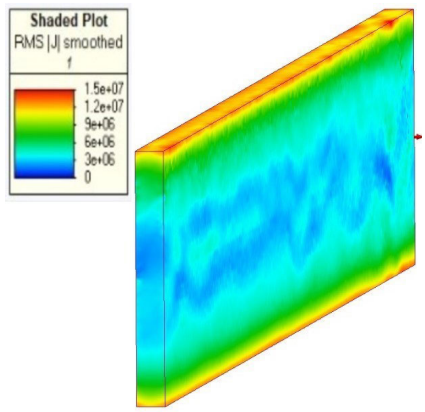

FIGURE 7. HCBL current density due to the skin effect.

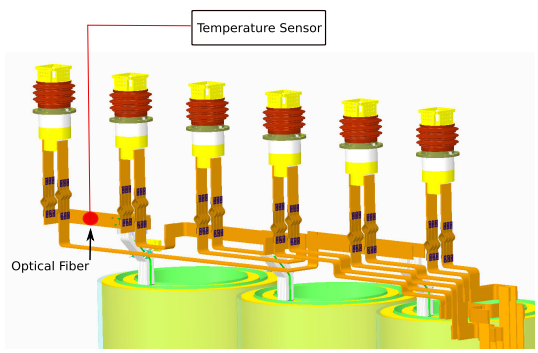

FIGURE 8. Position of optical fibers.

where all the variables are as a function of the final temperature at the copper surface ($T = \Delta T_{cu} + \Delta T_{to} + \Delta T_{pc} + T_a$), which in turns depends on the copper temperature rise ($\Delta T_{cu} = x_1$) and the temperature rise due to the paper cover ($\Delta T_{pc} = x_2$). The system can be solved by any Newton method guaranteeing a quadratic convergence.

III. STUDY CASE AND COMPARISON WITH MEASUREMENTS

We tested the methodology in the commissioning stage of a Power Transformer of 460 MVA, 13.2 kV low voltage, 60 Hz, and ODAF cooling system during 72 hours with 100% of the rated load (heat run test). The installed HCBL by the manufacturer had a section: $L = 152\ mm$ and $X = 16\ mm$.

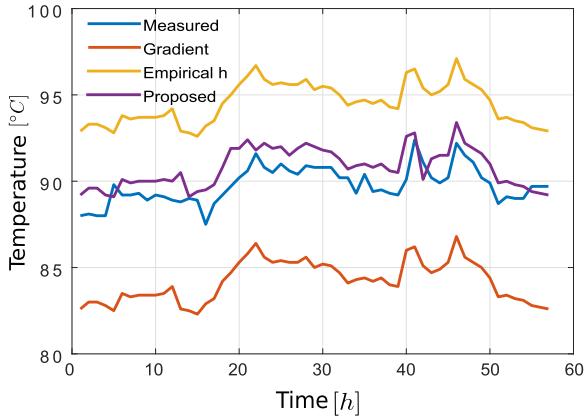

FIGURE 9. Comparison between methods and measured temperatures.

FIGURE 10. Equipment used for measurements.

The top oil temperature rise and all the heat test was done according to the standard IEEE C 57.12.90 [29]. To compare the real measured temperatures with the proposed method, we included two other ways used in industries for quick temperature checks:

- Empirical h: The manufacturer does not care about the precision of h. It uses a high empirical value for security. For comparison, we have used ($h = 50$) corresponding to horizontal leads.
- Gradient: A quick way to evaluate the surrounding HCBL temperature. It is simple because it considers that oil and bus bars are at the same temperature. Based on temperature rising measured from the winding block, it is a metric to predict the desired temperature.

All measurements were obtained in a controlled environment from a very reliable process during a heat-run test through 72 hours at nominal current after oil stabilization. The current was remained constant during the measurements, and the variation in the temperature varied only due to the ambient temperature. We did the calculation hourly fed by the temperature of the room. For the proposed method, the nonlinear system equations were coded and solved in MatLab. The optical fiber was installed, as shown in Fig. 8. The temperature sensor connected to the fiber was the model $T2^{TM}$ Fiber Optic from NEOPTIX, avoiding any external interference or electromagnetic noise during the measurement acquisition. The real power transformer and equipment are shown in Fig. 10.

Fig. 9 shows the comparison between the measured and calculated values for horizontal positioned HCBL, where the maximal error of the proposed method was around 0.78%, while the other methods presented errors above 5%. It should be noted that the design h yields values very high values due to the security margin design. The measured values were taken after having reached a steady-state temperature. The gradient method yielded lower temperatures because the amount of cooper mass between HCBL and winding could differ depending on the transformer. Winding and core heat the oil, so the oil bulk temperature change imposed by HCBL is not enough to reflect gradients. The calculation for horizontally positioned leads yielded higher temperatures than a vertically positioned. This is because depending on how the HCBL is installed, vertically or horizontally, $L > X$ or $X > L$, the heat transfer coefficients will undergo substantial changes (See eq. 3 where the calculation of the Nusselt number is directly related to L, the perpendicular length in relation to the fluid).

IV. CONCLUSION

We have presented an easy but accurate method to calculate the HCBL's surface temperature. The proposed method gives temperatures very close to real measurements. The temperature model behavior is presented by a nonlinear equation system that can be easily solved by any Newton-based method.

Looking to the other two approaches, its possible to see that the estimation by the gradient average winding temperature offers a good approximation as well, but in this case relies on real measured values, meaning that relying on analytical method could lead to a loss of accuracy.

The empirical method using a fixed h coefficient seems to be too conservative. The curves have a similar shape, but the y-axis shift reveals that a fixed h will lead to an erroneous evaluation of the phenomena. We are not judging h for design, but it is evident that it is not suitable for temperature calculation.

A worldwide manufacturer is employing the proposed methodology, which shows accurate results for predicting and

preventing hot spots into transformers with more than 100 m^3 of mineral oil. The analytical method avoids as far as possible a measurement, which implies a tough and expensive task during full operation in the field, especially during internal occurrences into the tank.

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