Journal of Energy

VOLUME 67 Number 3 | 2018 Special Issue

journal homepage: http://journalofenergy.com/

**R. SITAR**
**Ž. JANIĆ**

Končar - Electrical Engineering Institute
Siemens EM TR LPT GTC RES
Croatia

Končar Power Transformers - A joint Venture of Siemens AG and Končar d.d.
Croatia

# Determination of local losses and temperatures in power transformer tank

## SUMMARY

Paper presents research of local losses and temperature rise in transformer steel tank. First experimental method based on initial rate of rise of temperature is presented. This is a direct method for determining distribution of losses in transformer structural steel parts. Technique relies on the fact that after a body has settled at a steady state temperature and the internal heat source is suddenly removed or applied, the initial rate of temperature change at any point is proportional to heat input (loss density) at that point. To test applicability of sensors and instrument for the local loss measurement method, measurement system was tested on conductors (strips) and magnetic steel rings.

Second part of experimental work consisted of investigations on model for tank local overheating. The model consisted of excitation windings that were sources of magnetic field. Existence of three separate windings gave the possibility to change value and position of magnetic field source inside the tank. Local losses in the tank were evaluated by proposed method of initial rate of rise of temperature. Heat-run tests were made on the model and local temperatures on the tank were measured. Measured local losses and local temperatures were used for determining local heat transfer coefficients on tank – oil interface. It was concluded that heat transfer coefficients can be presented as function of heat flux from tank to oil.

Finally, temperatures in transformer tank were calculated by finite element method. Losses calculated by electromagnetic calculation represented heat sources in thermal numerical model. Heat transfer equations were solved in solid domain (tank) while cooling conditions were defined by heat transfer coefficients checked experimentally. Calculated temperatures were compared to measured temperatures and gave good agreement.

## KEYWORDS

Power transformer - coupled calculation - local overheating - heat transfer coefficient

## INTRODUCTION

When testing power transformers, total value of stray losses in steel structural parts can be challenging to determine. Stray losses represent only a smaller part of total losses in transformers. Furthermore, if stray losses are concentrated in small areas that are not properly cooled, local overheating can arise, causing transformer operation failure. Experimental research of this whole coupled electromagnetic-thermal behavior is very hard to make on a real transformer unit.

In order to verify and improve the parameters to be used in simulations a detailed research on local overheating in transformer steel parts on experimental models has been conducted. First part of the research was focused on stray magnetic field losses solely. Such work on losses in magnetic material has been elaborated in many papers [1], [2]. It consisted of experimental work and calculation in numerical tools that can be used for more complex geometries.

Second part was oriented on a geometry that is similar to configuration of power transformer tank - configuration most often submitted to local overheating in power transformer and easily detected by measurement with thermal IR cameras in test bays. Experiments were done in laboratory using the method developed in first part of research. In the end numerical tools were used to calculate temperature and compare calculated and measured temperature values. This made all stages of numerical modeling of real power transformers checked on an experiment.

## LOCAL LOSS MEASUREMENT

A possibility for determining local loss in constructional steel parts is to measure transient temperature-time curve and determine its initial slope. Example of determining the initial slope of a heated body is shown in Figure 1.

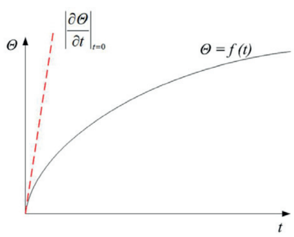


Figure 1. Principle of determining initial slope of a heating curve

The curve shown in Figure 1 can be mathematically expressed by heat diffusion equation

$$p = c\rho \frac{\partial \theta}{\partial t} + q \tag{1}$$

where $p$ is generated heat (power loss), ρ body temperature, $c$ thermal capacitance, Θ mass density and $q$ heat dissipated to surrounding regions. Surrounding regions to which heat dissipates are cold metal bodies (where generated heat is much lower than at the measurement point) and surrounding fluids (which cool the heated body by convection or radiation). Dissipated heat highly depends on temperature differences between the measurement point and surrounding regions. As temperatures of heated bodies grow dissipated heat from measurement points become higher and cause the initial straight line to turn into an exponential curve. So, if initial conditions consider all metal parts and the surrounding fluid at equal temperatures, for $t = 0$ it can be stated $q = 0$, and expression (1) can be written as

$$p = c\rho \left| \frac{\partial \theta}{\partial t} \right|_{t=0} \tag{2}$$

Therefore, heat loss at any point can be obtained by multiplying the initial rate of temperature rise, mass density and thermal capacitance of material under test. However, it is important to determine initial section where temperature-time curve can be considered as a straight line because of negligible heat dissipation. This will highly depend on how non-uniform power losses are in the body observed.

The first step when making a measurement system for local loss measurement method is to choose sensors for temperature measurements. The probes should be robust and have good thermal connection with the measurement point. Another important requirement is to be able to measure temperature instantly. Thus, sensors should have negligible heat capacity as recommended in [3]. To meet all of these requirements thermocouples were made from 0,08 mm thick constantan and copper wires. When working with AC power sources it is obligatory to twist the two wires together, so that AC pick-up in inductive loops of sensor leads is minimized.

The measurement junction was placed and fixed on a point where losses are to be measured, while the reference junction was inserted in a water bath at a stable and known temperature. The main disadvantage of thermocouples is that they have relatively weak signal. For example, copper-constantan (T-type) thermocouples have sensitivity of about 43 µV/°C. In order to detect temperature changes of 0,001 °C, a so-called nanovoltmeter with resolution of 1 nV was used. In order to test applicability of chosen sensors and instrument for the loss measurement method, measurement system was first tested on aluminium and copper strips. Thermocouple measurement junction was fixed in the middle of 1000 mm long copper and aluminium strips, as shown in Figure 2. Circuit breaker was used to apply a DC voltage source suddenly to the strips, while resistors were used to change current in the circuit.

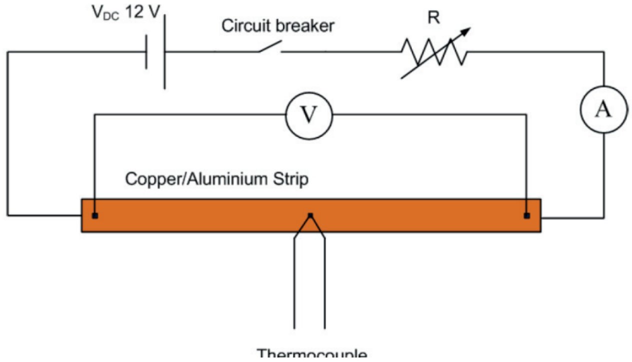


Figure 2. Measurement of losses on copper and aluminium strips

Initial rate of temperature rise was calculated from the temperature change in Δt = 1 s after the voltage source was applied. From measured temperature rise and expression (2) value of local losses in W/m$^3$ were evaluated. Specific heat capacity of copper was 385 J/kgK and of aluminium 890 J/kgK. Mass density of copper was 8940 kg/m$^3$ and of aluminium 2700 kg/m$^3$. At the same time current and voltage of tested conductors were measured. Total losses of conductors were evaluated by wattmeter and compared with results from the local loss measurement method in Table I.

Table I – Measured losses in copper and aluminium conductors

| Conductor | Current, A | Measured initial slope, °C/s | Total losses, W | Ratio (1)/(2) | |
|---|---|---|---|---|---|
| | | | Temperature-time method (1) | Wattmeter (2) | |
| Cu 1,0 x 15 mm$^2$ | 81,5 | 0,143 | 6,64 | 6,83 | 0,97 |
| Cu 5,6 x 4,0 mm$^2$ | 98,3 | 0,098 | 6,80 | 6,80 | 1,00 |
| Al 2,0 x 15 mm$^2$ | 80,8 | 0,088 | 5,71 | 5,51 | 1,04 |

Results from both measurement methods showed good agreement. Experiment has confirmed the suitability of thermocouples as sensors and nanovoltmeter as instrument for local power loss measurement.

Here it should be emphasized that losses that were measured were distributed uniformly inside the heated object (copper/aluminium conductors). This is not the case when losses are caused by eddy currents in thick magnetic materials. Due to small skin depth (from 1 to 3 mm) of magnetic steel parts, losses are localized in a thin layer at surface of a magnetic part. Cold metal interior cools the surface layer, making value of the dissipated heat from equation (1) substantial.

# EXPERIMENTAL RINGS

When heat sources are non-uniform, errors in measured losses will occur if the temperature rise being measured is not completed before appreciable heat diffuses to or from other parts of different temperatures. The errors in these cases can be estimated by experimental and numerical analysis of heat transfer on a simple geometry.

An experimental ring made of magnetic steel wound throughout its circumference with a copper conductor was considered as a model for evaluating possible measurement errors. Configuration is shown in Figure 3. Inner ring diameter $D_i$ was 325 mm, outer diameter $D_o$ 385 mm and thickness $b$ 8 mm. Coil wound around the ring was excited by a sinusoidal current source of frequency 50 Hz. Magnetic permeability of magnetic steel was modeled as a single-valued $B$-$H$ curve as in [4], while electrical conductivity was 6,56x10$^6$ S/m (value at 20 °C).

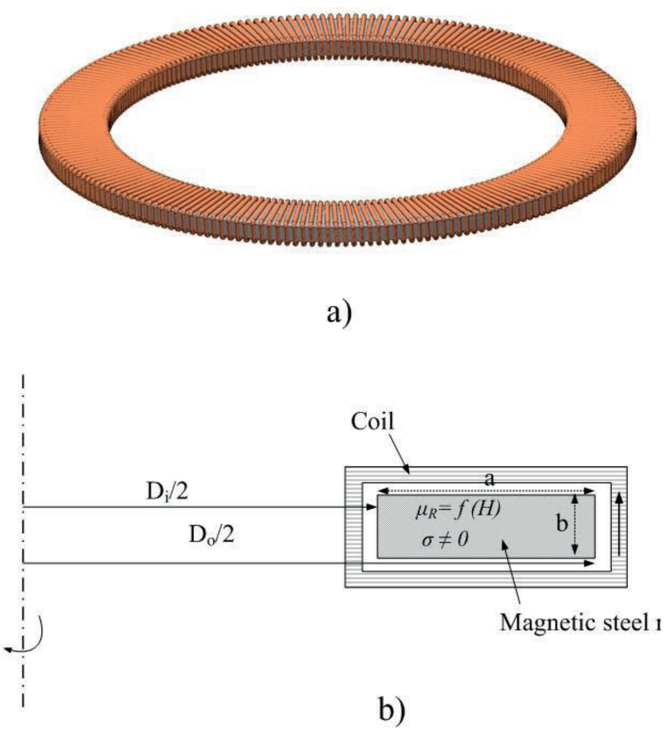


Figure 3. Experimental ring a) 3D view and b) 2D model with dimension description

Generally, depending on amount of magnetic flux penetrating into steel ring, loss distribution along skin depth varies. For 50 Hz sinusoidal source and stated material properties most of the losses are concentrated in 1 to 3 mm surface layer of steel [1]. Due to the fact that losses are not distributed uniformly along steel ring depth, problems in application of proposed local loss measurement method can occur.

Measurement results obtained by the method of initial rate of rise of temperature and wattmeter were compared to calculation results by numerical tool MagNet. Figure 4. shows comparison of total losses (W) and local surface losses (W/m²) to calculated losses obtained by nonlinear electromagnetic calculation.

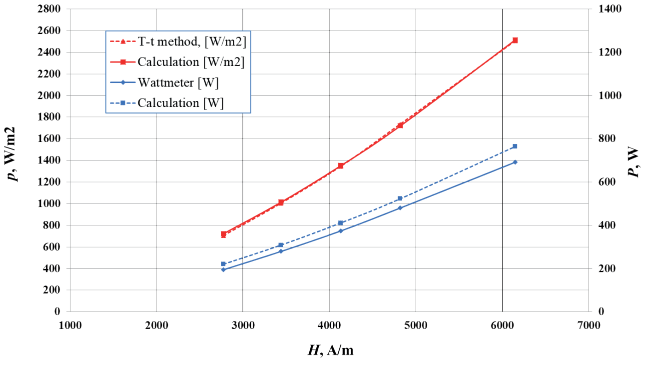


Figure 4. Comparison of loss measurement methods and calculation

It can be stated that nonlinear electromagnetic calculation by FEM can be used for estimation of local and total losses in nonlinear magnetic material. If only local surface losses are examined, difference of calculated and measured values on magnetic steel ring can be less than 3%. This leads to a conclusion of applicability of proposed local loss measurement method. Although losses are distributed non-uniformly along magnetic steel depth, surface local losses (W/m²) can be determined with high precision.

## MODEL FOR TANK LOCAL OVERHEATING

In order to investigate high local loss densities and consequent temperature rises a simple one phase experimental model was created. Steel tank was made of magnetic (carbon) steel, except one wider side that was made from nonmagnetic steel. For regulation of applied magnetic field model had three windings inside the tank that were concentric with separated leads. Magnetic flux would close through steel tank in such way that it would be highly localized and therefore could create temperature rises critical from perspective of power transformer operation. Also, a cooling system for the model was designed in such way that oil temperature inside the tank could be controlled and maintained at usual oil temperature in a power transformer. Experimental model is shown in Figure 5. Details of windings in experimental model are shown in Figure 6.

In order to determine local losses and temperatures on tank wall, thermocouples were installed on tank wall. Thermocouples on tank wall are shown in Figure 7. Such experimental model is used as a benchmark model for coupled electromagnetic-thermal numerical analysis.

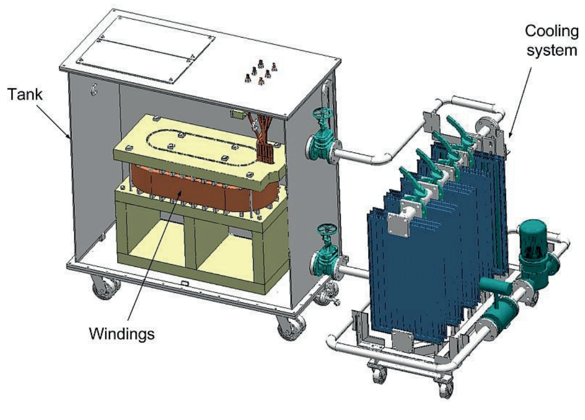


Figure 5. Experimental model for tank local overheating

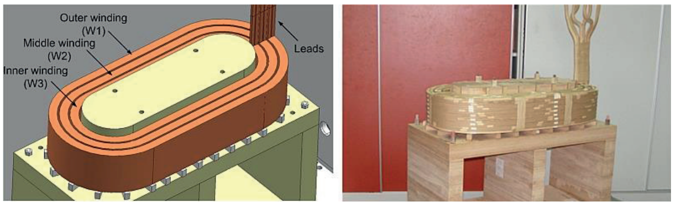


Figure 6. Windings used in experimental model

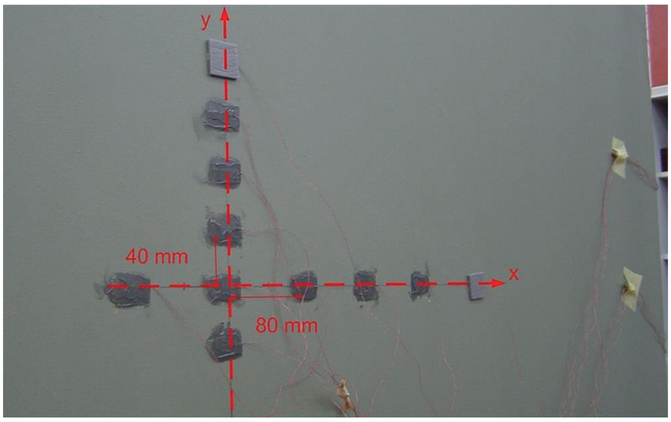


Figure 7. Thermocouples fixed on tank surface

## COUPLED ELECTROMAGNETIC-THERMAL MODELING IN FEM

Numerical calculation of losses in transformer steel tank is done in Infolytica's finite element software MagNet using the so-called time-harmonic solver. MagNet uses the edge element version of *T-Ω* method to solve Maxwell's equations and calculate losses in transformer metal parts. Calculation was performed at a single frequency (50 Hz) in complex domain with fields represented as phasors. Principles of the method are described in paper by Webb [5]. For the plate made from magnetic steel surface impedance boundary condition was used. No mesh was generated inside the plate, but the ratio of the tangential components of electric field $E_t$ and magnetic field $H_t$ was equal to the value of the surface impedance:

$$Z = \frac{E_t}{H_t} = \frac{1+j}{\delta\sigma} \tag{3}$$

where σ is electric conductivity of magnetic steel and δ skin depth:

$$\delta = \frac{1}{\sqrt{\pi f \mu\sigma}} \tag{4}$$

where *f* is the frequency and μ magnetic permeability of magnetic steel. For calculation of losses in nonmagnetic steel (one wider side of the tank) mesh was generated and calculated by expression

$$p = \int_V \frac{J^2}{\sigma} dV \tag{5}$$

For calculation of losses in magnetic steel electrical conductivity σ was 4,5x10⁶ S/m, while for nonmagnetic steel 1,3x10⁶ S/m (values for 75 °C). Nonlinear *B-H* curve was used for modeling magnetic permeability of magnetic steel. Nonlinearities in the MagNet models were handled by the Newton-Raphson linearization method. Although it was not theoretically correct to use nonlinear materials with phasor calculation, time-harmonic solvers could take into account saturation effects approximately. After losses were calculated, it was possible to conduct a temperature (heat transfer) FEM calculation. Local losses in the tank represented heat source in the heat transfer equation that was solved by Infolytica ThermNet software

$$-\nabla \cdot (k\nabla\theta) = p \quad (6)$$

where $k$ is thermal conductivity, $\Theta$ temperature, and $p$ power loss density. Value of thermal conductivity for magnetic steel was 40 W/mK and for nonmagnetic steel 20 W/mK. Cooling of metal parts was defined as a boundary condition on a surface in contact with the coolant (air/oil)

$$-\alpha(\theta - \theta_a) = k\frac{\partial\theta}{\partial n} \quad (7)$$

where $\alpha$ is the heat transfer coefficient and $\Theta_a$ ambient temperature. In short it can be stated that thermal computation was a conduction problem where convection was taken into accounted via heat transfer coefficients. In case of air-tank interface, heat transfer coefficient was given constant value 10 W/m$^2$K. However, dependence of heat transfer coefficients on heat flux is usually modeled using expression from literature. Such dependence is proposed in [6].

In this paper, availability of local losses and temperatures gave an opportunity to experimentally determine heat transfer coefficients and check such empirical expressions.

# EVALUATION OF HEAT TRANSFER COEFFICIENTS

Heat transfer coefficient is defined as heat flux at fluid-soil boundary divided with temperature rise of solid above fluid:

$$\alpha = \frac{q_{oil}}{\Delta\theta} \quad (8)$$

Temperatures rise can be measured with thermocouples while heat flux $q$ is more complicated to determine. With the initial rate of temperature rise method local losses were determined according to Figure 8:

$$P = \oiint_{\Delta V} q dS \quad (9)$$

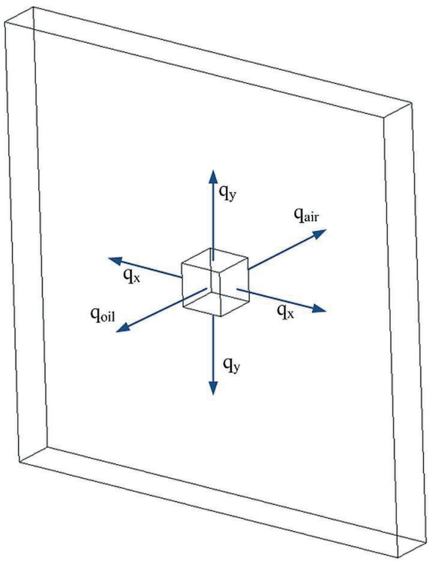


Figure 8. Heat transfer in steel wall at measurement point

Heat flux $q_{oil}$ is only one part of generated heat (losses) $p$ at measurement point. Therefore in order to evaluate local heat transfer coefficients from measured local losses it is important to check impact of local conditions and parameters at measurement location. In thermal stagnation there are high differences in tank temperatures where local overheating is taking place. To take into account this local heat transfer to surroundings ($q_x$, $q_y$, $q_{air}$), numerical model of tank was made. By calculating temperatures for different loss and $\alpha$ values, family of curves for determination of local heat transfer coefficients was created. Such curve family is shown in Figure 9.

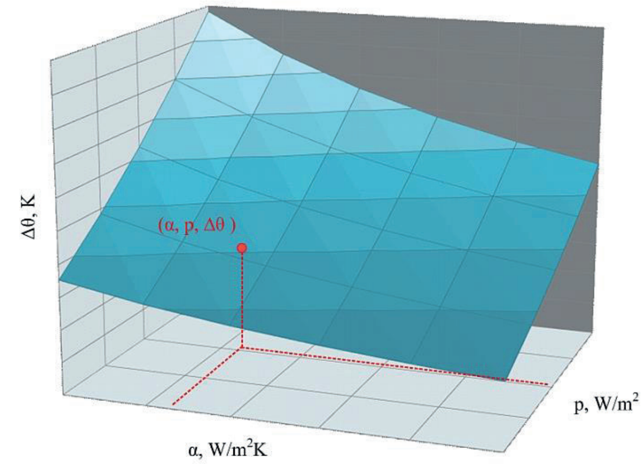


Figure 9. Family of curves for determination of heat transfer coefficients from measured losses p and temperature rise $\Delta\Theta$

Heat transfer coefficients for measured cases of local losses and temperatures on nonmagnetic and magnetic steel tank were determined. Obtained heat transfer coefficient values were compared to analytical expression according to literature [6]. Comparison is shown in Figure 10.

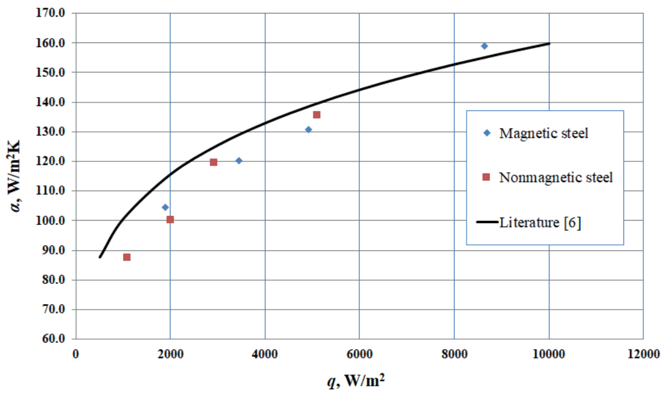


Figure 10. Comparison of experimentally determined heat transfer coefficients to empirical expressions

Differences were up to 15 %. It is important to note that heat transfer coefficients do not depend on steel type – magnetic or nonmagnetic. Experimental analysis on the benchmark model has shown that it is justified to use empirical expressions as in [6] for modeling of heat transfer coefficients.

# TEMPERATURE MEASUREMENT VS CALCULATION

## A - EXPERIMENTAL MODEL

Described modeling approach is used for calculation of losses on the experimental model. Figure 11. gives the comparison. All three windings of the model were connected in series and supplied with 250 A. This created high local losses in the middle of the tank causing high local temperatures. Temperature measurements with IR camera FLIR 460 were performed and compared to calculation. Emissivity for measurements with IR camera was set to 0.95. Difference between calculated and measured temperatures on magnetic side of the tank are not higher than 3 K.

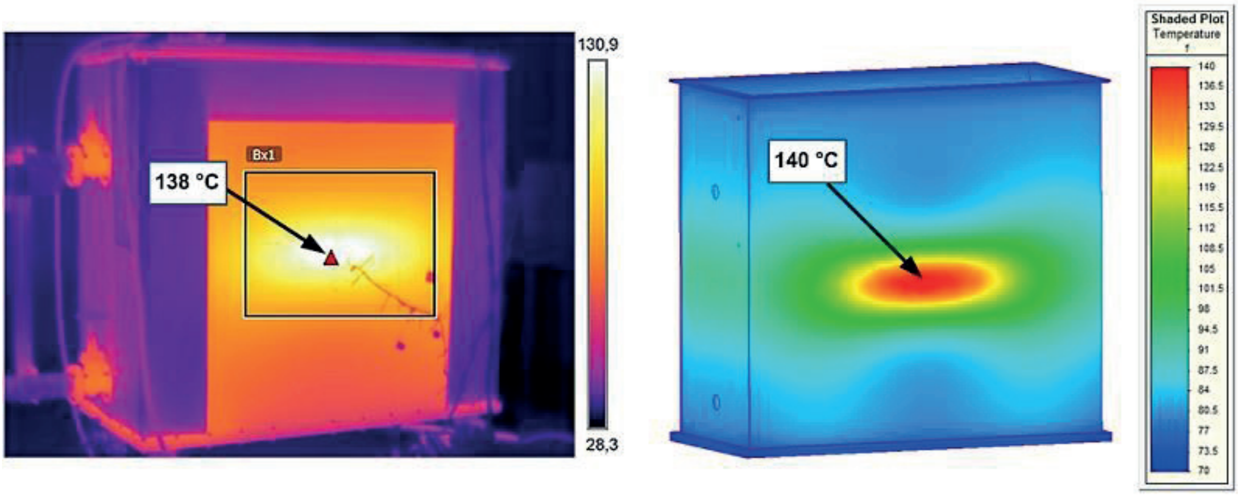


Figure 11. Comparison of measured and calculated temperatures on experimental model

B - 280 MVA THREE PHASE TRANSFORMER

Modeling approach is also checked on a real three-phase transformer. On a 280 MVA three phase transformer unit measurement of tank temperatures were made during heat run test. Phase current on LV side was 5,2 kA. Both winding and LV leads were modeled. Including leads in a transformer model made the model very demanding as the number of elements increase and computational time increases drastically. In this paper tank was modeled without additional details what made calculation results not fully accurate but comparable to a real transformer. It should be pointed out that tank magnetic shield on tank wall were also considered in this case. In Figure 12. measured temperatures by IR camera in the test bay are shown and compared to calculation. Temperature distribution fits very well with the measurements. Hotspots on tank are located correctly. Calculated hotspot value is 102 °C while measured 103 °C.

# CONCLUSION

Reliable measurement for verification of numerical software is very hard to make on real transformer units. In case of stray losses it is not easy to extract measured stray losses from total losses. In order to have reliable loss measurements and consequent temperature rises on configurations such as transformer tank, it is easier to make investigations on an experimental model. Local losses were measured using special method based on initial rate of rise of temperature. Method was tested on simple configurations (models) before it was successfully employed on a configuration of transformer steel tank. Using such technique tank local losses and temperature rises were measured on an experimental model and heat transfer coefficients were determined.

Heat transfer coefficients were used in coupled electromagnetic-thermal numerical model. Numerical calculation of experimental model and real three phase transformer showed good agreement with measurements. Therefore presented research in the paper has give a reliable modeling method for tank temperature determination.

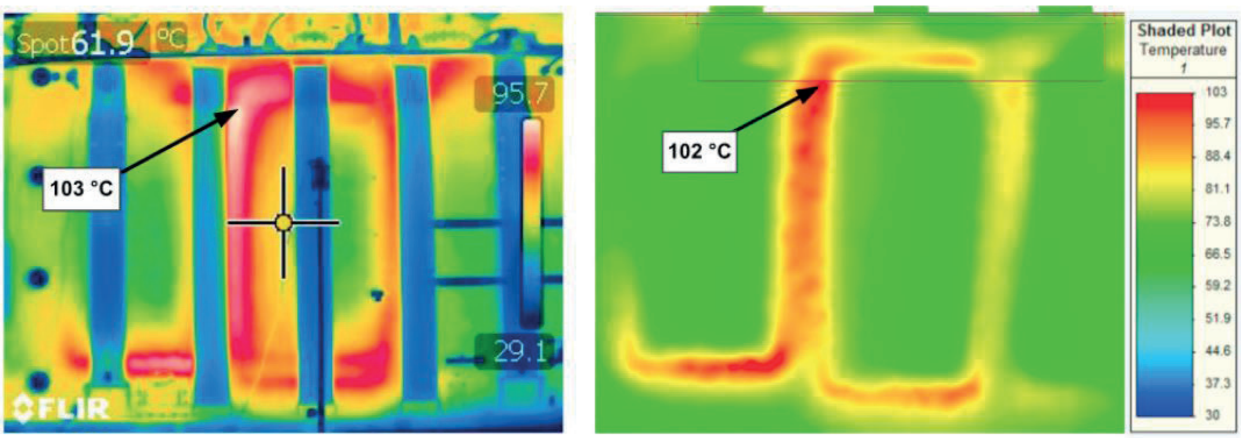


Figure 12. Comparison of measured and calculated temperatures on three-phase transformer

# BIBLIOGRAPHY


[1] N. Niewierowicz, J. Turowski, "New thermometric method of measuring power losses in solid metal elements", Proc. IEE Vol 119, No. 5, May 1972.

[2] H. Hamzehbahmani, A. J. Moses, F. J. Anayi, "Opportunities and Precautions in Measurement of Power Loss in Electrical Steel Laminations Using the Initial Rate of Rise of Temperature Method", IEEE Transactions on Power Delivery, vol 29., no. 2, pp.651-659, April 2014

[3] A. J. Gilbert, "A method of measuring loss distribution in electrical machines", Proceedings of the IEE, 1961, Vol A 108, p. 39, pp. 239-244, 1961.

[4] R. Sitar, I. Šulc, Ž. Janić "Prediction of local temperature rise in power transformer tank by FEM", Procedia Engineering 202, pp. 231-239, 2017.

[5] J. P. Webb, b. Forghani, "T-Ω method using hierarchical edge elements", IEE Proceedings – Science, Measurement and Technology, Volume 142, Issue 2, pp. 133-141, March 1995

[6] K. Preis, O. Biro, G. Buchgraber, I. Tičar, "Thermal-Electromagnetic Coupling in the Finite-Element Simulation of Power Transformers", IEEE Transactions on Magnetics, vol. 42, no. 4, pp. 999-102, April 2006.