Numerical calculation of thermal field distribution in oil immersed power transformer - a comparison of methods

VLADO MADZAREVIC, IZUDIN KAPETANOVIC
MAJDA TESANOVIC, MENSUR KASUMOVIC
Department of electrotechnics and systems of energy conversion
Faculty of electrical engineering, University of Tuzla
BOSNIA AND HERZEGOVINA
vlado.madzarevic@untz.ba
http://www.fe.untz.ba

Abstract: This paper summarise a few computational methods and engineering models proposed for transformer thermal analysis and the accurate prediction of transformer thermal characteristics. The paper presents different approach for numerical calculation of thermal field distribution in power transforemer.

The model presented facilitates the establishment of criteria for optimizing transformer operation under various load conditions, environments as well as in the case of failures. Thus, the transformer can operate at maximum capacity while, at the same time, the probability of faults due to overheating is reduced to a minimum. The choice of combination of oil and insulation material specifies transformer properties and directly influences on its field of application. Unconventional insulation systems are for example transformer insulation systems where mineral or some other type of oil is used as liquid dielectric. Coupled physical and mathematical models would assist in the development of a system that was both accurate and simple to implement. The performances of the models are compared to the analytically determined performance of transformer and the results obtained are in a good enough agreement with open literature. The thermal models based on finite element analysis are shown to be more accurate then the model based on equivalent electrical circuit.

Finite element software, as CAD tool or other application modes for fundamental physics provide several benefits: reduction of the costs for designing a new device, reduction of number of prototype, reduction of price, simplification of the manufacturing process, increase technical performance, ….

Key words: thermal field, numerical calculation, power transformer, hot-spot temperature

1 Introduction

The electrical devices are complicated mechanisms with specific interconnected elements and parts, and various physical phenomena that describe the real system behavior. In many cases demands for their proper operation force reconsideration conventional design methods to include complexity of non-linear materials, composite geometry structures, operation at transient and steady-state conditions. The prediction and determination of the thermal phenomena in the metal parts of transformers is a very important step in the process of designing equipment. Transformer faults always cause internal damage. The basic criterion that limits transformer loading and its lifetime is partially determined by the ability of the transformer to dissipate internally generated heat into the surrounding area.

Therefore, it is of great importance to predict the thermal behavior of a transformer under normal load. Also, creating a transformer model is very important for the process of monitoring transformer operation. This paper provides an overview of research, development and application of various computational methods for numerical calculation of thermal field of oil immersed power transformer.

The identification of oil-immersed transformers according to the cooling method consist the following information:
- type of internal cooling medium in contact with the windings
- identification of the circulation mechanism for internal cooling medium and external cooling medium

- identification of the circulation mechanism for external cooling medium [2].

For example, if the internal cooling medium is mineral oil, which is circulated with natural flow, and the external cooling medium is air, which is circulated with natural convection, then this cooling method is coded as ONAN (Oil Natural Air Natural). A four cooling methods exist: ONAF (Oil Natural Air Forced), OFAN (Oil Forced Air Natural) (OFAF Oil Forced Air Forced) and OFWF (Oil Forced Water Forced).

Transformer design must take into account numerous performance parameters and technical constraints.

Computational methods and engineering models proposed for transformer analysis and the accurate prediction of their characteristics can be categorized into four main groups:

1. Numerical techniques that consist some of the most widely used tools for transformer simulation. Among the proposed techniques of this group, the Finite Element Method (FEM) is the most prevalent one.
2. Stochastic methods including Artificial Intelligence (AI) techniques, such as Genetic Algorithms (GA), which have seen increased usage in the transformer design area over the last few years.
3. Versions of the transformer equivalent circuit. Its use is still common in the manufacturing industry, due to its simplicity and its ability to provide reliable results, especially in cases of standardized geometries.
4. Experimental methods, combining data provided by measurements with analytical or other methods, in order to provide efficient models for the accurate representation of certain transformer characteristics.

Power transformer data were used for the numerical determination of the distribution of the temperature field. The results obtained from the numerical calculation in the next chapter have been compared to the results obtained from analytical calculation.

The transformer data are as follows:

− type	TM–6300/35
− nominal power	6300 kVA
− nom.voltage,HVwinding	35±(2X2,5%)KV
− nominal voltage, LV winding	10,5 KV
− frequency	50 Hz
− Windings losses	Pk = 46 500 W
− Iron losses	Px = 7600 W
− Short circuit voltage	u_k = 7,5%
− Open circuit current	i_0 = 0,6 %

2 Mathematical model of thermal field

The sources of electromagnetic and thermal fields are currents that flow through transformer windings, i.e. joule losses that occur in consequence of the current flowing through conductors, i.e. transformer windings [2].

A thermal field is described by the following equation:

$$\nabla\left(\lambda\nabla T\right)-\rho c\frac{\partial T}{\partial t}+q_{\mathrm{v}}=0, \qquad (1)$$

and represents the differential equation of non-steady state heat transfer, in which:

T – the sought function of temperature distribution in space and time [K]

c – the specific heat capacity [J/kg·K]

ρ – the specific material density [kg/m^3]

λ – the coefficient of thermal conductivity [W/m·K]

q_{v} – heat generation of the eventual heat source at the observed point [J]

t – time [s],

where the above are functions of space and temperature.

Heat exchange among the surfaces of the conductor, core, oil and ambient air are given in the equation (2) :

$$-\lambda\frac{\partial T}{\partial t}=\alpha\left(T_{\mathrm{p}}-T_{\mathrm{f}}\right). \qquad (2)$$

For the solution of differential equations with the given initial and final conditions, the finite element method (FEM) was used. FEM is an approximate procedure. By applying this method, the problem of solving the partial differential equation of heat transfer is reduced to the solution of a system of simultaneous linear equations. The region within which the problem is solved is divided into a finite number of elements. The temperatures of the element nodes are obtained as solutions, while the temperatures within the elements are approximated using the values of the element nodes.

Transformer oil pumped through the coils perform the necessary cooling. The oil has a viscosity and density that vary with temperature, so heating affects the fluid-flow pattern. The model in this paper simulates the steady-state temperature distribution in the transformer by modeling both the conduction-convection problem and the non-isothermal flow field.

The model uses two stationary application modes to simulate the problem: Weakly Compressible Navier-Stokes and General Heat Transfer. It simulates the momentum transport and mass conservation with the Weakly Compressible Navier-Stokes equations that describe the fluid velocity, **u**, and the pressure field, *p*. In this case, the density, ρ, and the viscosity, η, are temperature dependent [5]:

$$\rho\mathbf{u}\cdot\nabla\mathbf{u}=\nabla\cdot\left[-p\mathbf{I}+\eta\left(\nabla\mathbf{u}+(\nabla\mathbf{u})^{T}\right)-(2\eta/3)(\nabla\cdot\mathbf{u})\mathbf{I}\right]+\rho\mathbf{g}$$

$$\nabla\cdot(\rho\mathbf{u})=0 \tag{3}$$

Variations in density result in buoyancy forces, expressed as ρ**g**, and a continuity equation for the total mass, as expressed in the previous equations.

The General Heat Transfer application mode is based on a general energy balance:

$$\nabla\cdot(-k\nabla T)=Q-\rho C_p\mathbf{u}\cdot\nabla T \tag{4}$$

k - thermal conductivity

C_p - (temperature-dependent) specific heat capacity

Q - heating power per unit volume.

The top oil thermal model is based on the equivalent thermal circuit shown in figure 3. A simple RC circuit is employed to predict the top oil temperature [1]. In the thermal model all transformer losses are represented by a current source injecting heat into the system. The capacitances are combined as one lumped capacitance. The thermal resistance is represented by a non-linear term. The differential equation for the first equivalent circuit on fig.3 is:

$$q_{Tot}=C_{th-oil}\frac{d\Theta_{oil}}{dt}+\frac{1}{R_{th-oil}}\left[\Theta_{oil}-\Theta_{A}\right]^{1/n} \tag{5}$$

q_{Tot} - heat generated by total losses, W

Cth-oil - oil thermal capacitance, Wmin /^{0} C

Rth-oil - thermal resistance C/W

Θoil - the top oil tempetature, ^{0}C

The differential equation for the second equivalent circuit on fig.3 is:

$$q_{w}=C_{th-H}\frac{d\Theta_{H}}{dt}+\frac{1}{R_{th-H}}\left[\Theta_{H}-\Theta_{oil}\right]^{1/m} \tag{6}$$

q_W - heat generated by the losses at hot spot location, W

Cth-oil - oil thermal capacitance at hot spot location

Rth-oil - thermal resistance at hot spot location ^{0}C/W

Θoil - the top oil tempetature, ^{0}C

In table 1 are given data about geomtry of oil transformer.

Table 1: Power transformer geometry data

Parameter	Description	Value in cm
COL_HT	Height of columns	143
COR_TK	Thickness of uperr and lower part of the core	34.84
COL_TK	Thickness of the column	34.84
COR_LH	Lenght of the core	168.84
INS_TK1	Thickness of insulator	1.75
INS_TK2	Thickness of insulator	2.7
C1_TK	Coil 1 thickness	4.86
C2_TK	Coil 2 thickness	5.27
COIL_HT	Coil height	123
R_INT	Inner diametter of calculation domen	222x258

Figure 1 shows geometry of transformer.

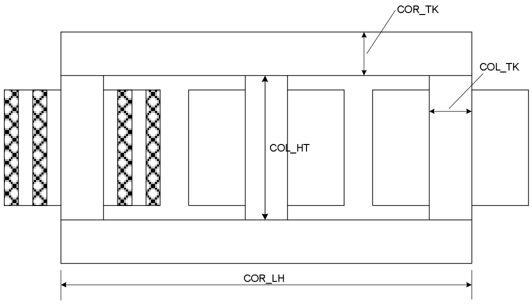
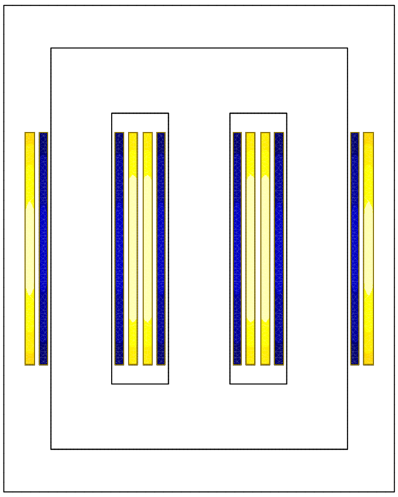
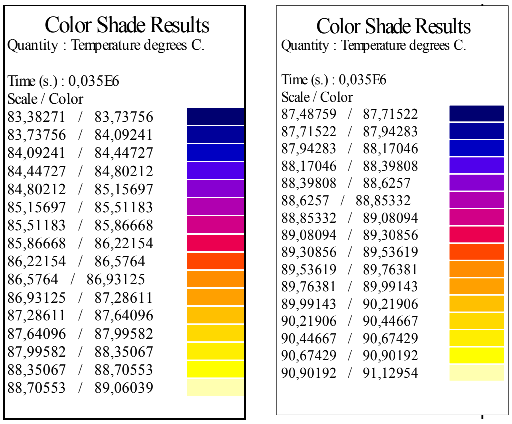


Figure 1. Transformer geometry

3 Different approach for numerical calculation of temperature field of power transformers

Presented models of oil immersed power transformer are intended to provide essential information about the status of a transformer.
They provided information about important thermal data for prognosis, simulation and analysis of the transformer operation.
Sources of electromagnetic and temperature field are currents in the coils, Joules losses which are consequence of current flow through transformer coils.
Numerical calculation of temperature field is realised with three methods: finite element method with CAD software package, finite element method using multi-physics application that involves heat transfer and fluid flow and using thermal-electrical analogy.





Color Shade Results
Quantity : Temperature degrees C.

Time (s.) : 0,035E6

Scale	/	Color
83,38271	83,73756	🟦
83,73756	84,09241	🟦
84,09241	84,44727	🟦
84,44727	84,80212	🟪
84,80212	85,15697	🟪
85,15697	85,51183	🟪
85,51183	85,86668	🟥
85,86668	86,22154	🟥
86,22154	86,5764	🟧
86,5764	86,93125	🟧
86,93125	87,28611	🟧
87,28611	87,64096	🟧
87,64096	87,99582	🟨
87,99582	88,35067	🟨
88,35067	88,70553	🟨
88,70553	89,06039	⬜

Color Shade Results
Quantity : Temperature degrees C.

Time (s.) : 0,035E6

Scale	/	Color
87,48759	87,71522	🟦
87,71522	87,94283	🟦
87,94283	88,17046	🟦
88,17046	88,39808	🟪
88,39808	88,6257	🟪
88,6257	88,85332	🟪
88,85332	89,08094	🟥
89,08094	89,30856	🟥
89,30856	89,53619	🟧
89,53619	89,76381	🟧
89,76381	89,99143	🟧
89,99143	90,21906	🟧
90,21906	90,44667	🟨
90,44667	90,67429	🟨
90,67429	90,90192	🟨
90,90192	91,12954	⬜

Figure 2. Temperature distribution in the coils of all three phases of power transformer during 35 000 sec

Results of these methods are shown on following figures.

The most warm up parts of power transformer are coils, LV coil with maximum temperature 91.12 ^{0}C.
Using thermal-electrical analogy [1], RC model of transformer is realised by PSPICE software package, figures 3.
Average temperature on the oil surface as a result of simulation is 65 ^{0}C. Hot-spot temperature as result of simulation is 100 ^{0}C.

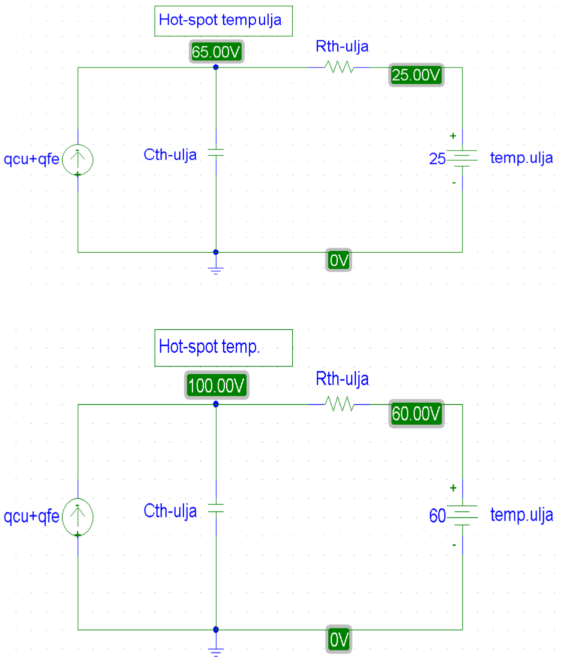


Figure 3. PSPICE model for calculation of hot-spot temperature

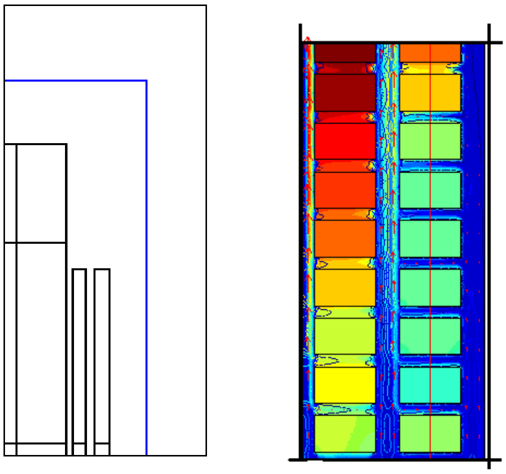


Figure 4. Temperature distribution and fluid flow in the one part of transformer cross section

For the non-isothermal model, the maximum temperature (at the hot spot) is 90 °C, occurring at the top inner coil, and the isothermal-flow model predicts a somewhat higher temperature 93 ^{0}C. The differences between the models are caused by different fluid flows, which are affected by the temperature change.

4 Conclusions

By analysis of results of temperature field distribution in the oil immersed power transformer cross section, also and characteristics of temperature changes in particular points during calculation period, can be concluded:

- The most warm up parts of transformer are coils, and then core and oil .

Conclusions based on analytical and numerical calculations are:

- The most warm up parts of power transformer are coils, LV coil with maximum temperature 91.12 ^{0}C, fig.2, or 90^{0}C, fig.4, or 100 ^{0}C, fig.3. According to analytical and numerical calculations, temperature of LV and HV coils over temperature of oil is 64 ^{0}C. Allowed temperature for class of insulation used in this transformer is 65 ^{0}C, and this is in harmony with analytical and numerical calculation results, and open literature.

In order to improve power transformer reliability, a special focus has been carried out on insulating oils and flow of fluid. The most common used oil is mineral oil because of low price and its good properties. Natural esters and vegetable oils could be very good substitute oils, because of their good properties such as safety against a fire, environmental friendliness and improved transformer performance.

Results accuracy of numerical and analytical calculation is very good. This shows importance of development of these numerical calculations for practical problems of different natures.

This types of calculations are very practical, by application of adequate software model of any kind of machines, including all types of transformers can be realised.

This is very practical by economic reasons; expensive laboratory experiments, measurements and repairs are reduced.

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