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Results of a novel algorithm for the calculation of the characteristic temperatures in power oil transformers

Z. Radaković, Dj. Kalić

Contents The application of the originally developed thermal model, intended to oil power transformers analyses, is presented in the paper. The model delivers the value of the insulation Hot-spot temperature, as the most critical quantity during transformer loading, and the value of the thermal ageing, both for variable load and variable ambient temperature. The results obtained using the original thermal model are compared with the experimental results and the results obtained by the model from the international standard IEC 354. A program is developed for this purpose, allowing some additional analysis in respect to the basic algorithm from IEC 354.

Besides, using experimentally obtained results, some approximations of the thermal model from IEC 354 and some factors important for development of thermal models are also analyzed.

Ergebnisse eines neuen Verfahrens zur Berechnung der charakteristischen Temperaturen in Leistungsöltransformatoren

Übersicht Das Thema dieses Beitrages ist die Anwendung eines von uns neuentwickelten thermischen Modells zur Analyse von Öltransformatoren. Das Modell liefert den Temperaturwert der Isolation an der heißesten Stelle, welches während der Belastung des Transformators der kritischste Wert ist, sowie die Werte der thermischen Alterung des Transformators, beides unter veränderlicher Belastung und Umgebungstemperatur. Die Ergebnisse unseres Modells werden mit Experimentaluntersuchungen und mit den Resultaten des Modells IEC Standard 354 verglichen. Dafür wurde ein Rechenprogramm ausgearbeitet, das größere Möglichkeiten zur Analyse als das Grundmodell Standard 354 hat.

Schließlich werden einige Vereinfachungen für das IEC-Modell vorgeschlagen und wichtige Faktoren, die während der thermischen Modellentwicklungen auftreten analysiert.

1
Introduction

The determination of temperatures in a power transformer, being a dominant factor in transformer loading, represents an extremely complex problem. The temperature has various values in different functional parts of the transformer (windings, core, oil, tank). It is also variable in the interior of these parts, its vertical gradient being the most outstanding. The heat generated in the active parts of the transformer (windings and iron core) is transferred first to the oil, and by its streaming further to the heat exchanger, wherefrom it is taken off by convection of the external cooling medium (air, in most cases). The oil streams in a closed space having a relatively complex geometry, which results in tedious application of the convection heat transfer theory [1]. The convection is highly non-linear process, i.e. the temperature differences of the surface and fluid, where heat is exchanged, are not proportional to the transmitted heat power. Owing to the time-variations of load and ambient temperature, the inner transformer temperatures change all the time, not following their causes immediately.

As a result, there is no algorithm which can determine the insulation Hot-spot temperature with sufficient accuracy when the load and/or the ambient temperature vary with time. The algorithm given in the international recommendations [2] contains a number of approximations regarding the most important factors and therefore is not of a high accuracy. Such a simplified model is acceptable for certain purposes (e.g. the estimation of ageing), but is too rough for some others (e.g. the calculation of the Hot-spot temperature during a short term overload).

In the algorithm given in the International Standard IEC 354 [2] the following approximations have been made:

- For ON cooling of transformers, the temperature of the oil leaving the winding and the top oil temperature (e.g. in the thermometer pocket) are assumed to be equal.
- At a constant current loading, it is taken that the effect of the viscosity changes with temperature is completely compensated by the effect of the winding ohmic-resistance variations, resulting in power loss changes. The drawbacks of such an approximation were analyzed in [3]. Actually, by this approximation, the effect of oil viscosity changes is compensated by power loss changes, including the stray losses, as a power loss component which decreases with the increase of the winding temperature [4].
- The dependance of the steady state temperature rises on the ambient temperature (which is especially effective at low ambient temperatures [5]) is not treated at all in [2].
- The Hot-spot factor (H) is assumed to be constant, independent on the load.

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Z. Radaković, Dj. Kalić
Faculty of Electrical Engineering, University of Belgrade,
Bulevar Revolucije 73, YU-11000 Belgrade, Yugoslavia

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- Oil mass temperature changes are assumed to follow a simple exponential law, i.e. to have single time constant not dependent on the temperature level. Actually, the time constant is variable, which is, among other references, shown in ANSI standards [6].

As a consequence of the approximations assumed in the thermal model used in [2], serious disagreements between the calculated and the real Hot-spot temperatures can appear. Therefore, numerous attempts have been made in order to improve the model from [2] or to establish a new, more accurate model.

In [5] the correction taking into account the variations of the ambient temperature is introduced, relating to rated temperature differences top-oil – ambient and Hot-spot – top-oil. The same author proposed in [4] a new method for the calculation of the Hot-spot temperature in steady states, based on the values of bottom oil temperature, temperature difference between top of winding surface facing the oil duct and bottom oil, and radial gradient winding temperature. The model is based on the experimental results obtained on a model of a winding cooling duct, 1.47 m high, having variable width (from 2.4 to 11.9 mm), through which various heat powers were transferred from the surfaces, at various oil temperatures at the bottom inlet. An empirical expression for the temperature difference between top of winding surface facing the oil duct and bottom oil is proposed. This expression has the form usual in the boundary layer theory, using equivalent parameters determined from the average oil temperature in respect to a height of the duct. This idea for Hot-spot temperature determination is important, as it is based on the convection heat transfer theory, used for establishing the temperature-gradient expression, which is the most difficult to determine. Nevertheless, some problems remained not quite explained. The following questions may be raised: 1. Are the values of the coefficients in the expression for the temperature difference at the top of the outer winding surface in respect to inlet oil dependent on the height? 2. Are the results obtained on the physical model of the winding duct applicable to the real transformer, as in the latter the flow is going up in a enclosure of complex shape, including a few surfaces cooled by convection? 3. How can the temperature at the cooling duct top (which is needed for equivalent viscosity calculation) be determined? 4. Is the hottest spot really at the winding top or it is somewhat lower [7]?

The usual approach is the determination of a thermal model with parameters according to the cooling class of the transformer. It is necessary if the model application requires the knowledge of quantities difficult to determine experimentally. For instance, measurements of outer-surface temperature or, which is more emphasized, the inner-winding temperature are not practical – even when the prototype test is made. Such an approach does not provide satisfying results, as the common parameters cannot be determined precisely enough due to the complexity of the phenomena.

On the other hand, it is possible to define thermal models with parameters which can be easily determined by means of a set of simple experiments. The original model developed by the authors is based on this principle. As a result, thermal parameters of each transformer may be obtained with pretty good accuracy. In this way, the error due to uncertain parameters may be practically eliminated. The developed model treats thermal transient processes in an original way, taking into account the variable character of thermal time constants.

2
Analysis of relevant thermal model parameters on the basis of experimental results

Experimental research was made on three phase transformers of ONAN cooling type with ratings shown in Table 1 (S_r – rated power of a transformer, U_1, U_2 – rated voltages of higher and lower transformer winding, u_k – short-circuit voltage, P_{Fer} – rated core losses and P_{Cur} – rated copper losses).

In all three cases, four sensors for local temperature measurements outside the transformer were used. In transformers 2 and 3, additional sensors were placed inside the tanks. Eight copper-constantan thermocouples were built inside transformer 2. They measured the oil, core and outside winding surface temperatures. Extensive researches have been carried out with transformer 3, with 114 built-in temperature sensors, 70 of them built in winding during its production. The analysis of experimentally obtained data for transformer 3 is not yet completed (some ideas for a future work are presented in Section 6).

2.1
Upper oil and duct-outlet oil temperatures

The measurement of the temperature at the cooling duct outlet (at transformer 2) has been carried out at a single point. Although the positioning of a sensor for this temperature measurement is very delicate [7], the obtained results are highly illustrative for the ratio of temperature rises of duct-outlet oil and upper oil. In three steady states, corresponded to three different power load losses realized in the short-circuit tests, i.e. P_r, 80% P_r, 62.5% P_r (P_r denotes rated total losses), the obtained duct-outlet temperature rise was about 20% higher than that of the upper oil (more precisely, 17.5%, 20.4%, 20.3%). Term temperature rise denotes the difference of the temperature value and the ambient temperature value. The smaller time constant of the duct-outlet oil temperature rise (6.3 to 8.1 min) is close to that belonging to the average winding temperature rise (3.9 to 4.5 min), whereas the upper oil temperature has a considerable "dead time" (about 10 min).

Table 1. Ratings of tested transformers

	Transformer 1	Transformer 2	Transformer 3
S_r(kVA)	16	6.6	630
U_1/U_2 (kV/kV)	6/0.4	0.38/0.22	10/6
u_k(%)	6.5	5	4.45
P_{Fer} (W)	160	64	1875
P_{Cur} (W)	740	336	8790

It is interesting to note the type of oil streaming and heating-up. Only a thin layer of oil takes part in heat exchange from winding surfaces. The oil mass inside the tank warms up due to heat conduction through the layers situated on the same height, and to global circulation of the oil through the tank. It is not, therefore, sufficient to study the convection heat transfer from the winding to the boundary oil layer and to replace the oil carrying the heat off the winding by upper oil, when the upper oil temperature is discussed.

2.2
Variations of the oil time constant and winding time constant

A procedure has been developed by the authors [8] for determining time constants in the expression having the form of a sum of simple exponential functions, as well as the corresponding partial temperature rises, all based on the transient temperature curves obtained in tests. The parameters of each simple exponential function are determined step by step, starting from the function with the highest time constant and ending by that with the lowest time constant. Utilizing this procedure, characteristic winding and oil temperature rises, when the short-circuited transformer is heated up with constant power loss or cooled down after being shut off after a thermal steady state, are easily represented as a sum of three exponential functions, having distinctly different values of time constants. The numerical results have been exposed in [8].

The obtained results show that time constants are, in fact, variable. The most outstanding difference occurs between the values of heating-up and cooling-down processes: the dominant time constant becomes approximately doubled. A qualitative explanation could be given on the basis of the fact that the space distributions of temperature in these two processes are different, i.e. the "active" mass of the oil taking part in the heat transfer is substantially not the same. Apart from this enormous change of the main time constant, time constants depend on the load level and also that - for fixed load - the corresponding time constants of winding and of oil are not quite equal. The last two facts may be considered as a consequence of non-linear phenomena.

2.3
Exponents in temperature rise functional dependencies

The analysis is made for temperature rises of upper oil ($\theta_{Oil,t}$) and of Hot-spot ($\theta_{Cu,hs}$). For the upper oil, it is convenient to choose the oil in thermometer pocket; $\theta_{Cu,hs}$ is determined by four measured temperatures in accordance with the expression

$$\theta_{Cu,hs} = \theta_{Oil,t} + 1.1\left(\theta_{Cu,a} - \left(\theta_{Oil,t} - \frac{\theta_t - \theta_b}{2}\right)\right) . \quad (1)$$

The Hot-spot temperature rise is determined by means of the thermal model from [2], using the temperatures measured on easily accessible spots, i.e. ambient ϑ_a, the inlet (i.e. top) $\vartheta_t(\theta_t = \vartheta_t - \vartheta_a)$ and outlet (i.e. bottom) $\vartheta_b(\theta_b = \vartheta_b - \vartheta_a)$ of the oil/air heat exchanger. The average winding temperature $\vartheta_{Cu,a}(\theta_{Cu,a} = \vartheta_{Cu,a} - \vartheta_a)$, measured by the resistance-increase method, is also used.

The most convenient and the most commonly used expression for any steady state temperature rise (θ) as the function of reference temperature rise (θ_{ref}) and the corresponding per-unit (p.u.) power losses (P/P_{ref}) taken of by convection is [2]

$$\theta = \theta_{ref}\left(\frac{P}{P_{ref}}\right)^n , \quad (2)$$

where n represents the coefficient determining the convection heat transfer. For simplicity reason, the temperature difference of the winding in respect to the oil, determined by winding power losses, will be considered. If the p.u. power loss is taken to be equal to the square of p.u. current ($K^2 = (I/I_{ref})^2$), the obtained values for p.u. winding losses would be too high if it were less than 1, and too low if it were greater than 1, because the resistivity varies with temperature.

Three heating-up tests have been made on transformer 1, holding the short-circuited transformer current constant ($I_1 = 1.3,\ I_2 = 1.76,\ I_3 = 2.08$ A). If the formula

$$\theta = \theta_{ref} K^{2\,n} \quad (3)$$

were valid, the temperature rise curve drawn in the diagram with double logarithmic scale as the function of current should be a straight line. When the steady state has been reached in heating-up tests, the values of temperature rises were $\theta_{Cu,hs} - \theta_{Oil,t} = 17.63;\ 28.67;\ 38.85$ K, $\theta_{Oil,t} = 28.70;\ 48.57;\ 66.51$ K and powers $P = 560;\ 1060;\ 1530$ W. The slopes on the current-squared diagram, when determined by the lowest and middle load, are smaller than those determined by the middle and the highest load, in the ratios 0.802/0.9 for ($\theta_{Cu,hs} - \theta_{Oil,t}$) and 0.869/0.941 for $\theta_{Oil,t}$. Assuming the middle load as the referent one, the obtained result may be explained easily by the fact that the approximation has been made that the power loss ratio is equal to the current squared ratio. Having in mind that the losses at light load are over-estimated, the obtained exponent must be lower than the value characterizing convection; on the other hand, at higher load, losses are under-estimated, and the exponent must be higher than the value characterizing convection. The other temperature-rise functions, i.e. those depending on the power losses in steady-state, are nearly the same straight line (in spite of neglecting the variation of viscosity with temperature), having the slopes 0.784 for $\theta_{Cu,hs} - \theta_{Oil,t}$ and 0.835 for $\theta_{Oil,t}$.

From the foregoing it may be concluded that, in high-precision determination of temperatures, the copper power loss ratio rather than current squared ratio should be taken into account.

2.4
Ratio of purely resistive to stray load losses

If thermal models are based on power losses as input quantities, it is important to know how they vary with temperature changes when the loading current is constant. At constant current, purely resistive losses increase with the temperature according to the formula

$$P_{pr,h} = P_{pr,c}\frac{235 + \vartheta_{Cu,ah}}{235 + \vartheta_{Cu,ac}} \quad (4)$$

(where $P_{pr,h}$ are purely resistive losses at "hot" condition and $P_{pr,c}$ are purely resistive losses at "cold" condition). The stray losses, on the contrary, decrease:

$$P_{s,h} = P_{s,c}\frac{235 + \vartheta_{Cu,ac}}{235 + \vartheta_{Cu,ah}} \tag{5}$$

(where $P_{s,h}$ are stray losses at "hot" condition and $P_{s,c}$ are stray losses at "cold" condition). The ratio of these two kinds of load loss (typical ratio of these losses is given as 80 : 20 [4]) may be determined by examining the variation of total winding losses with temperature during the heating-up test with constant current. If the relative ratio of purely resistive losses to total load losses, in cold state ($\vartheta_{Cu,a} = \vartheta_{Cu,ac}$), is designated by f, total losses at any other temperature ($\vartheta_{Cu,a} = \vartheta_{Cu,ah}$) may be written as

$$P_{Cu,h} = f\,P_{Cu,c}\frac{235 + \vartheta_{Cu,ah}}{235 + \vartheta_{Cu,ac}} + (1 - f)P_{Cu,c}\frac{235 + \vartheta_{Cu,ac}}{235 + \vartheta_{Cu,ah}} \tag{6}$$

(where $P_{Cu,h}$ are total copper losses at "hot" condition and $P_{Cu,c}$ are total copper losses at "cold" condition). The factor f may be determined by means of losses and temperature in the steady-state reached in the constant-current test. The power losses and the winding temperature are continuously measured during the complete short-circuit test, by means of a computer controlled acquisition measuring system. In our experiments, the average winding temperature is obtained by measuring the resistance between the neutral and short-circuited terminals, with a superimposed d-c current. According to values $P_{Cu,h}$ and $\vartheta_{Cu,ah}$ measured in steady states, the f-value is calculated, starting from (6), as

$$f = \frac{\dfrac{P_{Cu,h}}{P_{Cu,c}} - \dfrac{235 + \vartheta_{Cu,ac}}{235 + \vartheta_{Cu,ah}}}{\dfrac{235 + \vartheta_{Cu,ah}}{235 + \vartheta_{Cu,ac}} - \dfrac{235 + \vartheta_{Cu,ac}}{235 + \vartheta_{Cu,ah}}}\ . \tag{7}$$

For transformer 1, following values have been obtained: $f = 0.90$ (for $I = 0.8$ p.u.), $f = 0.84$ (for $I = 1.14$ p.u.) and $f = 0.81$ (for $I = 1.35$ p.u.). By means of simultaneous measurement of current, power and average temperature (in a number of tests), the validity of the established expression (5) may be checked. A similar procedure could be carried out on a really loaded transformer, by using adequate measuring methods. In such an experiment, a more realistic value of f would be obtained, as the flux pattern is somewhat different.

3
Outline of the method

The method is based on the representation of heat processes by circuit diagrams. The advantage of this approach is that the analyses can be made using well-known methods from the Electric circuit theory. In establishing such circuits, individual parts of a transformer are represented by corresponding nodes, representing the complete volume of a part of the transformer. The most frequently used circuit has two nodes (see Fig. 1) [8, 9] and is sufficient for the global heat flow representation.

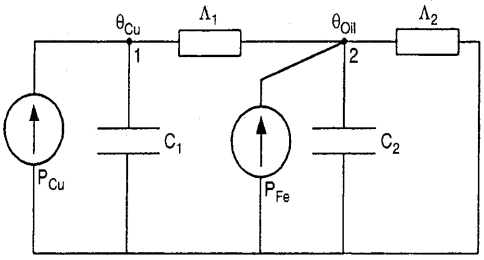


Fig. 1. The circuit diagram with two nodes

Following designations are used in Fig. 1:

P_{Cu} - winding (copper) power loss;
C_1 - winding (both primary and secondary) heat capacity;
Λ_1 - heat conductance due to the heat transfer from windings to oil;
C_2 - over-all heat capacity of oil, core and tank;
Λ_2 - heat conductance due to heat transfer from the oil, across the tank wall surfaces to the outer cooling medium;
P_{Fe} - core power loss;
θ_{Cu} - winding temperature rise;
θ_{Oil} - oil temperature rise.

The main problem in application of the method represents the non-linear nature of the equations corresponding to the circuit diagram, as well as the determination of the parameters of circuit diagram elements. As for non-linear conductances, they are most frequently represented by formulas, either in polynomial

$$\Lambda = \sum_{i=0}^{n} a_i\,\Delta\theta^i\ , \tag{8}$$

or in exponential form

$$\Lambda = b_1\,\Delta\theta^{b_2}\ . \tag{9}$$

In formulas (8) and (9) $\Delta\theta$ represents the temperature difference or temperature rise, and a_i and b_i -parameters.

During the research, a method including program for determining circuit parameters has been developed [9].

It was shown [9] that the heating-up and cooling-down processes cannot be described with the same set of parameter values (providing that the functional dependence is of the type (9)) if high-precision results are needed. A good agreement of experimental and calculated values can be achieved if three set of values are used: the first, when the load and power losses increase, the second, when they decrease, and the third when the load is completely switched off. Consequently, three tests should be made (one heating up and two cooling down tests), where average winding temperature and 4 local temperatures (ϑ_a, ϑ_t, ϑ_b and $\vartheta_{Oil,t}$) are continuously recorded. According to thermal equivalent circuit and its determined parameters, temperatures resulting from arbitrary loading diagrams can be calculated.

Concerning the parameters estimation, it should be noted that in reference [10] a method for parameters estimation from test data is given, using pseudo-binary noise signal (power loss) as the excitation signal for the system. Such an approach was used because a natural excitation signal (e.g. a power step function) is often subjected to limitations regarding the completeness of information about the system.

4

Results of the algorithm application

In this section the results of the algorithm application to temperature rises of top oil $\theta_{Oil,t}$ and of winding Hot-spot ($\theta_{Cu,hs}$) will be presented. For each of the three tested transformers, the parameter values are given and the comparison of Hot-spot temperatures, obtained by test and by calculation, are presented in the form of graphics. To this end, a typical daily load diagram (Fig. 2e) with corresponding losses is applied. For the transformer 1, additional analysis was made. More specifically:

- results for a set of various loading diagrams types are presented, utilizing one or two parameter sets;
- results obtained utilizing the algorithm from the standard [2] and
- ageing estimation results are also given.

The aim of this extended analyses is to show the advantages of the proposed algorithm, specifying those problems where advantages are the most outstanding.

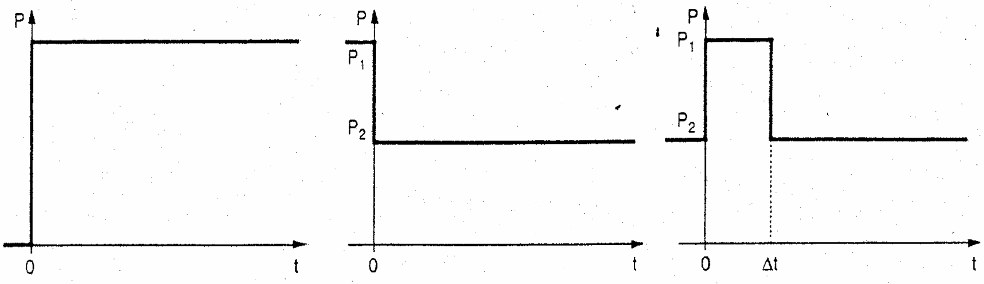
Parameters A_1, n_1, A_2 and n_2, with the thermal circuit heat conductance (Fig. 1) functional form

$$\Lambda_1 = A_1(\theta_{Cu} - \theta_{Oil})^{n_1} , \quad (10)$$

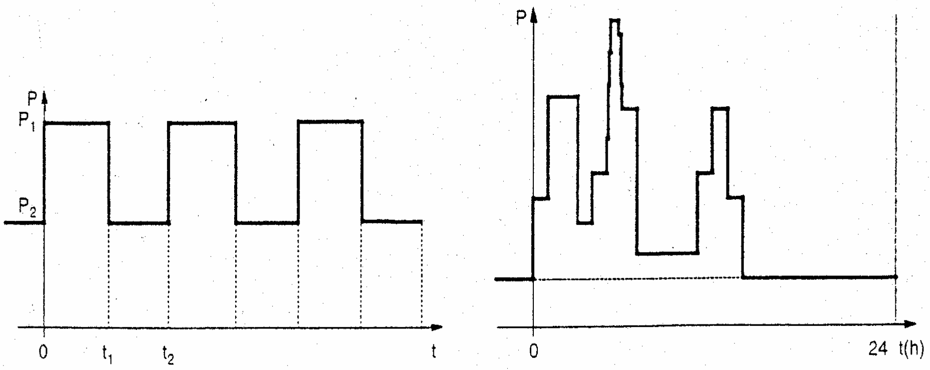
$$\Lambda_2 = A_2\theta_{Oil}{}^{n_2} , \quad (11)$$

have been determined according to steady-state values of temperatures and power losses for different loads. The values of heat capacitances are determined by an original method for parameters estimation [9], on the basis of the heating-up process beginning from the cold state (temperatures of all transformer parts are equal to the ambient temperature). All of these parameter values are listed in Table 2 (in the further text they will be called "Heating-up parameters").

Parameters obtained in this way can describe transformer thermal processes rather well, especially those where power is stepped up or down, which will be proved later (Table 4 and Figs. 3, 4 and 5), by results of a series of testings. At the cooling-down processes, when the transformer is disconnected, the agreement of test and calculation results is not so good as in the heating-up and power-decrement cases; fortunately, this mode of operation is not so important. The temperature values obtained by means of simulation, according to the equivalent circuit and the parameters obtained in the heating-up test, deviate from measured ones for more than 5.5 K (for transformer 1). However, when another set of parameters was used, i.e. parameters estimated from a single cooling-down process after the transformer had been switched off, the simulated temperatures became very close to the measured ones (the differences were as low as 1.5 K), although numerous cooling-down processes beginning from very various initial states were considered. The parameters of transformer 1 for such cases are listed in Table 3 under the heading "Switch-off parameters".



a Constant power b Power step-down c Short-time overload



d Intermittent duty e Typical daily load diagram

Fig. 2. Testing load profiles

Table 2. "Heating-up parameters" of thermal circuit

	Transformer 1	Transformer 2	Transformer 3
A_1	14.465	12.885	168.54
n_1	0.2758	0.1044	0.2203
A_2	10.07	3.075	42.864
n_2	0.1976	0.3393	0.3268
C_1 (kJ/K)	8.269	7.500	133.33
C_2 (kJ/K)	145.733	103.448	833.33

Table 3. Thermal parameters of transformer 1

	Switch-off parameters	Power step-down parameters
A_1	35.28	11.53
n_1	0.5513	0.3202
A_2	21.07	5.308
n_2	0.2738	0.3683
C_1 (kJ/K)	59.691	8.269
C_2 (kJ/K)	455.900	145.733

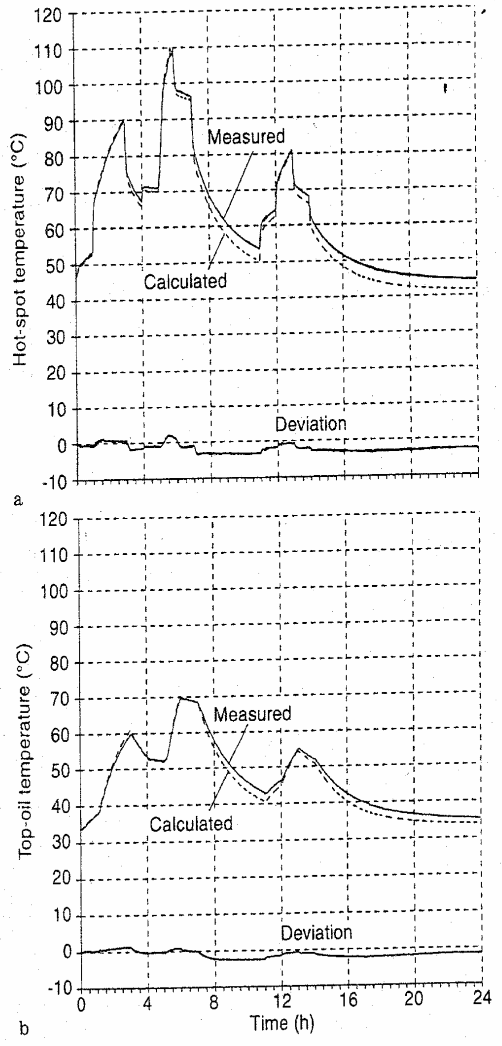


Fig. 3a, b. a Winding Hot-spot temperature of transformer 1 in the daily diagram b Top-oil temperature of transformer 1 in the daily diagram

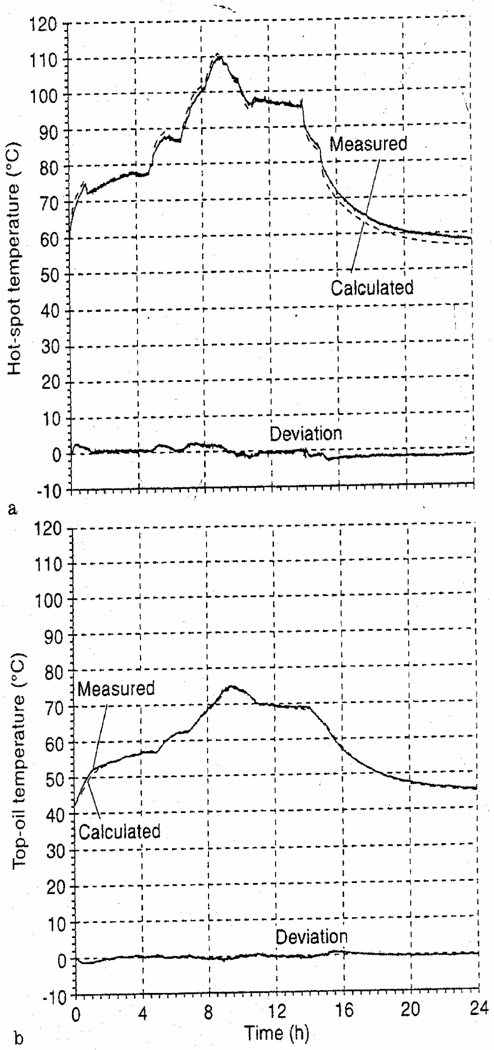


Fig. 4a, b. a Winding Hot-spot temperature of transformer 2 in the daily diagram b Top-oil temperature of transformer 2 in the daily diagram

Introduction of another, separate parameter set for processes of cooling-down, when the power losses decrease, results in further improvement of calculated temperatures, which will be shown later on, by the results represented in Table 4. The conductance parameters of transformer 1, given in the last column (under the heading "Power step-down parameters") in Table 3, have been obtained from a test assigned "power step-down", using the originally developed method [9].

In order to verify the proposed algorithm, a set of test loadings, i.e. loss variation with time (the typical examples being represented in Fig. 2) has been simulated, using the thermal circuit from Fig. 1. The method was verified with the short-circuited transformer, which means that core losses P_{Fe} in the equivalent circuit were practically equal to zero.

For transformer 1, the results in the form of the maximum deviation between the calculated and the measured temperatures $\vartheta_{Cu,hs}$ and $\vartheta_{Oil,t}$, are presented in Table 4. The column marked "Original algorithm – unique paramet."

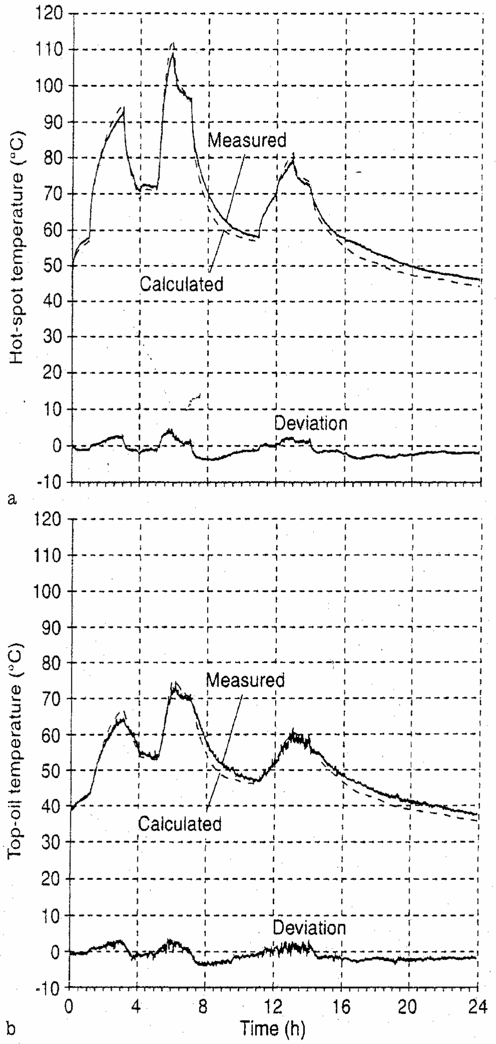


Fig. 5a, b. a Winding Hot-spot temperature of transformer 3 in the daily diagram b Top-oil temperature of transformer 3 in the daily diagram

contains the simulation results when only one single set of parameters ("Heating-up parameters") was used. The column marked "Original algorithm - differ. paramet." contains the results of simulation when two parameters sets were used in the application of the algorithm proposed. When the load jumps from a lower to a higher value, the set "Heating-up parameters", and when the load steps down from a higher to a lower value, the set "Power step-down parameters" was used. The column named "Standards [2] - parameters given in tables" contains the results of simulation made according to the algorithm given in [2] with thermal model parameters tabulated and recommended in IEC standard [2]. Finally, the results of simulation made in accordance with the algorithm from [2], but with parameters obtained by the experiment and with the winding time constant ($\tau_{Cu} = 4$ min), are listed under the heading "Standards [2] - realistic parameters and τ_{Cu}". The power losses and the current are given as p.u. values (rated total loss is 900 W and rated current is 1.54 A). Every model has additional errors originated from unavoidable noise in temperature measurements, which is estimated to be as low as ± 0.2 K.

Temperature values at loadings corresponding to a typical daily diagram (Fig. 2e) are shown in Figs. 3 and 5 (transformers 1 and 3, respectively). Fig. 4 relates to a somewhat different daily diagram applied to transformer 2. Calculated temperatures were obtained by simulation in accordance with the proposed algorithm and using parameters given in Table 2. The results represented in Table 4 and Figs. 3, 4 and 5 show that the proposed algorithm delivers high precision results. Even when the model with unique parameters is accepted, the obtained results for $\vartheta_{Cu,hs}$ and $\vartheta_{Oil,t}$ are very accurate. As to the algorithm given in [2], it does not provide results with sufficient accuracy, as shown in the case of transformer 1. Even introducing actual values of thermal parameters, instead of approximated ones (given in tables from [2]), the resulting deviation does not reach the level from the model presented here. Due to the similar way in which the steady-state is treated in both approaches, the main advantages of the proposed algorithm exist in the treatment of transient states.

Table 5 contains values of the calculated relative ageing, obtained by using various transformer thermal models, applied to transformer 1. The authors have developed a program wich allows easy calculation of ageing in accordance with [2], having the additional facilities for other calculations, being useful in the course of this research. These additional facilities are: introduction of the winding time constant (as a constant value), avoiding of cycling load introduction (which is reflected to the convergence criterion at temperature calculations), handling arbitrary loading cycles - with no limits of duration, and calculation of ageing in accordance with Hot-spot temperature values which are known at equidistant time intervals. In Table 5, for simplicity sake, thermal models are designated by the following numbers:

Model 1 - the model from [2], with thermal characteristics taken from tables for ONAN type of transformers (rated top-oil temperature rise $\Delta\theta_{or} = 55$ K, rated Hot-spot to top oil temperature rise $Hg_r = 26.9$ K, oil exponent $x = 0.8$, winding exponent $y = 1.6$, oil time constant $\tau_0 = 3$ h, Hot-spot temperature corresponded to the relative rate of thermal ageing equal to unity $\vartheta_{hsr} = 98\,°\mathrm{C}$)

Model 2 - the model from [2], with realistic thermal characteristics obtained by tests ($\Delta\theta_{or} = 42.6$ K, $Hg_r = 27.4$ K, $x = 0.835$, $y = 1.568$, $\tau_0 = 3$ h, $\vartheta_{hsr} = 98\,°\mathrm{C}$)

Model 3 - the model with realistic characteristics (like Model 2) and with the winding time constant ($\tau_{Cu} = 4$ min)

Model 4 - the original authors' model, based on the thermal circuit and two sets of parameters

Model 5 - the Hot-spot temperature calculated by means of expression (1) and in accordance with measured temperatures.

It may be concluded that the calculation of ageing, being a cumulative process, can be successfully made by means of both the original thermal model and that given in [2], but with thermal parameters obtained by experiment in the case of the latter one (note that neglecting of winding time constant does not practically affect the re-

Table 4. Maximum errors of estimated temperatures in respect to measured values

Load (p.u.) and time	Fig.	Original algorithm – unique paramet.		Original algorithm – differ. paramet.		Standards [2] – parameters given in tables		Standards [2] – realistic parameters and τ_{Cu}	
		$\Delta\theta_{Cu,hs}$	$\Delta\theta_{Oil,t}$	$\Delta\theta_{Cu,hs}$	$\Delta\theta_{Oil,t}$	$\Delta\theta_{Cu,hs}$	$\Delta\theta_{Oil,t}$	$\Delta\theta_{Cu,hs}$	$\Delta\theta_{Oil,t}$
Constant power $P = 1.1$	4a	1.78	1.80	1.78	1.80	28.36	10.48	5.24	6.73
Constant current $I = 0.844$		1.12	1.88	1.12	1.88	15.39	5.65	3.17	3.23
Constant current $I = 1.14$		2.58	2.84	2.58	2.84	30.23	7.71	5.74	6.02
Constant current $I = 1.35$		3.16	3.68	3.16	3.68	37.89	7.02	10.81	10.28
Power step-down $P_1 = 1.1$, $P_2 = 0.55$	4b	3.15	1.60	0.938	0.534	10.47	6.63	1.26	0.76
Overload $P_1 = 1.1$, $P_2 = 0.55$ $\Delta t = 15$ min	4c	2.76	1.32	1.31	0.671	11.96	6.08	2.78	0.93
Overload $P_1 = 1.1$, $P_2 = 0.55$, $\Delta t = 63$ min	4c	3.25	1.57	1.08	0.906	12.18	6.63	3.03	2.60
Intermittent duty $P_1 = 1.28$, $P_2 = 0.28$, $t_1 = 0.5$ h, $t_2 = 1.5$ h	4d	2.55	1.22	2.55	1.58	27.96	7.22	4.72	3.88
Intermittent duty $P_1 = 1.39$, $P_2 = 0.28$, $t_1 = 0.5$ h, $t_2 = 1$ h	4d	2.73	1.44	2.76	1.86	28.59	7.08	6.55	5.02
Intermittent duty $P_1 = 1.39$, $P_2 = 0.28$, $t_1 = 15$ min, $t_2 = 30$ min	4d	2.02	1.26	2.64	1.79	25.83	4.51	5.74	4.57
Daily diagram	4e	3.81	2.73	3.42	2.27	19.30	8.34	8.02	7.54

Table 5. Values of relative ageing, obtained in different ways for Hot-spot temperature calculation

Load (p.u.) and time	Ageing				
	Model 1	Model 2	Model 3	Model 4	Model 5
Constant power $P = 1.1$	1.4093	0.3853	0.3852	0.4695	0.4771
Power step-down $P_1 = 1.1$, $P_2 = 0.55$	0.0594	0.0376	0.0386	0.0394	0.0398
Short-time overload $P_1 = 1.1$, $P_2 = 0.55$, $\Delta t = 15$min	0.0469	0.0309	0.0303	0.0330	0.0315
Short-time overload $P_1 = 1.1$, $P_2 = 0.55$, $\Delta t = 63$min	0.0942	0.0619	0.0617	0.0649	0.0619
Intermittent duty $P_1 = 1.28$, $P_2 = 0.28$, $t_1 = 0.5$h, $t_2 = 1.5$h	0.1111	0.0540	0.0491	0.0545	0.0466
Intermittent duty $P_1 = 1.39$, $P_2 = 0.28$, $t_1 = 0.5$h, $t_2 = 1$h	0.3905	0.1709	0.1516	0.1862	0.1574
Daily load diagram	0.3226	0.1109	0.1134	0.1612	0.1388

sults of ageing calculation). It can be seen that the deviations obtained do not exceed 20% in respect to the results on the basis of the measured temperatures. On the other hand, if the thermal parameters were taken from tables in [2], the resulting deviations could become intolerable. For the transformer under consideration, resulting deviations can be explained by the fact that the heat exchanger oil/air area (i.e. the radiator area) has too large dimensions in respect to the transformer rated power.

5

Discussion of the practical aspect of high-precision thermal models

The increase of the precision in sizing a new transformer and the optimal utilizing the units already being in operation has – by all means – high practical effects, from both engineering and economic points of view. An accurate thermal model allows an accurate obtaining the Hot-spot temperature, which is the most important item when loading a transformer. It represents the basis for the determination of the relative ageing, which is an important parameter when long-term loadings are concerned. When the need for high-precision thermal model is discussed, it must be born in mind that commonly used expression for ageing calculation (that the ageing is doubled for every temperature rise of 6 K [2]) is substantially approximate, and that the knowledge of insulation features is necessary. Also, it is impossible to predict precisely the load and the ambient temperature during a planned long-term loading.

Due to formerly mentioned reasons, first of all the accurate thermal model is significant when real-time applications are made, e.g. when thermal protective devices are to be set. The direct measurement and supervision of Hot-spot temperature is neither easily attainable nor comfortable, especially at higher voltage levels, although today optical fibre systems exist. The developed thermal model could be used as the basis for the implementation of protective devices built with microprocessors.

Another possible application of the thermal model in the real time is that it could be a component in a remote supervising and control system. It is possible to simulate the load which the dispatching operator intends to apply, using the proposed model. The implementation may be either at the PLC (Programmable Logic Controller) or at the central computer level. In such a way, it may be answered whether it is allowed to make the intended loading during the pre-viewed period of time. In other words, it would be possible to utilize the thermal capability of each transformer in an optimal way, i.e. to go up to the allowed temperature limits as close as possible, without the danger to exceed their critical values. The thermal capacity of the winding could also be utilized in such applications of the proposed model.

6

Prospects for future work – consideration of the winding Hot-spot

According to expression (1), the difference between the Hot-spot and upper oil temperatures is calculated as the product of the Hot-spot coefficient ($H = 1.1$) and the difference between the winding average and oil average temperatures. In order to verify the accuracy of such a calculation, a number of tests on transformer 3 were made with numerous sensors built in the winding and placed in the oil and on the tank.

Further on, starting from these measurements on transformer 3 an original model is in course of establishing, aimed to deliver the space distribution of temperatures, as well as Hot-spot allocation and its temperature. The results of similar experiments can be found in [7], but only for an isolated winding (i.e. without core and neighboring windings) placed in an oil-filled tank. In addition, in [7] there is not a model allowing the calculation of the temperature distribution, including its value at the hottest spot. Such a thermal model was developed for the air-cooled transformers [11], where the radiation heat transfer also exists. The main problem of oil-immersed transformers is the determination of the convection heat transfer coefficients (average as well as local ones), because the corresponding expressions cannot be found in reference books and published papers. Such convection heat transfer coefficient expressions, obtainable in reference books dealing with a constant heat flux and cylinders in large fluid mass, with a single or both-side heated ducts and with a cylinders situated in a rectangular container (e.g. [1, 12–14]), are valid under certain conditions which are not present in power transformers. Note that such problems do not arise in treating dry-type, air-cooled transformers.

7

Conclusions

A survey of up-to-date thermal models of oil power transformers is given in the paper, as well as the results obtained studying the complex phenomena appearing when the transformer is being loaded. Based on their experimental research, the authors have shown how large errors (deviations from accurate results) can appear using the simplifications made in setting up the model from international standards [2].

The applications of the model proposed by the authors show that high precision results were attained. It came out that using two sets of circuit parameters (one when power steps up and the other when it steps down) when simulating the varying load operation leads to the improvement of temperature calculation accuracy. The procedure is based on the simulation of a non-linear process, so that the notion of a time constant must be abandoned. In the era of wide-spread use of computers, the conventional approach with time constant, which is characteristic in linear systems, is not necessary. The problem of time constant variation, which is neglected [2] or treated in a very approximate way [6], is now solved by the proposed model.

As for the ageing calculation, the authors' proposition is that the procedure given in [2] may be used provided the realistic thermal characteristics obtained by tests are applied. The reasons are approximations and uncertain knowledge of quantities needed for ageing determination, as shown in Section 5. In addition, the procedure given in [2] is the standard treatment, whose goal is to obtain a comparative, general insight of this problem for a wide range of transformers and loadings.

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