# Numerical Determination of Characteristic Temperatures in Directly Loaded Power Oil Transformer

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**Abstract**

*The paper presents the application results of original non-linear non-stationary thermal model of the oil power transformers. The main advantage of the model is precise treatment of non-linear convection heat transfer influence to the transient thermal process. It is convenient to calculate the model parameters from the short-circuit heating experiment. The aim of this paper is to investigate the precision of such obtained parameters application to a transformer in normal operation. For that purpose, the precise calculation of power losses distribution is needed and is proposed in the paper. For experimental verification of the model accuracy the measuring method for continuous monitoring of mean winding temperature of directly loaded transformer is developed.*

## 1 Introduction

The basic criterion for transformer loading is the temperature of the winding's hot-spot. Its determination represents a very complex task. To solve it, two approaches are possible: a1) to measure it, using fiber-optic techniques, which is still of no practical (commercial) use, and b1) to calculate it, using a thermal model of power transformer and real time-varying load information. Due to the complexity of the phenomena there exists no exact thermal model. A number of papers have been published proposing improvements of the thermal model from the valid IEC standard [1]. Results of a thermal model application can be: a2) the temperature distribution over the whole winding, or b2) the temperature values at the characteristic points.

The approach with complete temperature distribution requires the use of a heat flux winding network with exactly defined convection heat transfer coefficients over the whole winding surface. Such an approach is possible in transformers of a dry type [2] and in an oil filled transformer with directed oil flow and forced air flow (ODAF cooling type), used in high rated units [3]. In the cases of transformers of these two types the main convection heat transfer characteristics can be determined by heat transfer theory [4]. The boundary convection conditions on the winding surface can be approximately described as theoretically known cases of a channel or of a surface in a free fluid stream, both with constant heat flux and with free or forced fluid flow. The problem appears when transformer with natural oil flow (ON) is treated. The conditions of oil streaming in enclosure and return oil path through radiators disable us to use formulas from convection heat transfer theory [5, 6].

That is why thermal models for transformers with ON cooling system are established by using characteristic points temperatures. For example, such models are published in [7] and [8]. They use relations known from the convection heat transfer theory and empirical expressions obtained on experimental basis. Application of these formulas to ON power transformers is not quite correct as the conditions under which they are established differ from those existing in oil power transformers. Transformer characteristic temperatures measuring, in order to obtain reliable parameters in the formulas mentioned above, is a possible approach. Models given in [7] and [8] need the temperatures which are difficult to measure – for example, the oil temperature at the top of the cooling duct [7] or temperature at the outer surface of the winding top [8]. There is a real need for use of a model whose parameters can be determined by simple experiments. It would be convenient to use experiments with no additional sensors inside the transformer tank.

Originally developed algorithm for temperature calculation [9, 10] needs no measurements difficult to perform. All measurements can be obtained without positioning additional sensors inside the tank. The procedure for continuous measurement of mean winding temperature during the short-circuit heating experiments, using measuring DC current superposed to AC load current, was developed [11]. The radial temperature gradient, the effect of additional conductor losses due to stray fields and change of local convection heat transfer coefficient with winding height are taken into account in a simplified manner, by the factor $H = 1.1$ (as in IEC 60354 standard). As for factor $H$, some analyses based on extensive experimental research on 630 kVA transformer with 114 thermocouple sensors built in it have been published in [12].

This paper treats the precision of the thermal model application on a real operating transformer since the analyses in author's previous papers were predominantly oriented to a transformer heated in a short-circuit heating test.

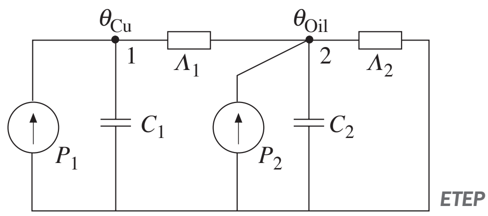


**Fig. 1.** The circuit diagram with two nodes

## 2 Short description of the original thermal model

The characteristic temperatures calculation method is based on the representation of the heat processes by circuit diagrams. The most frequently used circuit with lumped parameters has two nodes (as shown in **Fig. 1**). In establishing the circuit diagrams, individual parts of a transformer are represented by corresponding nodes, each representing the complete volume of a part of a transformer – the first one for windings and the second one for the core, oil and tank. Temperature rises with respect to ambient temperature are used in the thermal circuit. Copper temperature is represented by hot-spot, and oil temperature by top-oil. Hot-spot temperature ($\vartheta_{Cuhs}$) is calculated on the basis of easily measuring temperatures – mean winding temperature ($\vartheta_{Cua}$), ambient temperature ($\vartheta_a$), top-oil temperature ($\vartheta_{to}$) and temperatures of the radiator outer surface – at the top ($\vartheta_{rt}$) and the bottom ($\vartheta_{rb}$). Definition formula, expressed by temperature rise values, is:

$$\theta_{Cuhs} = \theta_{to} + 1.1\left(\theta_{Cua} - \left(\theta_{to} - \frac{\theta_{rt} - \theta_{rb}}{2}\right)\right) \tag{1}$$

The powers of heat generation inside the windings, i.e. the core and tank, are denoted as $P_1$ and $P_2$, respectively.

The thermal conductances $\Lambda_1$ and $\Lambda_2$ are temperature dependent:

$$\Lambda_1 = K_1\,(\theta_{Cu} - \theta_{Oil})^{n_1} \tag{2}$$

and

$$\Lambda_2 = K_2\,(\theta_{Oil})^{n_2}, \tag{3}$$

where $K_1$, $n_1$, $K_2$, $n_2$ are constants. That is why the system of two differential equations describing the circuit in Fig. 1 is non-linear and has to be solved by using numerical methods.

In [9] and [10] the procedure for thermal circuit parameters determination, based on short-circuit heating experiment results, was presented. Thermal conductance parameters can be calculated from several thermal steady-states. Thermal capacitances ($C_1$ and $C_2$) determination needs recorded values in transient process; they can not be calculated as a product of mass and specific heat. Using recorded data from thermal transient process, determination of thermal conductance parameters is also possible.

Using the thermal equivalent circuit and its determined parameters, temperatures resulting from arbitrary loading diagrams can be calculated. Equations corresponding to the thermal circuit are solved using numerical method; power losses are calculated on the basis of load and winding temperature, as described in Chapter 3.

The basic idea was that thermal conductivity parameters and thermal capacitances do not depend on thermal source locations, which are different in short-circuit test and in real load conditions of the transformer in normal operation. This assumption enables temperatures determination from relatively simple short-circuit heating-up tests. Experimental investigation of this assumption is done on a small, specially constructed transformer of ratings 6.6 kVA, $3 \times 380$ V/$3 \times 220$ V and is presented in the paper.

## 3 Power losses

### 3.1 Short-circuit heating-up test

In short-circuit heating-up test, losses are dominantly concentrated in windings, but they are somewhat higher with AC supplying than when measured with direct current (generally taken into account by the field coefficient); also, there are power losses in construction parts of the transformer, due to inducted currents ($P_{\gamma\,constr.}$). Their value can be obtained in the following way. First, losses due to the hypothetical direct current having the same rms value as the realistic alternating current in both high- ($P_{\gamma DC1}$) and low-voltage ($P_{\gamma DC2}$) windings are calculated. Losses $P_{\gamma DC1/2}$ are calculated as the product of measured current squared and the winding resistance which is continuously measured by injecting a small superimposed direct current [11]. Next, the winding losses are obtained by applying the field factor:

$$P_{\gamma Cu} = k_{F1}\,P_{\gamma DC1} + k_{F2}\,P_{\gamma DC2}. \tag{4}$$

The value of $P_{\gamma\,constr.}$ is obtained by subtracting the value of $P_{\gamma Cu}$ from the value of total, directly measured value of short-circuit power losses ($P_{\gamma SC}$):

$$P_{\gamma\,constr.} = P_{\gamma SC} - P_{\gamma Cu}. \tag{5}$$

From the measured values of current and power during short-circuit heating-up test, the value of coefficient $f$, representing the ratio $(P_{\gamma DC1} + P_{\gamma DC2})/P_{\gamma SC}$ at reference current $I_r$ and reference mean winding temperature $\vartheta_{Cuar}$ can be determined; the referent short-circuit power losses amount $P_{\gamma SCr}$. In [13] it is shown how this can be made. Losses caused by an arbitrary current $I$ at a given temperature $\vartheta_{Cua}$ may be calculated by using the expression

$$P_{\gamma SC} = \left(f\,\frac{235 + \vartheta_{Cua}}{235 + \vartheta_{Cuar}} + (1 - f)\,\frac{235 + \vartheta_{Cuar}}{235 + \vartheta_{Cua}}\right) P_{\gamma SCr}\left(\frac{I}{I_r}\right)^2. \tag{6}$$

Eq. (6) is based on the fact that referred currents in both windings are equal in the short-circuit test and that the temperatures in both windings are approximately equal.

### 3.2 Normal operation

When a transformer operates in real conditions, power losses in magnetic core are present ($P_{Fe}$), because the magnetic induction is very much higher than in the short-circuit. It is generally assumed that this losses are constant when the supply voltage is maintained on the constant (rated) value, so their value can be taken from the no-load test.

Load losses can be calculated by the basic eq. (6), supposing that the factor $f$ is the same as in the short-circuit test. Due to the magnetizing current component (having the complex value $\underline{I}_m$), the referred currents in h-v and l-v windings are not equal, which must be taken into account when accurate evaluation of losses is made. Let the load current referred to the side connected to the supply be $\underline{I}'_{load}$, then the resulting current in winding connected to the supply is

$$\underline{I}_{supply} = \underline{I}'_{load} + \underline{I}_m. \tag{7}$$

The difference of referred currents $\underline{I}'_{load}$ and $\underline{I}_{supply}$ makes demand to take into account the difference of referred winding resistance values. If the resistance of the winding connected to the supply is $R_{DC2}$ and the referred resistance of the winding connected to the load is $R'_{DC1}$, both at the same reference temperature, then the power of load losses in both of these windings – the load side ($P_{I\,load}$) and the supply side ($P_{I\,supply}$) – may be written as

$$P_{I\,load} = f\,\frac{P_{Cur}}{1+k}\,k\,\frac{235+\vartheta_{Cua}}{235+\vartheta_{Cuar}}\left(\frac{I'_{load}}{I_r}\right)^2 + (1-f)\,\frac{P_{Cur}}{1+k}\,k\,\frac{235+\vartheta_{Cuar}}{235+\vartheta_{Cua}}\left(\frac{I'_{load}}{I_r}\right)^2 \tag{8}$$

and

$$P_{I\,supply} = f\,\frac{P_{Cur}}{1+k}\,\frac{235+\vartheta_{Cua}}{235+\vartheta_{Cuar}}\left(\frac{I_{supply}}{I_r}\right)^2 + (1-f)\,\frac{P_{Cur}}{1+k}\,\frac{235+\vartheta_{Cuar}}{235+\vartheta_{Cua}}\left(\frac{I_{supply}}{I_r}\right)^2, \tag{9}$$

where $k$ is the ratio of $R'_{DC1}/R_{DC2}$. Note that both expressions are valid if mean temperatures of both windings are equal; the same assumption has already been included in thermal circuit shown in Fig. 1. The total load loss in the really loaded transformer is equal to the sum

$$P_I = P_{I\,load} + P_{I\,supply} \tag{10}$$

The loss is divided into two parts: the first, generating the heat in windings ($P_{\gamma JAC}$), and the second, creating the heat in construction parts of the transformer ($P_{\gamma\,constr.}$). The former can be calculated as

$$P_{\gamma JAC} = 3\,\frac{235+\vartheta_{Cua}}{235+\vartheta_{Cuac}}\left(I^2_{supply}\,k_{F1}\,R_{DC2C} + I'^2_{load}\,k_{F2}\,R'_{DC1C}\right). \tag{11}$$

### 3.3 The distribution of losses between the nodes in the thermal circuit

When the transformer is heated up in the short circuit test, the power $P_1$ is equal to $P_{\gamma Cu}$, which is calculated by eq. (4), and the power $P_2$ is equal $P_{\gamma\,constr.}$ which may be obtained by eq. (5). Following quantities are to be measured: the total loss $P_{\gamma\,SC}$, the current and direct current winding resistance.

In the case when the transformer is heated up in normal operating conditions, the procedure of calculating losses $P_1$ and $P_2$ is as follows:

- load losses are calculated according to eqs. (8), (9) and (10), the load current and the average winding temperature being measured (see Chapter 4); since the average winding temperature measurement is not quite easy to perform in plants in normal use, alternative way through the calculated hot-spot temperature and easily measured temperatures $\vartheta_a$, $\vartheta_{to}$, $\vartheta_{rt}$ and $\vartheta_{rb}$ (using eq. (1)) can be used;
- winding losses are calculated by means of eq. (11);
- losses in construction parts ($P_{\gamma\,constr.}$) are found subtracting winding losses from load losses; and
- power losses $P_1$ are equal to $P_{\gamma JAC}$, and $P_2 = P_{Fe} + P_{\gamma\,constr.}$

## 4 Measuring of mean winding temperature

The measuring method for transformer in short-circuit heating experiment is given in [11]. The circuit diagram of the mean winding temperature measuring method of directly loaded transformer is shown in **Fig. 2**.

The mean winding temperature is obtained from the measured DC "cold" and "hot" resistances. An artificial neutral point is formed by means of three 220 kΩ, one-watt resistors; in such a way the problem of measuring the DC voltage for R-obtaining is solved. In our experiments the measurements were done on both l-v and h-v sides of the transformer, the l-v case being only represented in Fig. 2.

The measurement of average l-v winding temperature was carried out by means of DC resistance variation of three phase windings connected in parallel; the measuring circuit was 1.0 A DC, and the resulting cold resistance (at ambient temperature) was 43.7 mΩ. The AC voltage between the neutral of the tested transformer and the artificial neutral point was 1.5 V (at the loading current 0.7 p.u. (per unit)), and that at the capacitance terminals of the low-pass filter (having the aim to separate the DC component of the voltage) was 5 mV.

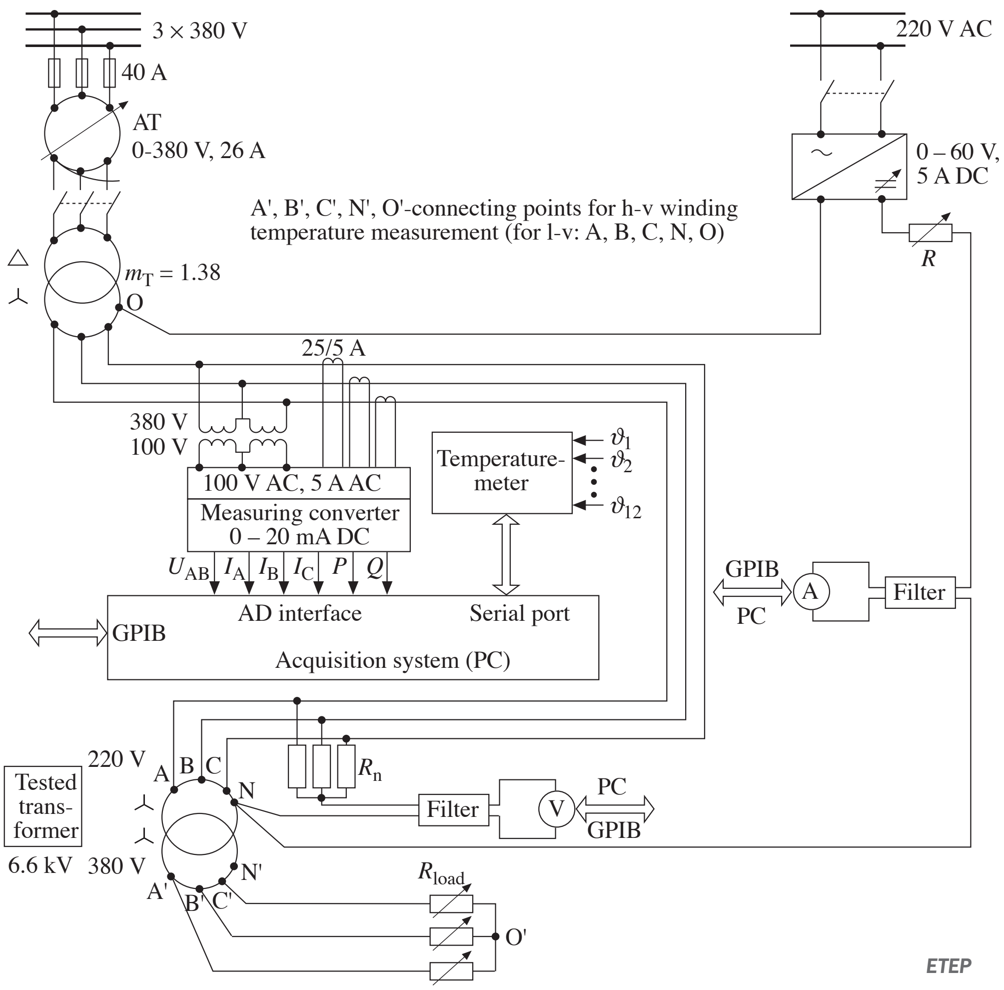


**Fig. 2.** Method of continuous mean winding temperature measuring

## 5 Experimental results

### 5.1 Reference values of power losses

The no-load test at rated voltage, with the h-v side connected to the supply, gave the following results:

$P_{Fe} = 64$ W, $\underline{I}_m = (0.0975 + j\ 1.03)$ A

Reference value of load losses was obtained from the short-circuit heating test made with the h-v windings connected to the supply, in the steady state:

$I_r = 10.02$ A, $P_{\gamma SCr} = 320$ W and $\vartheta_{Cuar} = 72.2$ °C.

From the same test, the factor $f$ was obtained as $f = 0.946$.

Values of winding resistances on both h-v and l-v sides were obtained by means of the U/I method; they were very close to the values computed by using design data: on the l-v side, this was $R_{DC2C} = 0.1215\ \Omega$, and on the h-v side (referred to the l-v) it was $R'_{DC1C} = 0.1540\ \Omega$ at the temperature 20 °C. Power loss values in both primary and secondary windings loaded with the direct current 10.02 A, and $10.02 \times \sqrt{3}$ A, respectively, were (at the reference temperature 72.2 °C) $P_{\gamma DC1} = 167.55$ W and $P_{\gamma DC2} = 132.18$ W. Field's factor, calculated for the specific arrangement of windings were obtained as $k_{F1} = 1.000392$ and $k_{F2} = 1.000557$ [14]. Therefrom, the power load loss situated inside the windings with AC current was $P_{\gamma JAC} = 299.87$ W, and that outside the windings $P_{\gamma constr.} = 20.374$ W. The ratio $(P_{\gamma DC1} + P_{\gamma DC2})/P_{\gamma SC}$ was 93.66 %, which coincides pretty well with the $f$ value calculated in other way ($f = 0.946$). As an illustration, values of all relevant quantities resulting from measurements in steady states with different currents are listed in **Tab. 1**.

### 5.2 Parameters of thermal conductances

In earlier authors publications [4, 5] parameters of thermal circuit elements were determined from the short-circuit heating tests, assuming that all losses are concentrated in the node 1. The following results are obtained after separation of the losses $P_{Constr.}$ and their

| **I** (A) | $P_{\gamma SC}$ (W) | $\vartheta_{Cua}$ (°C) | $R_{DC1}$ (Ω) | $R_{DC2}$ (Ω) | $P_{\gamma DC1}$ (W) | $P_{\gamma DC2}$ (W) | $P_{\gamma JAC}$ (W) | $P_{\gamma constr.}$ (W) |
|---|---|---|---|---|---|---|---|---|
| 5.85 | 100 | 40.8 | 0.49974 | 0.39423 | 51.3 | 40.5 | 91.8 | 8.2 |
| 6.52 | 125 | 43.5 | 0.50463 | 0.39809 | 64.4 | 50.8 | 115.2 | 9.8 |
| 7.78 | 180 | 50.1 | 0.51659 | 0.40753 | 93.8 | 74.0 | 167.9 | 12.1 |
| 8.97 | 250 | 62.5 | 0.53906 | 0.42525 | 130.1 | 102.7 | 232.9 | 17.1 |
| 10.02 | 320 | 72.2 | 0.55627 | 0.43883 | 167.6 | 132.2 | 299.9 | 20.4 |
| 11.05 | 400 | 83.6 | 0.57729 | 0.45541 | 211.5 | 166.8 | 378.5 | 21.5 |
| 12.81 | 550 | 94.7 | 0.5974 | 0.47128 | 294.1 | 232.0 | 526.3 | 23.7 |

**Tab. 1.** Power loss characteristic components

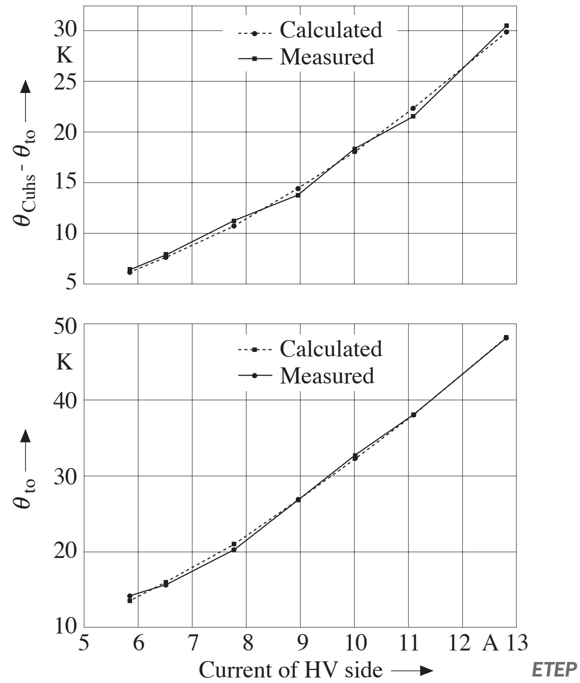


**Fig. 3.** Temperature rises – short-circuit heating tests

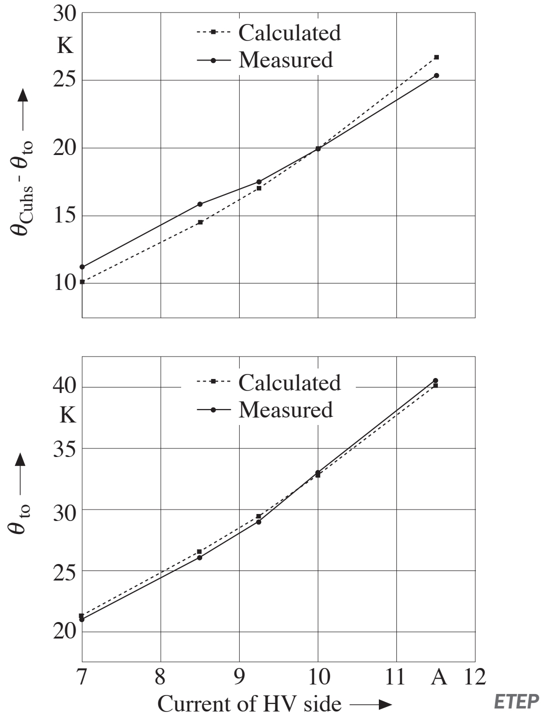


**Fig. 4.** Temperature rises – directly loaded transformer

injection in the node 2 ($P_2 = P_{Constr.}$). Values of hot-spot temperature rises (eq. (1)) and the upper oil temperature rises are shown in **Fig. 3**. Displayed are the values $\theta_{Cuhs} - \theta_{to}$ and $\theta_{to}$ obtained by measurement and calculation, parameters of thermal conductances being determined by minimizing the sum of mean square deviation of calculated to measured temperatures in thermal steady states. The obtained functional dependencies

$\Lambda_1^{(1)} = 11.726\ (\theta_{Cuhs} - \theta_{to})^{0.11877}$ and

$\Lambda_2^{(1)} = 2.997\ (\theta_{to})^{0.34502}$

result with maximum deviations of calculated from measured temperature rise values

$\Delta(\theta_{Cuhs} - \theta_{to}) = 0.76$ K and $\Delta\theta_{to} = 0.71$ K.

If the thermal conductances $\Lambda_1^{(1)}$ and $\Lambda_2^{(1)}$ were used for calculation of steady-state temperatures of transformer in normal operation, the maximum deviations of calculated to measured temperature rises are $\Delta(\theta_{Cuhs} - \theta_{to}) = 2.38$ K and $\Delta\theta_{to} = 5.51$ K. The deviations can be reduced by correcting either the parameters of thermal conductances and/or power loss values. Changing, i.e. adapting of the power losses is not favorable for the proposed way of calculating. Such a procedure would require additional measurements. Some attempts were made on the basis of calculating the power losses as input-output power difference, in spite of the fact that such a method suffers from requiring very high accuracy for measuring input and output power values. The other idea was the application of calorimetric method, but unfortunately it was not accessible to the author, at least for the time being. Correction of parameters, resulting in forming a new set of parameters, can be made using the principle of parameter estimation based on measurement results on the really loaded transformer. **Fig. 4** presents temperature rises, obtained by the previously described new set of parameters, amounting:

$\Lambda_1^{(2)} = 10.782\ (\theta_{Cuhs} - \theta_{to})^{0.11877}$ and

$\Lambda_2^{(2)} = 3.600\ (\theta_{to})^{0.34502}$.

Before the estimation procedure is applied, the exponents were fixed to the values given in $\Lambda_1^{(1)}$ and $\Lambda_2^{(1)}$. Maximum deviations of calculated from measured values are $\Delta(\theta_{Cuhs} - \theta_{to}) = 1.35$ K and $\Delta\theta_{to} = 0.47$ K.

### 5.3 Thermal capacitances

Applying the procedure of thermal capacitances estimation to the case of divided power losses in short-circuit heating experiment, the following values were obtained: $C_1^{(1)} = 6561$ J/K and $C_2^{(1)} = 94500$ J/K. For the calculation, the data of heating experiment with constant power losses, amounting to 37.5 % higher value than the total rated losses were used. Using the parameters $\Lambda_1^{(1)}$, $\Lambda_2^{(1)}$, $C_1^{(1)}$ and $C_2^{(1)}$, the simulations of heating process in short-circuit heating experiments with different current time shapes and values were done. Maximal deviations from measured values for series of tests were: for the hot-spot 4.26 K and for the top-oil 3.43 K.

As expected, calculation of temperatures in the transformer in normal operation with the previous set of parameters has somewhat lower precision: maximal deviations from measured values are 8.34 K for the hot-spot and 6.23 K for the top-oil.

Finally, the values of $C_1$ and $C_2$ were estimated from one recorded transient thermal process in transformer in normal operation. The thermal conductances parameters had been fixed at $\Lambda_1^{(2)}$ and $\Lambda_2^{(2)}$ and the thermal capacitances were calculated from the test with constant load (75 % of rated current). The values $C_1^{(2)}$ = 6652 J/K and $C_2^{(2)}$ = 139091 J/K are so obtained. For the group of simulations, with parameters $\Lambda_1^{(2)}$, $\Lambda_2^{(2)}$, $C_1^{(2)}$ and $C_2^{(2)}$, of thermal process in the transformer in normal operation, the results will be exposed more in detail. In **Tab. 2** the list of tests (starting from different temperature conditions) is given, as well as the maximal deviations of calculated from measured temperatures. In **Figs. 5–8** the time change of characteristic temperatures, to different current shapes are given.

| Load | Maximal temperature deviation (K) | |
|---|---|---|
| | **Hot-spot** | **Top-oil** |
| Constant load (0.7 $I_r$) | 2.54 | 0.795 |
| Constant load (0.85 $I_r$) | 1.89 | 2.17 |
| Constant load ($I_r$) | 1.34 | 2.77 |
| Constant load (1.15 $I_r$) | 2.55 | 2.16 |
| Short-time overload (basic load 0.75 $I_r$, overload 1.1 $I_r$, 1 h) | 3.39 | 1.08 |
| Short-time overload (basic load 0.7 $I_r$, overload 1.25 $I_r$, 2 h) | 3.10 | 2.27 |
| Intermittent load (0.635 $I_r$, 30 min; 1.21 $I_r$, 30 min) | 4.81 | 1.57 |
| Intermittent load (0.795 $I_r$, 1 h; 1.3 $I_r$, 30 min) | 5.05 | **2.92** |
| Complex real daily load diagram | **5.25** | 2.56 |

**Tab. 2.** Overview of the tests on transformer in normal operation

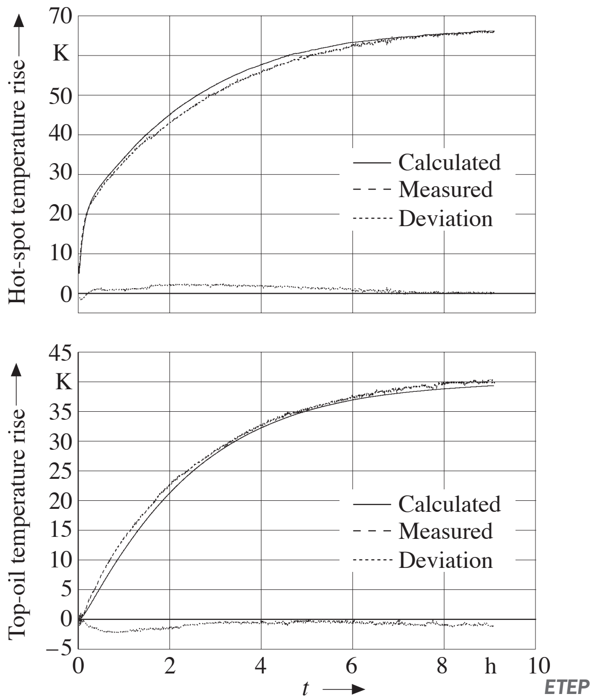


**Fig. 5.** Constant load of 1.15 $I_r$

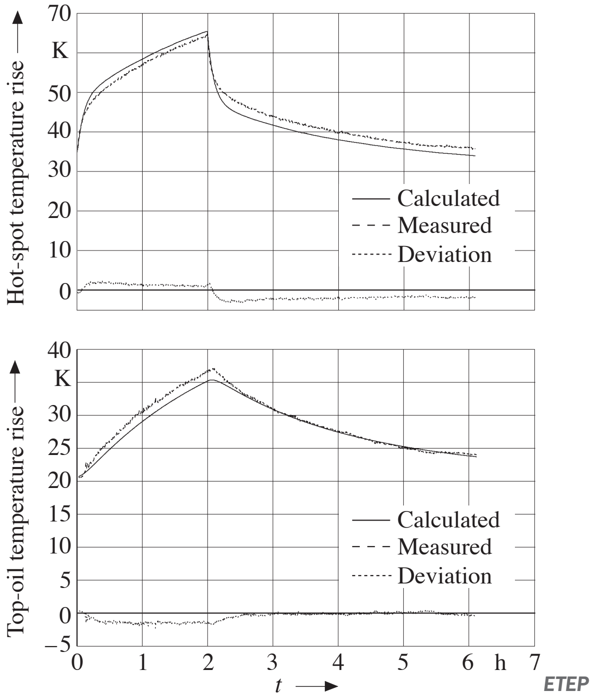


**Fig. 6.** Short-time overload (basic load 0.7 $I_r$, overload 1.25 $I_r$)

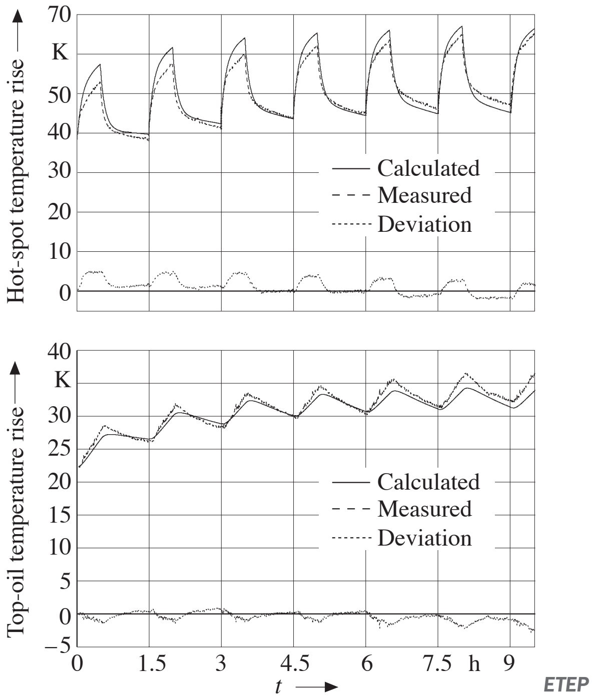


**Fig. 7.** Intermittent load (lower load 0.795 $I_r$, higher load 1.3 $I_r$)

It can be seen that calculation accuracy for directly loaded transformer with the new parameters set is on the same level as precision for short-circuit heating test.

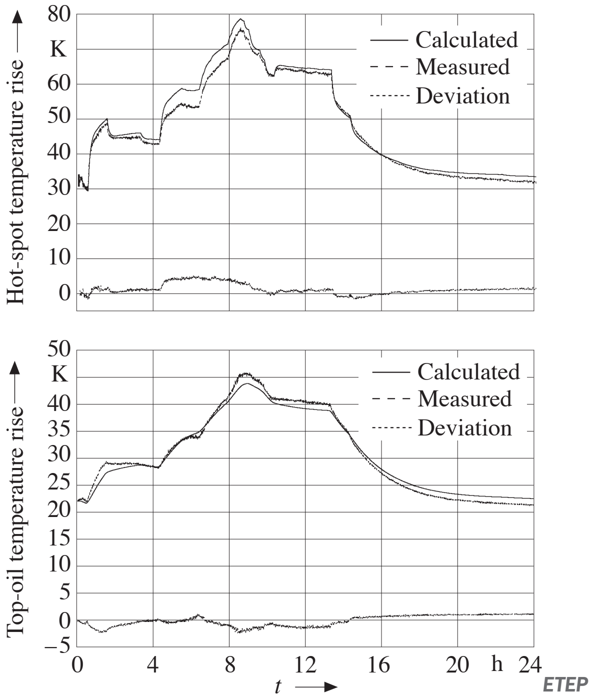


**Fig. 8.** Complex daily load diagram

## 6 Conclusion

An accurate method for assessing the load losses (including stray losses in windings and losses in adjacent construction parts of the transformer) is exposed. Also, the method of continuous monitoring of mean winding temperature of transformer in normal operation is developed. The evaluation is used to state the possibility of applying the thermal parameters of the original model obtained from short-circuit heating tests to the directly loaded transformer. The results showed that the model gives somewhat less precise results if no corrections of thermal parameters obtained from short-circuit heating tests are made.

Experiments and analyses were made on a relatively small transformer, designed and built specially for laboratory investigation. The similar research on ONAN type transformers of larger ratings may lead to more general and more reliable recommendations regarding the influence of different heat sources space distribution in transformer in short-circuit heating test and in normal operation to the transformer thermal parameters.

## 7 List of symbols, subscripts and superscripts

### 7.1 Symbols

| | |
|---|---|
| $H$ | hot-spot factor from IEC 60354 |
| $\vartheta$ | temperature |
| $\theta$ | temperature rise in respect to ambient temperature |
| $P_1$ | power of heat generation inside the windings |
| $P_2$ | power of heat generation inside the core and tank |
| $\Lambda_1$ | thermal conductance copper – oil |
| $K_1$, $n_1$ | parameters of thermal conductance $\Lambda_1$ |
| $\Lambda_2$ | thermal conductance tank – air |
| $K_2$, $n_2$ | parameters of thermal conductance $\Lambda_2$ |
| $C_1$ | thermal capacitance of the windings |
| $C_2$ | thermal capacitance of the oil, core and tank |
| $P_{\gamma\,\mathrm{constr.}}$ | power losses in construction parts of the transformer |
| $P_{\gamma\mathrm{DC1}}$ | hypothetical direct current losses in the higher voltage windings |
| $P_{\gamma\mathrm{DC2}}$ | hypothetical direct current losses in the lower voltage windings |
| $P_{\gamma\mathrm{Cu}}$ | total winding losses |
| $k_{\mathrm{F1}}$ | Field (eddy current) factor for the higher voltage winding |
| $k_{\mathrm{F2}}$ | Field factor for the lower voltage winding |
| $P_{\gamma\mathrm{SC}}$ | total, measured, short-circuit power losses |
| $I$ | current |
| $f$ | $(P_{\gamma\mathrm{DC1}} + P_{\gamma\mathrm{DC2}})/P_{\gamma\mathrm{SC}}$ ratio at rated values of $I$ and $\vartheta_{\mathrm{Cua}}$ |
| $P_{\mathrm{Fe}}$ | iron core losses |
| $\underline{I}_{\mathrm{m}}$ | complex value of magnetizing current |
| $\underline{I}'_{\mathrm{load}}$ | load current referred to the winding connected to the supply |
| $\underline{I}_{\mathrm{supply}}$ | current in the windings connected to the supply |
| $R_{\mathrm{DC2}}$ | resistance of the lower voltage windings |
| $R'_{\mathrm{DC1}}$ | referred resistance of the higher voltage windings |
| $R'_{\mathrm{DC2}}$ | referred resistance of the lower voltage windings |
| $R_{\mathrm{DC1}}$ | resistance of the higher voltage windings |
| $k$ | $R'_{\mathrm{DC1}}/R_{\mathrm{DC2}}$ ratio |
| $P_{\mathrm{I\,load}}$ | power of load losses in windings on loaded side |
| $P_{\mathrm{I\,supply}}$ | power of load losses in windings on supplied side |
| $P_{\mathrm{I}}$ | total power of load losses |
| $P_{\gamma\mathrm{JAC}}$ | total power of heat generation in windings |

### 7.2 Subscripts

| | |
|---|---|
| a | ambient |
| Cuhs | insulation hottest spot (hot-spot) |
| Cua | mean winding |
| to | top-oil |
| rt | radiator top |
| rb | radiator bottom |
| Cu | copper |
| Oil | oil |
| c | values in the “cold” conditions $\vartheta_{\mathrm{Cuac}} \approx 20$ °C |
| r | rated quantity value |

### 7.3 Superscripts

| | |
|---|---|
| (1) | parameters determined from short-circuit heating experiments |
| (2) | parameters determined from measurements on directly loaded transformer |

## References


[1] International Standard IEC 60354: Loading guide for oil immersed transformers. 1991

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