Thermal behaviour of transformers with natural oil convection cooling

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Abstract

This paper contains the results of characteristic temperature measurements at a 630 kVA (10 kV / 6 kV) three phase transformer. Inside the central positioned 10 kV winding there were built 102 temperature sensors during the winding manufacturing process; in addition, 10 temperatures inside and outside the transformer tank were measured. A series of heating experiments was done on the transformer with short-circuited 10 kV side. The measured values were used to analyse the characteristic temperature differences. As a very important quantity, the average winding temperature is measured, using continuously superimposed measuring DC current. The values of temperatures in steady-states and in transient regimes were analysed.

1. INTRODUCTION

There is a strong interest for the hot-spot temperature, which represents the limiting factor of transformer loading. One of the possibilities is to calculate it based on outer cooling medium temperature and transformer load as input data.
Due to the complexity of the phenomena there exists no exact thermal model. At the moment the IEC 60354 standard for transformer loading, including transformer thermal model, is under revision. Some quite fundamental changes were made in a new draft [1]. They were analysed, i. e. the results of the proposed calculation method are compared with the measuring results. A special attention is paid to the hot-spot factor value and to the manner of hot-spot to top oil transient values calculation. In this analyses, different top oil temperatures in the transformer were used.

2. MEASUREMENTS AND EXPERIMENTS

The positions of sensors built inside the central positioned 10 kV winding are shown in Fig. 1. Additional 10 measuring points were: the oil entering (top) and exiting (bottom) the radiator, the top oil (two position – in the pocket and in the central horizontal position), five positions at different height of the outer surface of the radiator, ambient temperature. The principal electrical scheme of the experiment is given in [2]. During the transient thermal processes the following 15 local temperatures were measured, 11 positions denoted in Fig. 1: three positions at which hot-spot could be expected –

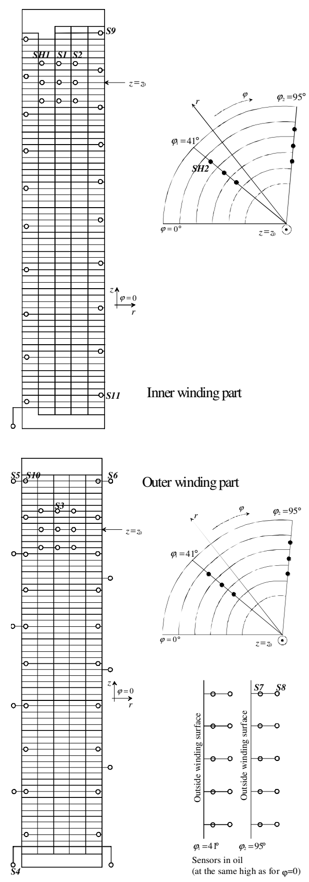

Fig. 1. The positions of temperature measuring sensors

sensors 1 – 3, oil in the cooling channel between the inner and the outer winding parts – sensors 4 and 5, oil near (3 mm) the outer winding surface – sensors 6 – 7, oil at 10 mm from the outer winding surface (undisturbed oil mass) – sensor 8, two positions at the inner winding surface– sensors 9 and 11, one position at the outer winding surface – sensor 10), the oil entering (top) and exiting (bottom) the radiator, the top oil in the pocket and the ambient. The values of other temperatures were measured only in thermal steady-states at different transformer constant loads.

The series of heating experiments was done with different load profiles [3]. Steady states were reached at 10 different loads, ranging from 26.8 % to 122.8 % of losses due to rated current – $P_{Cu\,r}$ = 8650 W; rated iron (no-load) losses amount to $P_{Fe\,r}$ = 1875 W.

3. Characteristic steady-state temperature values

In this section the hot-spot factor is analysed.

Table 1 contains the basic data of registered steady-states and Table 2 different top-oil temperatures and the values of temperature measured by sensor S1, appearing as the hottest measured copper temperature in transient thermal processes.

Table 1

Current at 6 kV side(A)	Power losses (W)	Ambient temperature (^{0}C)	Hot-spot temperature* (^{0}C)	Average winding temperature (^{0}C)	Bottom-oil temperature (^{0}C)
32	2320	16.8	47.7	38.2	24.8
34.27	2631	18.7	51.5	41.0	28.5
41.18	3808	14.1	56.4	43.5	26.5
43.7	4433	16.6	67.4	54.4	33.2
46.61	4997	16.7	70.4	56.0	35.7
48.99	5662	22.0	77.1	61.3	40.0
52.54	6342	11.7	72.6	54.9	32.0
59.92	8650	14.0	94.6	73.8	45.7
63.79	9672	6.7	90.1	71.3	38.5
65.6	10633	9.9	103.8	82.6	46.2

* - achieved at the sensor position SH1 (87.3 % of the winding high) or SH2 (82.8 % of the winding high)

Table 2

Power losses (W)	Temperature measured by sensor S1 (^{0}C)	Top oil temperature (^{0}C)					
		In the pocket	Entering the radiator	10 mm from the outer surface	3 mm from the outer surface	Central horizontal position	Top of the channel
2320	45.2	37.0	37.7	39.3	41	41.6	43.3
2631	50.5	41.4	42.2	43.6	45.4	45.2	47.8
3808	54.2	42.0	43.5	45.4	48.0	48.5	50.9
4433	64.5	50.2	53.1	54.5	57.1	57.0	60.5
4997	67.1	53.1	56.2	56.8	59.5	59.1	61.9
5662	74.1	60.1	63.1	63.8	66.5	67.7	69.4
6342	70.3	53.0	55.8	58.0	61.6	61.9	64.6
8650	91.1	69.6	74.1	76.1	80.5	82.4	82.2
9672	89.3	67.1	71.9	73.8	78.1	74.9	79.3
10633	99.7	73.1	80.0	81.5	85.8	88.9	89.1

The hot-spot appeared in the inner part of the winding, in its inner layer, at about 85 % of the winding height. The continuously measured temperature by the sensor S1 is somewhat lower than the hot-spot temperature values registered by other sensors (SH1 or SH2) in the steady-states: from 0.8 K to 4.1 K.

The value of the top oil temperature changes strongly by the change of the measuring position. As expected, the lowest value appears in the pocket, while the highest value emerge at the top of the cooling channel. A high top oil temperature value was registered in the central horizontal position, between the iron core and tank cover. The value measured by this sensor is comparable with the oil temperatures cooling the winding surfaces (at the top of the channel and 3 mm from the outer surface).

The relation between different top oil temperatures will be illustrated also on the measuring example on a small transformer of rated power 6.6 kVA and total rated power loss of 400 W – see Table 3.

By the usage of different top oil temperatures, different hot-spot factors can be expected. In the Figs. 2 – 4 the influence of top oil selection on the hot-spot factor (*H*), i. e. on the relation between the average copper minus average oil temperature gradient ($\theta_{Cua,\,oa}$) and hot-spot minus top oil gradient ($\theta_{Cuhs,\,ot}$) is shown.

Table 3

Power losses (W)	100	125	184	400	550
Top of the channel	40.4	42.2	47.6	68	80.6
Central horizontal position	36.5	38	42.3	60.5	71.3
In the pocket	33.1	34.4	37	51.9	60.9

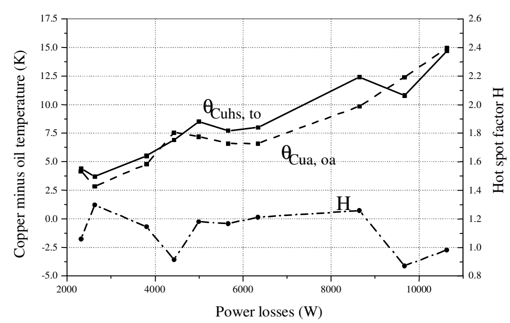

Fig. 2 Oil at the channel top; steady states

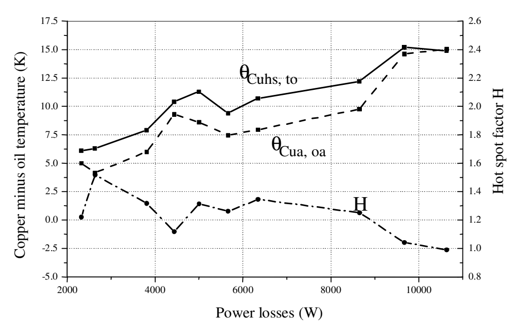

Fig. 3 Central horizontal position oil; steady states

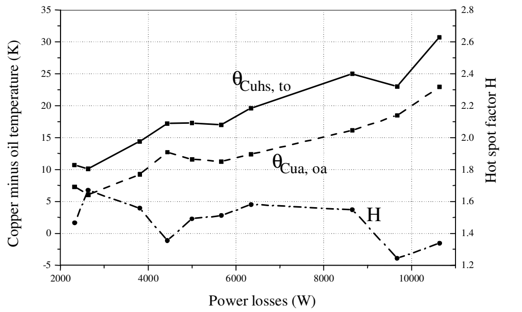

Fig. 4 Oil in the pocket; steady states

If the value of $H = 1.1$, recommended in [1] for distribution transformers, is used, the following error ranges appear: [-1.66, 1.96] K, for top oil temperature at the central horizontal position and [2.65, 7.24] K, for top oil temperature in the pocket.

4. Characteristic transient temperature values

In Figs. 5 – 7 the differences of the temperature measured by the sensor S1 and the top oil temperature in transient process, starting at transformer temperature equal ambient temperature, are shown. The losses were equal the rated copper losses (8650 W).

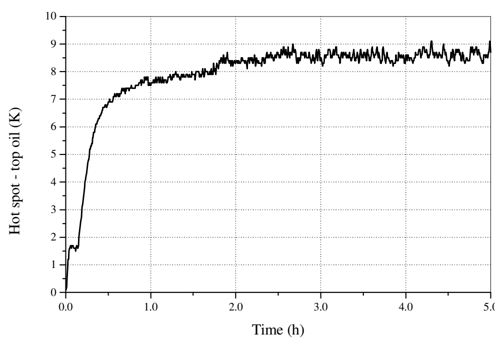

Fig. 5 Oil at the channel top; transient process

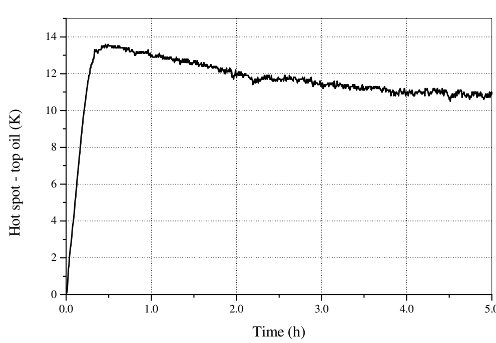

Fig. 6 Oil 3 mm from the surface; transient process

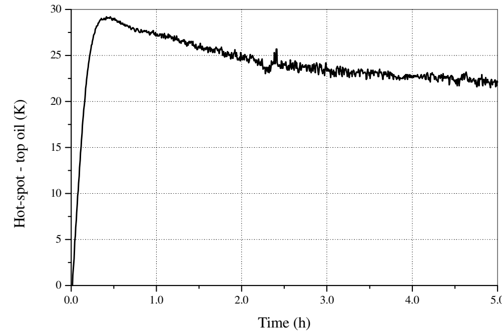

Fig. 7 Oil in the pocket; transient process

Depending on the top oil selection overshoots are different. For oil at the channel top the overshoot even does not exist. For oil 3 mm from the outer winding surface, maximum temperature difference amounts to 13.5 K, while the steady-state temperature is 10.6 K. It means the overshoot is 27 %. For oil in the pocket, overshoot is 35 %. Unfortunately, the oil temperature at the central horizontal position was not measured in transient processes.

The temperature (time) functions show the oil temperature at the top of cooling channel follows the copper temperature immediately (more precisely, the power of the heat transferred from the windings to the oil) and the oil in the pocket has a delay. Based on this, it can be concluded that the oil in the pocket temperature shape is the consequence of oil mixture, not of "the fact that it takes some time before the oil circulation has adopted its speed to correspond to the increased load level", as stated in [1].

Fig. 8 shows the copper to oil temperature gradient based on bottom oil temperature. The shape without overshoot is quite promising, i. e. the usage of bottom oil temperature could eliminate the problem caused by hot-spot minus oil in the pocket temperature gradient overshoot.

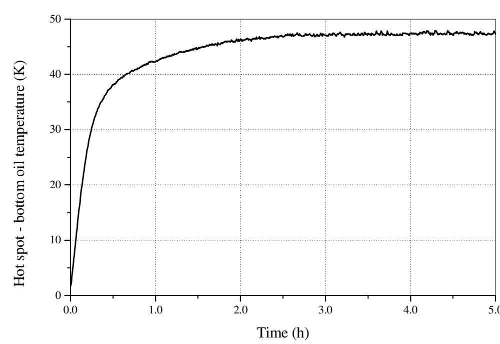

Fig. 8 Temperature difference using the bottom oil

The further measuring results are exposed for the oil temperature in the pocket, since it is the conventionally used temperature. The aim was to investigate the precision of hot-spot to top oil temperature gradient change in transients by the function introduced in the IEC draft [1].

5. Analysis of the hot-spot minus top oil gradient overshoot

By the IEC draft [1] the transient hot-spot minus top oil temperature gradient change by the load increase can be calculated as

$$\Delta\theta(t) = \Delta\theta_i + (\Delta\theta_s - \Delta\theta_i)\, f(t),$$

where are: $\Delta\theta_i$ – starting value and $\Delta\theta_s$ –steady-state value corresponding to a new load and $f(t)$ the function

$$f(t) = k_1\,(1 - e^{-t/k_2\tau_w}) - (1 - k_1)\,(1 - e^{-t/\tau_o/k_3}).$$

The values k_1, k_2 and k_3 and the time constants of the winding τ_w and the oil τ_o are transformer specific, but constant. It means that a normalised value $\Delta\theta_{rel} = (\Delta\theta - \Delta\theta_i) / (\Delta\theta_s - \Delta\theta_i)$ for one transformer has always the same time profile. The results of two types of experiments are shown in Table 4: first - constant load from the cold state and second - higher constant load from the steady-state reached with a lower load.

Table 4

Power from / to	Time in which max $\Delta\theta_{rel}$ is reached	$\Delta\theta_s$ (K)	Max $\Delta\theta_{rel}$ (K)
0 / 3750 W	0.55 h	12.2	1.39
0 / 6375 W	0.48 h	17.1	1.48
0 / 8650 W	0.45 h	21.5	1.35
6375 / 9750 W	0.58 h	21.9	1.12
4433 / 10633 W	0.5 h	26.4	1.15

It is clear that the time change of $\Delta\theta_{rel}$ is not constant. At least two different sets of parameters have to be used – the first when transformer is loaded from the cold state (temperatures equal to the ambient temperature) and the second when the starting temperatures are higher than the ambient temperature. If the value of max $\Delta\theta_{rel}$= 1.4 would be used for calculation at load increase, an overestimation of the overshoot of 6.1 K (for 6375/9750 W), i. e. 6.6 K (for 4433/10633 W) would be made.

6. Influence of a non-linear character of the heat transfer

In [3] the calculation method taking into account the influence of a non-linear character of the heat transfer to transient thermal characteristics is exposed. This influence is not included in the draft [1], with the explanation "It can be shown that the error is not great". In Table 5 this influence is exposed for the considered oil power transformers, of the rated power (S_r) 16 kVA and 630 kVA. Values in the rows denoted with "Included" are the results of calculation using [3].

Table 5

		S_r = 16 kVA	S_r = 630 kVA
Top oil [K]	Included	2.5	4.1
	Not included	4.9	9.4
Hot-spot [K]	Included	3.7	6.8
	Not included	9.3	12.5

7. Conclusions

Based on previous extensive experimental research, important parameters characterising thermal steady-states and transient processes in oil power transformers were analysed. First of all, the essential components of the thermal model from up-to-date draft of a new standard for oil transformer loading were studied. The error caused by each of approximations was precisely quantified, using the data of measurements on 630 kV power transformer with a large number of temperature sensors build inside the tank and in the winding. Improvements of the thermal modelling, especially in the direction of numerical solution of the differential equations describing the thermal circuit of a transformer, could be made using bottom oil instead of top oil. This research is prospect for the future work.

8. Literature

[1] IEC 60076-7 – Power transformers – Part 7: Loading guide for oil-immersed power transformers. Committee draft 14/403/CD

[2] Radakovic, Z.; Lazarevic, Z.: Novel methods for determining characteristic quantities for developing a thermal model of power transformers. Proceeding of the 31st Universities Power Engineering Conference 1996, Iraklion, Greece, pp. 481-485

[3] Radakovic, Z.; Kalic, D.: Results of a novel algorithm for the calculation of the characteristic temperatures in power oil transformers. Electrical Engineering, Vol. 80, No. 3, 1997, pp. 205-214