Temperature Distribution in Windings of Transformers with natural Oil circulation

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Abstract — **Based on extensive measurements on two transformer windings with installed sensors for local temperature measurements, the most significant hot-spot calculation procedures are analysed. Heating of the first winding is investigated in the case when it was a part of the complete transformer and in the case when it was situated autonomous in the tank. The second winding is investigated only autonomous positioned in a tank. The method of continuous mean winding temperature, using superimposed measuring DC current, is developed and successfully applied.**

1. Introduction

The basic criterion for transformer loading is the temperature of the winding’s hot-spot; it must not exceed the prescribed value in order to avoid the irreversible insulation faults as well as the pre-mature long-term ageing. The determination of the temperature of the winding’s insulation hot-spot represents a very complex task. To solve it, two approaches are possible: a1) to measure it, using fibre-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]. Standard approach to hot-spot temperature calculation is through using characteristic points temperatures. For example, such models are published in [2], [3] and [4]. The model from [3] is of special interest since it is given in the latest IEEE guide [5] as alternative temperature calculation method.

In fact, it is not a problem to establish a thermal model, than to define its parameters. They can be defined: a2) from a general heat transfer theory, b2) from especially provided measurements on a test model or c2) from easy measurements made as a transformer type test. The most convenient would be to use general relations from heat transfer theory, but it is possible very rear in a correct manner, i. e. in a way to keep the calculation accuracy. The reason is deviation of oil streaming conditions in a real transformer and in a setting under which the formulas are established in heat transfer theory. The same doubts hold for a2). The idea developed in a previous work of the authors [2] was to define the thermal model with parameters which can be in a great extend determined based on easy measurements.

The aim of the work presented in the paper was to make the measurements and to investigate the influence of different oil streaming conditions to parameters of thermal models. Also, the influence of the adopted constant hot-spot factor (H = 1.1) in originally developed thermal model [2] is analysed.

2. Experimental research

The measurements were made on two windings: the first one was a three-phase transformer 630 kVA (10 kV side) – 10 layers, conductor cross-section 9.8 mm^2 and the second one was the test winding consisting of 4 layers with 99 turns each (of 17.45 mm^2 cross-section). In the first winding were built 98 temperature sensors during the winding manufacturing process, as shown in Fig 1. In the second winding 30 sensors are installed (Fig. 2): 10 in the first (outer) layer, 5 in the upper part of the second layer, 10 in the oil positioned corresponding to sensors in the first winding layer and 10 mm from the winding surface, 3 at the top of the cooling channel and 2 for the top tank oil. Measurements on the first winding are made in two cases: for the winding as normal transformer part and for the winding positioned autonomous in the tank. The second winding was loaded positioned autonomous in the tank only. In the case of the first winding, continuous measurement of 15 selected temperatures was made, while other temperatures were measured only in thermal steady-states. In the case of the second winding, all quoted temperatures were measured continuously.

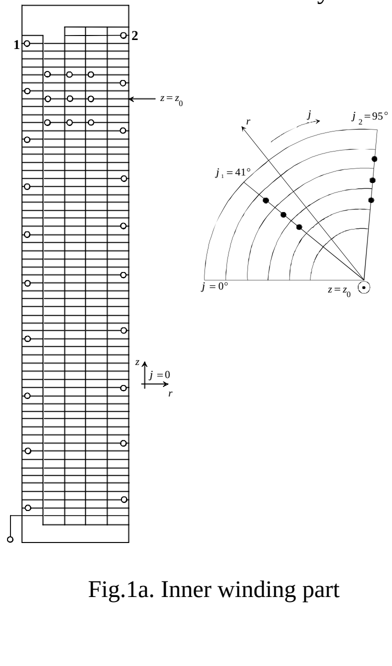

Fig.1a. Inner winding part

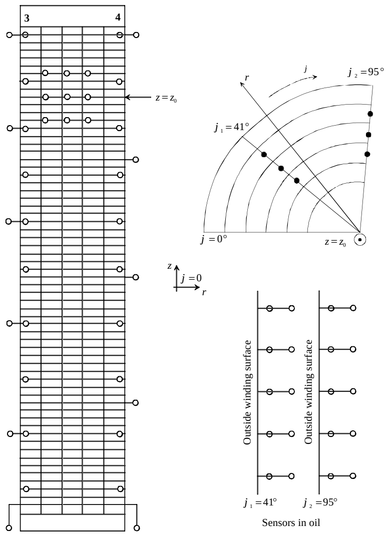

Fig.1b. Outer winding part

Fig.1. Sensor positions in winding 1

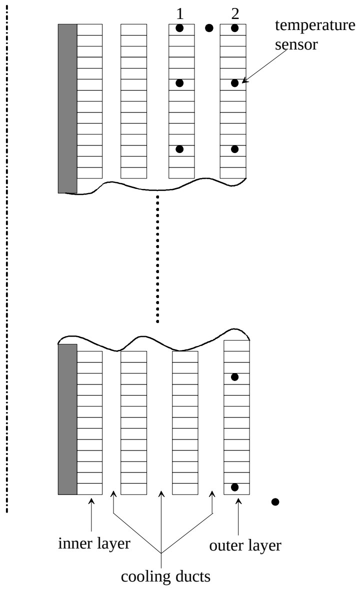

Fig.2. Sensor positions in winding 2

Additional to the measuring of the local temperatures, the mean winding temperature was recorded continuously during the heating tests. For that purpose, a special measuring method of mean winding temperature, exposed in Section 3., is applied.

Experiments in all three cases were made for different loads. Experiments had always sufficient duration to reach steady-state copper minus oil temperatures. In the cases of the windings positioned autonomous in the tank there was the limitation of oil temperature due to the limited intensity of oil to ambient air heat exchange. In addition, a high power loss generation existed in the tanks due to the high stray flux (in that case, the complete winding flux was in fact the stray flux). Due to this fact, the measuring results interpretation have to be done carefully; for the copper-oil heat transfer, relevant transferred power is much lower than the electric power passed on the winding. The winding power loss is approximately equal to the measured RMS current squared multiplied by the winding resistance measured by the U/I method proposed.

3. On-load measurement of mean winding temperature

The method of continuous measurement of the mean winding temperature is based on a superimposed direct current to an alternating load current. The connection diagram of the experimental setup for the mono-phase windings is shown in Fig. 3, while the measuring method for a transformer in a short-circuit heating experiment is given in [6]. The alternating power supply was provided by the block designed as "supply", containing functions of isolation and adjusting of the load current. The direct current circuit is coupled to the main circuit by the usage of the resistance R_2 that is continuously loaded by the required load current, somewhat increased by parasite DC component. Decrease of R_2 decreases dissipated heat at this couple resistance and needed supply voltage, but increases the needed current of DC source. DC source is made as DC current source, by the selection of the resistance R_1 dominant comparing to the other active resistances and corresponding high DC voltage U_{dc}. Reactance L_1 is used to protect DC rectifier from the AC load current flow, as well as to improve wave form of the DC current. Reactive power compensation by usage of capacitance C_k was applied in order to reduce the load of alternating power supply and the load of the resistance R_2.

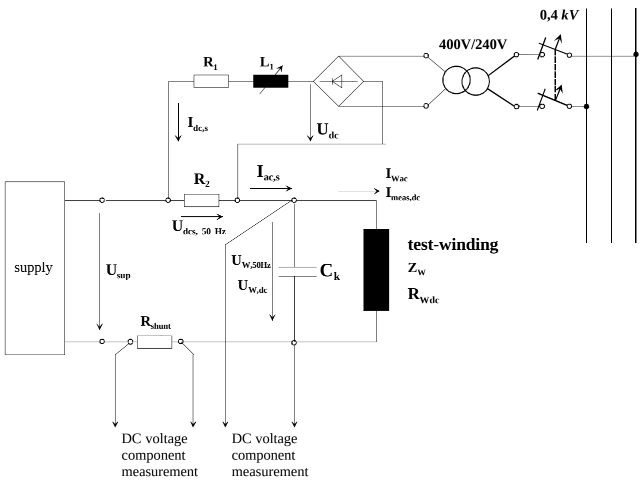

Fig.3. Connection diagram of continuous measurement of mean winding temperature

The current signal is converted to the voltage signal by the shunt resistor R_{shunt}. The extraction of DC component from this voltage signal, as well as the DC component from the total voltage signal on a test winding, can be done either using a network analyser or a low-pass filter with a DC voltmeter. Computer data acquisition can be easily carried out in both cases. The current value of the temperature dependent DC winding resistance is equal to the ratio of $U_{W,dc}$ and $I_{meas,dc}$.

The values of relevant parameters of windings 1 and 2, as well as of the adjusted elements of the measuring setups are given in Table I.

TABLE I
DESCRIPTION OF CONNECTION DIAGRAM ELEMENTS FROM FIG. 3

	R_{Wdc} Ω	Z_W Ω	I_{Wac} A	C_k μF	R_2 Ω	U_{sup} V	$U_{dcs,\,50Hz}$ V	$I_{meas,\,dc}$ A	$I_{dc,\,s}$ A	U_{dc} V	R_1 Ω
Winding 1	1.1	3.5+j19.9	32	166	3.9	680	125	1.3	1.7	200	150
Winding 2	0.3	1.2+j3.3	58	798	1	221	21	5.3	6.9	198	29

R_{Wdc} and Z_W are the values at 20 ^{0}C; I_{Wac}, U_{sup}, $U_{dcs,\,50Hz}$ are the values at maximal load

4. Results

A. Top insulation surface minus bottom oil temperature gradient

The model from [4] is based on this temperature gradient (J_s - J_b). The equation for its calculation at different power winding loss (P_γ) is proposed based on the experimental results obtained on the model of a winding cooling duct, 1.47 m height, having variable width (from 2.4 mm to 11.9 mm). The possible sources of method vagueness and problems in a practical model application are quoted in [2]. Using measuring results, the exact parameter values in suggested expression,

$$J_s - J_b = \left(J_{sr} - J_{br}\right)\left(\frac{n_{eq}(J_b, J_i)}{n_{eq}(J_{br}, J_{ir})}\right)^{n_1}\left(\frac{P_g}{P_{gr}}\right)^{n_2} \quad (1)$$

where determined (n_1 = 0.263 and n_2 = 0.671) and intended to have a general value. The calculation of the equivalent viscosity n_{eq}, throughout the cooling duct,

$$n_{eq} = \int_0^1 n(x)\, dx \quad (2)$$

assumes a linear temperature distribution, rising from the bottom to the top channel oil temperature (J_i):

$$J(x) = J_b + (J_i - J_b)\, x. \quad (3)$$

Vertical position is expressed as per unit value to the winding height. In our experiments, the used oil has the following kinematic viscosity characteristic

$$n(J) = (334.96\, J^{-0.848} - 4.684)10^{-6}\, m^2/s. \quad (4)$$

Since all relevant temperatures for this thermal model were measured, the accuracy of procedure (J_s - J_b) calculation is tested. First, based on the measuring results, parameters n_1 and n_2 were determined by minimization the sum of mean square deviation of calculated to measured temperatures. As an example, on Fig. 4 the values of (J_s - J_b) obtained by measurement and calculation are shown, for the winding 1 positioned autonomous in the tank ($J_s = (J_2 + J_3) / 2$, see Fig. 1). The obtained coefficients are presented in Table II and the maximum deviations of calculated from measured temperature gradient in Table III.

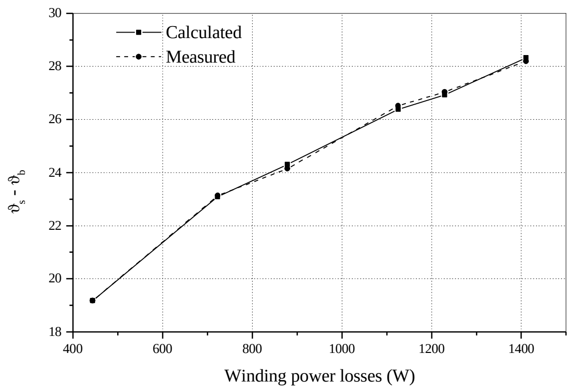

Fig.4. Fitting of the parameters

TABLE II
EXPERIMENTALLY DETERMINED COEFFICIENTS OF (1)

	Representative temperature J_s	Range of load (I / I_r)	Range of temperature gradient (K)	n_1	n_2
Winding 1 as a normal transformer part	(J_2 + J_3) / 2 (Fig. 1)	0.528 – 1.08	19.7 – 50.1	0.60965	0.011844
Winding 1 autonomous in the tank	J_1 (Fig. 1)	0.522 – 0.880	18.5 – 25.9	0.34631	0.048369
	(J_2 + J_3) / 2 (Fig. 1)		19.2 – 28.2	0.41448	0.080083
	J_4 (Fig. 1)		14.5 – 21.0	0.40591	0.06907
Winding 2 autonomous in the tank	J_1 (Fig. 2)	0.486 – 0.919	9.8 – 20.1	0.53801	0.05
	J_s = J_2 (Fig. 2)		8.58 – 14.1	0.51575	0.05

TABLE III
MAXIMAL DEVIATIONS FOR THE CASE OF EXPERIMENTALLY DETERMINED COEFFICIENTS OF (1)

	Representative temperature J_s	Δ(J_s - J_b)
Winding 1 as a normal transformer part	(J_2 + J_3) / 2 (Fig. 1)	1.74
Winding 1 autonomous in the tank	J_1 (Fig. 1)	0.362
	(J_2 + J_3) / 2 (Fig. 1)	0.176
	J_4 (Fig. 1)	0.566
Winding 2 autonomous in the tank	J_1 (Fig. 2)	0.899
	J_2 (Fig. 2)	0.726

The next step was to investigate the precision of usage the coefficients suggested by the authors of the model [4]. There are two important facts: since the authors did not recommend how to calculate oil at the channel top, the data of measurements on the windings were used and the referent (J_{sr} - J_{br}) temperature gradient was also adopted from the measuring results. The results, in the same form as in Table III, are shown in Table IV.

TABLE IV
MAXIMAL DEVIATIONS FOR THE CASE OF COEFFICIENTS OF (1) FROM [4]

	Representative temperature J_s	Δ(J_s - J_b)
Winding 1 as a normal transformer part	(J_2 + J_3) / 2 (Fig. 1)	4.41
Winding 1 autonomous in the tank	J_1 (Fig. 1)	2.50
	(J_2 + J_3) / 2 (Fig. 1)	1.75
	J_4 (Fig. 1)	1.52
Winding 2 autonomous in the tank	J_1 (Fig. 2)	1.77
	J_2 (Fig. 2)	1.41

The errors are somewhat higher than when the exact parameters are used, but still acceptable. Higher calculation error appears only for the case of the winding 1 inside the transformer. It could be noticed that oil streaming conditions in a transformer are the most complex and differs in a greatest extend from those existing in the model used by the authors in [4]. The last test was applying the exact parameters obtained on the winding 1 in the transformer to the winding 1 in the tank and contra; the results in Table V relates to $J_s = (J_2 + J_3) / 2$.

TABLE V
MAXIMAL DEVIATIONS FOR THE CASE OF SUBSTITUTED PARAMETERS OF THE WINDING 1

	Δ(J_s - J_b)
Winding 1 as a normal transformer part	6.43
Winding 1 autonomous in the tank	5.06

It can be concluded that it is not possible to define a unique set of parameters which delivers a high precision (J_s - J_b) temperature gradient, i. e. that this gradient depends also on oil circulation conditions outside a winding.

B. Top channel minus bottom oil temperature gradient

The model from [3] is based on this temperature gradient (J_t - J_b), as a dominant one. The equation for its calculation is proposed based on the measurements on the test winding:

$$J_t - J_b = \left(J_{tr} - J_{br}\right)\left(\frac{P_g}{P_{g\,r}}\right)^n \tag{5}$$

where n = 0.413. A similar examination procedure as in section 4. A. was applied to this temperature gradient. The results are shown in Tables VI – IX.

TABLE VI
EXPERIMENTALLY DETERMINED COEFFICIENTS OF (5)

	Range of temperature gradient (K)	n
Winding 1 as a normal transformer part	19.1 – 42.7	0.52763
Winding 1 autonomous in the tank	17.5 – 24.6	0.32147
Winding 2 autonomous in the tank	8.88 – 16.1	0.41598

TABLE VII
MAXIMAL DEVIATIONS FOR THE CASE OF EXPERIMENTALLY DETERMINED COEFFICIENTS OF (5)

	Δ(J_t - J_b)
Winding 1 as a normal transformer part	1.67
Winding 1 autonomous in the tank	1.36
Winding 2 autonomous in the tank	0.451

TABLE VIII
MAXIMAL DEVIATIONS FOR THE CASE OF COEFFICIENTS OF (5) FROM [3]

	Δ(J_t - J_b)
Winding 1 as a normal transformer part	4.58
Winding 1 autonomous in the tank	2.28
Winding 2 autonomous in the tank	0.866

TABLE IX
MAXIMAL DEVIATIONS FOR THE CASE OF SUBSTITUTED PARAMETERS OF THE WINDING 1

	Δ(J_t - J_b)
Winding 1 as a normal transformer part	7.85
Winding 1 autonomous in the tank	4.17

The conclusions holds the same as for the (J_s - J_b) temperature gradient.

C. Local convection heat transfer at hot-spot vertical location

The model from [3] contains separated temperature gradient due to local convection heat transfer from the winding surface to the adjacent oil at hot-spot vertical location – 85 % of the winding height (J_{shs} - J_{ohs}). The equation for its calculation is adopted as commonly used one in heat transfer texts,

$$J_{shs} - J_{ohs} = \left(J_{shsr} - J_{ohsr}\right)\left(\frac{P_g}{P_{g\,r}}\right)^{n1}\left(\frac{m}{m_r}\right)^{n2} \tag{6}$$

where n_1 = 0.8 and n_2 = 0.2. The viscosity m (m (J) = n (J) r (J); r (kg / m3) is oil density: r (J) = 887.5 – 0.644 (J - 10)) is calculated for the oil film temperature, equal to $(J_{shs} + J_{ohs}) / 2$. The results of calculation show that the optimal coefficients are quite different from those proposed in [3], but the application of $n_1 = 0.8$ and $n_2 = 0.2$ does not lead to high errors in ($J_{shs} - J_{ohs}$), as shown in Table X.

TABLE X
GRADIENT ($J_{SHS} - J_{OHS}$)

	Range of temperature gradient (K)	Calculation error using $n_1 = 0.8$ and $n_2 = 0.2$
Winding 1 as a normal transformer part	4.92 – 16.7	2.47
Winding 1 autonomous in the tank	4.72 – 7.70	1.66
Winding 2 autonomous in the tank	0.31 – 2.48	0.899

It can be noticed that the vertical oil temperature gradient is much higher than the winding surface to adjacent oil gradient. So, the vertical oil temperature gradient should be specially precise treated. In the valid IEC Standard [1], the rated value of vertical temperature gradient is estimated as 22 K and surface to oil about $23 / 1.1 – 6 \text{ K} \approx 15$ K (average winding - average oil temperature is $23 / 1.1 \approx 21$ K and radial gradient, according to [4], is 6 K). This estimation is based on mixed top oil (in the pocket), which is somewhat colder than the oil at the channel top. Example for the case of a 630 kVA transformer is given in Table XI.

TABLE XI
MIXED TOP OIL AND OIL AT THE CHANNEL TOP TEMPERATURES: CASE 630 KVA TRANSFORMER

Power losses (W)	2320	2631	3808	4433	4997	5664	6342	8650	9672	10633
Top channel oil (^{0}C)	43.3	47.8	50.9	60.5	61.9	69.4	64.6	82.2	79.3	89.1
Mixed top oil (^{0}C)	37.7	42.2	43.5	53.1	56.2	63.1	55.8	74.1	71.9	80.0

The advantages and disadvantages of using top channel or pocket oil in the hot-spot temperature calculation are obvious: top pocket oil is easy to measure and top channel oil describes the physical heat transfer process.

In Table XII the characteristic temperature gradients for the experimentally tested cases are shown.

TABLE XII
MIXED TOP OIL AND OIL AT THE CHANNEL TOP TEMPERATURES: CASE 630 KVA TRANSFORMER

	I/I_n	J_b	J_t-J_b	J_{shs}-J_{ohs}	J_s-J_b
Winding 1 as a normal transformer part	0.867	31.8	32.7	9.8	35.6
Winding 1 autonomous in the tank	0.880	56.7	24.6	7.7	27.3
Winding 2 autonomous in the tank	0.919	54.46	16.1	2.5	18.6

The temperature gradients for winding 1 are higher in the case of the winding inside the complete transformer than in the case of the winding autonomously positioned in the tank. Although the bottom oil temperature is lower, i. e. the viscosity is higher for the winding inside the transformer, the main reason for higher gradients is higher hydraulic resistance in a closed oil circulation loop and consequent lower oil flow.

For both of the windings tested in the tank, the temperature gradients for winding 2 are much lower than the gradients for winding 1. It is the consequence of lower current density in winding 2 (at the rated current: 3.03 A / mm^2 for winding 2 and 3.7 A / mm^2 for winding 1) and larger cooling surface: the density of power transferred from the winding surface to the oil is 132 W / m^2 for winding 2 and 689 W / m^2 for winding 1.

D. The hot-spot factor

The parameters of thermal model from the valid IEC standard [1] can be in a great extend determined by using easy measurements [2]. It should be stressed that it was not the case at the models from [3] and [4]. The only factor difficult to define precisely is the hot-spot factor (H), taking into account non-uniform power losses in windings, change of local heat transfer coefficients over the winding height and edge effects of oil streaming at the winding´s ends. A constant approximate value could be applied: for the considered winding $H = 1.1$.

Since other parameters are easy to calculate from results of inexpensive measurements in a short-circuit heating experiment, the influence of approximate value $H = 1.1$ is analysed in this section. The analyses is related only to the case of complete transformer while the heating conditions in a transformer and in a tank differ significantly. Before this analysis, the comparison of mean winding temperatures obtained by the method proposed (Section 3 and [6]) and by the 70 sensors built in winding 1 will be exposed. The values for the transformer are shown in Table XIII and for the winding in the tank in Table XIV. It can be concluded that the agreement of the temperatures is very high.

TABLE XIII
COMPARISON OF MEAN WINDING TEMPERATURES: WINDING 1 IN THE TRANSFORMER

Power losses	2320	2631	3808	4433	4997	5664	6342	8650	9672	10633
By the local temperatures	37.9	42.0	43.9	53.8	59.6	61.7	55.7	73.4	68.3	81.3
By the method proposed	38.4	41.0	43.6	53.8	59.0	61.4	54.6	73.8	71.4	82.8
Difference	0.5	-1.0	-0.3	0.0	-0.6	-0.3	-1.1	0.4	3.1	1.5

TABLE XIV
COMPARISON OF MEAN WINDING TEMPERATURES: WINDING 1 IN THE TANK

Winding power losses	444	723	878	1125	1229	1411
By the local temperatures	41.5	49.6	57.3	67.0	71.9	76.9
By the method proposed	41.0	48.7	57.4	66.4	72.7	76.1
Difference	-0.5	-0.9	0.1	-0.6	0.8	-0.8

Table XV contains the hot-spot calculation error due to the constant factor $H = 1.1$. The vertical oil temperature gradient is calculated as the temperature gradient on the radiator surface; the mean oil temperature (J_{Oa}) is calculated as the sum of the bottom oil and the half of vertical oil gradient and the top oil temperature (J_{Ot}) as the sum of the bottom oil and of the vertical oil gradient. Average winding temperature (J_{Cua}) is measured by the U/I method [6] and the hot-spot temperature is calculated as

$$J_{Cuhs} = J_{Ot} + 1.1\left(J_{Cua} - J_{Oa}\right) \qquad (7)$$

TABLE XV
INFLUENCE OF THE CONSTANT FACTOR H = 1.1 TO THE CALCULATION PRECISION

Power losses	2320	2631	3808	4433	4997	5664	6342	8650	9672	10633
Measured hot-spot	47.7	51.5	56.4	67.4	70.4	77.1	72.6	94.6	90.1	103.8
Hot-spot calculated by (7)	46.26	49.9	54.86	66.86	68.94	75.4	70.52	92.87	88.5	103.4
Difference	-1.44	-1.60	-1.54	-0.54	-1.46	-1.7	-2.08	-1.73	1.62	0.4
0.1 * (J_{Cua}-J_{Oa})	0.61	0.55	0.81	0.86	0.89	0.94	0.97	1.2	1.4	1.6

The deviations can be considered as small. The last row in Table XV shows the sensitivity of the calculated hot-spot temperature to the hot-spot factor value: it contains the change of the hot-spot temperature for every change of the hot-spot factor of 0.1 amount.

5. Conclusions

The general important conclusion is that temperature gradients copper-oil depends not only on the winding construction, but also on the complete oil streaming loop. The same holds for vertical oil gradients; a return cooling part of an oil circulation loop influences not only the bottom oil temperature, but also through the hydraulic resistance the vertical oil temperature gradient. It means that relations from general heat transfer theory and relations developed on a basis of measurements on models can not be applied to a real transformer without loss of precision.

That is why an attempt should be made to define a thermal model of transformer in which the parameters can be determined from easy measurements, meaning not to measure local temperatures inside a transformer tank. Such a model is developed in the previous work of the authors and the only factor which can not be determined from easy measurements is the hot-spot factor (ratio of hot spot to top oil gradient and average copper to average oil temperature gradient). Extensive experimental results has shown that the hot-spot temperature is not strongly influenced by the value of the hot-spot factor, i. e. a discrepancy of the real hot-spot factor from a supposed value does not lead to a high error in a calculation of the hot-spot temperature.

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