THE INFLUENCE OF CHOSEN FACTORS ON THERMAL CONDUCTIVITY OF PAPER USED AS TRANSFORMER WINDINGS INSULATION

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Abstract: The analysis of an influence of various factors on thermal conductivity of paper, used as transformer windings insulation, was an objective of presented in the article investigations. Water content in paper, degree of polymerization of paper, neutralisation value of oil, and type of used paper were numbered as the factors. All factors probably have the influence on thermal conductivity of paper. The conductivity determines the temperature distribution in a transformer, and temperature of hot spot, which defines very strongly lifetime of transformer insulation. The article presents the results of measurements of thermal conductivity of paper samples. Value of the conductivity was used to calculate hot spot temperature. Next, value of hot spot temperature was used to estimate a change of transformer insulation lifetime, what was made on the basis of “five degree law”. In this way, the influence of some parameters on transformer insulation lifetime was evaluated.

1 INTRODUCTION

Power transformers, which work in electric grid, are the more important and the more expensive element of the grid. Transformers should perform two fundamental operating functions: high level of power-carrying capacity (1), and long failure-free lifetime (2) [1, 2]. Both these functions are closely connected with temperature inside transformers, what is presented on Fig. 1 [3, 4].

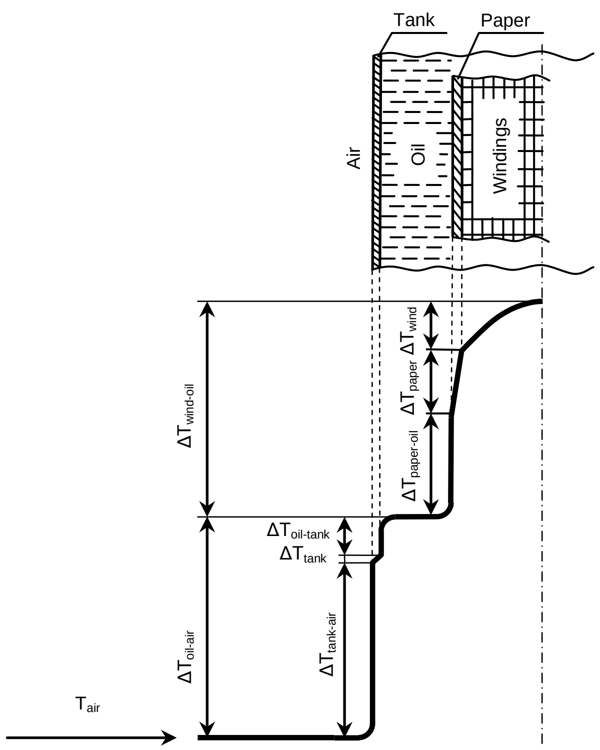

Figure 1: Temperature distribution inside a power transformer [2]

High level of power-carrying capacity (1) is connected with current and voltage of transformer. The current causes significant losses in transformer core and windings. Losses in the core are connected with a hysteresis and eddy currents. Losses in windings are connected with Joule-Lenz losses in copper [5]. Losses in windings are about four times bigger than losses in the core. The voltage has the influence on dielectric losses, which are located mostly in paper insulation of transformer windings. The losses depends on electric field stress, electric permittivity, pulsation and dielectric losses factor tan(delta). Losses connected with the current and the voltage are source of heat energy. So, the losses have significant influence on temperature in transformer.

Long failure-free lifetime (2) is closely connected with conditions of insulation system of transformer. Operating of transformer causes the aging process of insulation system. Temperature has a significant influence on the intensity of this process, what “five degree law” describes very well [5]. The law says that the increase or the decrease of temperature about 5°C can cause respectively the decrease or the increase of lifetime two times. The law can be used in case of temperature in range from 75°C up to 100°C and for cellulose paper. The influence of temperature on aging process is described also in [1] (table 1). The table presents relative speed of aging process of transformer insulation system as a function of hot spot temperature. How it is seen, the increase of temperature about 6°C (from 98 to 104°C) causes the increase of speed of aging process two times.

Table 1: Relative speed of aging process of transformer insulation system as a function of hot spot temperature [1]

Hot spot temperature [^oC]	Relative speed of aging process of transformer insulation system
80	0.125
86	0.25
92	0.5
98	1.0
104	2.0
110	4.0
116	8.0
122	16.0
128	32.0
134	64.0

Figure 1 shows that hot spot temperature depends, among other things, on the temperature decrease on paper layer (windings insulation) ΔT_{paper}. The decrease was described using equation:

$$\Delta T = p\ g\ /\ \lambda \qquad (1)$$

where: ΔT – Temperature decrease on paper layer (^oC), p – Heat load of paper insulation (W/m^2), q – Thickness of insulation paper layer (m), λ – Relative thermal conductivity coefficient (W/m^oC).

The temperature decrease on paper layer (windings insulation) depends on relative thermal conductivity coefficient λ. So, we can say that thermal conductivity can have the influence on hot spot temperature in transformer. The bigger λ the smaller hot spot temperature.

The coefficient λ of a large majority of insulation materials, used in high voltage engineering, has relatively small value, comparing to water or metal. Table 2 shows chosen values of the coefficient λ for various materials. How it is seen, thermal conductivity of insulation materials is about thousand times smaller than the conductivity of metal.

Table 2: Relative thermal conductivity coefficient λ for chosen insulation materials, water and some metals [2, 6÷8]

Material	Relative thermal conductivity coefficient λ [W/m^oC]
Dry paper	0.040
Oil-impregnated paper	0.166
Pressboard	0.190
Cable paper	0.100
Mineral transformer oil	0.145
Dry brick	0.350
Wet brick	1.000
Water (20^oC)	0.599
Copper	401.0
Aluminium	237.0

On the basis of Table 2 and equation 1, the temperature decrease ΔT on paper layer can be calculated. Following values in equation 1 were used: thickness of paper layer g = 1.5 mm, heat load of the layer p = 2000 W/m^2 [2]. Relative thermal conductivity coefficient λ of oil-impregnated paper is 0.17 W/m^oC (table 2). Calculated temperature decrease ΔT on paper layer is 17.7^oC.

If thermal conductivity increases from 0.17 to 0.18 W/m^oC, calculated ΔT on paper layer is 16.7^oC. So, ΔT is smaller about 1^oC. It means that hot spot temperature is smaller about 1^oC, too. On the basis of “five degree law”, it is possible to say, that the decrease of hot spot temperature about 1^oC makes the transformer insulation system lifetime longer about 4.5 year. So, relatively small change of thermal conductivity (from 0.17 to 0.18 W/m^oC – about 5%) can have significant influence on failure-free lifetime of insulation system of power transformer.

2 OBJECTIVE AND RANGE OF INVESTIGATIONS

The analysis of influence of chosen factors on thermal conductivity of oil-impregnated paper, used as transformer windings insulation, was main objective of presented investigations. Two kinds of factors were investigated. First one was a group of factors, which describe conditions of insulation system of transformer. Second one was type of used insulation material.

Following factors, describing conditions of insulation system of transformer, were investigated: Water Content in Paper (WCP), Degree of Polymerization of paper (DP), and Neutralisation value of oil (N_v). All these factors were investigated for their two extreme values.

Paper samples, for two extreme values of water content in paper (WCP), were investigated. In case of cellulose and aramid (Nomex) paper, lower value of WCP was about 0%. In case of cellulose paper, upper value of WCP was 5.0%, but in case of aramid paper, upper value of WCP was 2.8%. The reason of the difference, in case of upper value of WCP, was fact, that cellulose paper is able to absorb about two times more water, than aramid paper.

Thermal conductivity of cellulose paper was measured for two extreme values of degree of polymerization (DP) of paper. The degree was DP = 1300, what corresponds to new paper, and DP = 300, what is typical of very aged paper.

Oil-impregnated cellulose paper samples, which had two extreme values of neutralisation value N_v, were investigated. The value was 0.10 $mgKOH/g_{oil}$, what characterises aged oil, and less than 0.01 $mgKOH/g_{oil}$ in case of new oil.

Two types of paper were investigated: cellulose and aramid paper. The samples of paper were impregnated in mineral oil in case of both types of paper.

3 MEASUREMENT RESULTS

Water content in paper (WCP) was a first analysed factor, which could have the influence on thermal conductivity of oil-impregnated paper and on temperature distribution in transformer. The analysis was made for two kinds of new paper: cellulose and aramid paper, impregnated in new mineral oil.

Measured thermal conductivity of cellulose paper, with WCP equal about 0%, was $\lambda = 0.162$ W/m^{o}C. Thermal conductivity of cellulose paper, with WCP equal 5.0%, was $\lambda = 0.175$ W/m^{o}C. It means that the increase of water content about 5.0% (from about 0% to 5.0%) caused the increase of thermal conductivity about 0.013 W/m^{o}C. The increase of the conductivity caused that ΔT on paper layer (windings insulation) was smaller about 1.4^{o}C. So, hot spot temperature would be smaller about the same value, too. On the basis of “five degree law”, it was possible to calculate, that lifetime of cellulose paper would be longer about 6.3 years.

Measured thermal conductivity of aramid paper, with WCP equal about 0%, was $\lambda = 0.131$ W/m^{o}C. The conductivity of aramid paper, with WCP equal 2.8% was $\lambda = 0.135$ W/m^{o}C. The increase of WCP about 2.8% (from 0% to 2.8%) caused small increase of thermal conductivity about 0.004 W/m^{o}C. It means that ΔT on paper layer was smaller about 0.7^{o}C. So, hot spot temperature would be smaller about the same value, too. It was impossible to calculate how lifetime of aramid paper would be changed, because “five degree law” concerns just to cellulose paper.

Degree of polymerization (DP) of paper, which describes level of aging process in the paper, was next factor, which could have the influence on thermal conductivity of oil-impregnated paper. The investigations were made for cellulose paper, impregnated in new mineral oil. Water content in paper WCP was 3.5%. Measurement of thermal conductivity were made for new paper (DP = 1300) and aged paper (DP = 300). Measured thermal conductivity was $\lambda = 0.171$ W/m^{o}C for new paper (DP = 1300) and $\lambda = 0.175$ W/m^{o}C for aged paper (DP = 300). The decrease of DP caused the increase of thermal conductivity about 0.004 W/m^{o}C. It means that ΔT on paper layer was smaller about 0.4^{o}C. So, hot spot temperature would be smaller about the same value. On the basis of “five degree law”, it was calculated, that lifetime of cellulose paper would be longer about 1.7 years.

Neutralisation value N_v of oil, which describes level of aging process in oil, was next analysed factor, which could have the influence of thermal conductivity of oil-impregnated paper. New cellulose oil-impregnated paper, with WCP equal 5%, was used. Mineral oils with neutralisation value equal 0.10 mgKOH/g_{oil} (what corresponds to aged oil) and less than 0.01 mgKOH/g_{oil} (what is typical of new oil) were used. Measured thermal conductivity in case of new oil was $\lambda = 0.175$ W/m^{o}C, and in case of aged oil $\lambda = 0.176$ W/m^{o}C. It means that neutralisation value of oil did not have any influence on thermal conductivity and on ΔT on paper layer (windings insulation). So, neutralisation value of oil would not be able to change lifetime of cellulose paper.

Type of paper was the last analysed factor, which could have the influence on thermal conductivity of oil-impregnated paper. Cellulose and aramid papers were investigated. The paper was impregnated in new mineral oil. WCP of paper, in case of both types, was about 0%. Measured thermal conductivity was 0.162 W/m^{o}C in case of cellulose paper, and 0.131 W/m^{o}C in case of aramid paper. On the basis of that it is possible to say that ΔT on cellulose paper layer was smaller about 4.4^{o}C than ΔT on aramid paper layer. So, hot spot temperature would be smaller about the same value, too. It means, that cellulose paper, with bigger thermal conductivity, is more advantageous than aramid paper, from temperature distribution point of view. But, it is necessary to remember, that aramid paper is much more resistant to high temperature than cellulose paper. Summarizing, application of aramid paper is more beneficial than cellulose paper, even if aramid paper can cause the bigger hot spot temperature.

4 CONCLUSIONS

The increase of water content in paper (cellulose and aramid paper) caused the increase of thermal conductivity of the paper (about few percent). It can be a reason of the decrease of hot spot temperature in transformer.

The aging process of cellulose paper, which is described by degree of polymerisation of the paper (DP), had influence on thermal conductivity of the paper. Smaller DP caused the increase of the conductivity. It means that aging process of paper, which is described by DP, causes the decrease of hot spot temperature and makes the lifetime of windings insulation longer.

Deterioration of oil, which is described by neutralisation value of the oil, did not have any influence of thermal conductivity of oil-impregnated paper. The conductivity, in case of both extreme value of neutralisation value (0.10 mgKOH/g_{oil} – aged oil, less than 0.01 mgKOH/g_{oil} – new oil) had almost the same value. It means that neutralisation value had no influence on hot spot temperature in transformer.

Type of paper, which is used as windings insulation in power transformer, had significant influence on thermal conductivity of the paper. Cellulose paper had much bigger thermal conductivity than aramid paper (about 20%). It means that application of cellulose paper causes that hot spot temperature is a little smaller than in case of aramid paper. But it is necessary to remember that aramid paper is much more resistant to high temperature.

5 ACKNOWLEDGMENTS

Presented results were made in the frames of the project “The influence of moisture of transformer paper insulation on thermal conductivity of paper” sponsored by Polish National Science Centre (number of the project NN510-678840).

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