Assessment of Long Thermal Ageing on the Oil-Paper Insulation

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Abstract. *Electric power equipment has complex construction. Therefore, it is very important to have enough information about the state of equipment. High voltage transformers play a very important role in the electric power system. One of the most important parts of electric power equipment is the insulation system. Insulation system must be in a good condition for reliable and safe operation of electrical devices. Insulation system of electrical equipment is exposed to various factors which could have negative influence on its condition. Oil impregnated insulation paper is one of the oldest insulation systems used in electrical power equipment. Mineral oils have been used for decades as transformer fluids because of their excellent dielectric properties and availability. However, performance of mineral oil starts to be limited due to environmental consideration. The aim of this paper is to simulate a real insulation system of transformer and to show the influence of accelerated thermal ageing on the insulation system. Properties such as relative permittivity, dissipation factor and the breakdown voltage will be described and analysed.*

Keywords

Breakdown voltage, dissipation factor, oil-paper insulating system, permittivity, thermal ageing.

1. Introduction

Proper operation of electrical equipment requires the use of high quality insulating materials. Power equipment as transformers are one of the vital and expensive elements in the industry of electrical energy [1]. The insulating system is composed of the combination of oil and Kraft paper. The oil is providing both electrical insulation and a means for transferring thermal losses to a cooling system, so as coolant. For more than one hundred years, the majority of liquid-immersed transformers have been filled with mineral oil. The significant use of this petroleum-based product has been justified until now by its wide availability, its good properties, its good combination with cellulose and its low cost [2]. The main oil properties can be divided to three categories: physical, chemical and electrical. Viscosity, flash point, pour point and interfacial tension are the main physical properties of oil. Water content, oxidation stability, total acid and sulphur corrosion are the most important chemical properties. Breakdown voltage, dissipation factor and permittivity belong to the group of important electrical properties. Mineral oil is mainly used in power transformers for its good oxidation stability and low water content. Disadvantages of this naphthenic product are poor biodegradable and low flash point. In recent years, the research thinks ahead for the esters as insulating fluids, which could replace the conventional used insulation liquids based on naphthenic oils [3] and [4]. These liquids are more environmentally friendly because they are almost fully biodegradable (95 %) in relation to the conventional mineral oils, and also they have higher fire point, about 300 °C [5]. This work investigates the influence of temperature on the high voltage transformer system composed of the insulating liquid and Kraft paper.

2. Measurement Methods

There were used some measurements for investigating the ageing mechanism. Dielectric properties as relative permittivity, dissipation factor and breakdown voltage were analysed.

2.1. Breakdown Voltage and Electrical Breakdown Strength

Electrical breakdown voltage U_b is one of the most important properties of the dielectric material. It presents a degree of the insulation ability to resist the electric stress [6]. It is the minimal voltage value, which causes growth of the electric conductivity to the level that initiates an electric breakdown. High value of the current flowing through the breakdown area causes mechanical, thermal and chemical processes that change dielectric characteristics [7]. Electric breakdown strength E_b is one of the basic qualitative characteristics of the dielectrics in addition to the breakdown voltage and the dielectric loss. In the electric field, the dielectric keeps its insulating characteristic only up to the specific value of the electric field intensity. After reaching the boundary of the critical field intensity, the dielectric resistance decreases rapidly to the resistance level of the conductive material. In the case of a homogeneous electric field, the field intensity is the same in the whole space between electrodes, therefore the electric breakdown strength can be calculated using the formula Eq. (1), where d is the thickness of the insulation material [8].

$$E_b = \frac{U_b}{d} . \quad (1)$$

Figure 1 shows general dependence of electrical breakdown strength on thickness of the insulation material.

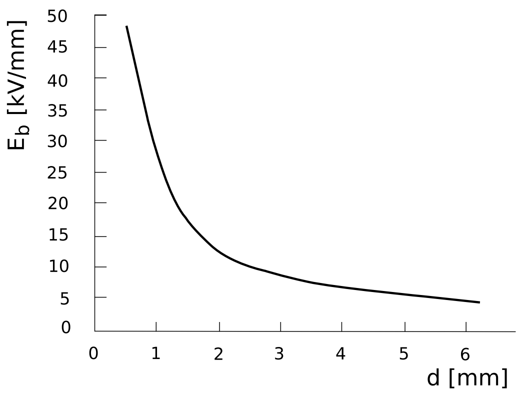

Fig. 1: Dependence of the electrical breakdown strength on the insulation thickness.

2.2. Dissipation Factor

Dielectric dissipation factor ($\tan\delta$) is another of important diagnostic tools to monitor the condition of the solid/liquid insulation. Periodical measurement of $\tan\delta$ gives the rate of the deterioration of the insulation state [9]. The dissipation factor is a parameter which is a dimension for the quality of the dielectric losses in the insulation system and it gives the relation between the real and reactive components. The total dissipation factor of the whole insulating system depends on the dissipation factor and quality of each component. Higher values of the dielectric dissipation factor indicate presence of moisture and contaminating agents [10]. Tan delta of the insulation is dependent on the water content, impurities and the presence of partial discharges. Besides temperature and frequency, applied voltage has one of the strongest influence on the values of the dissipation factor. General characteristic of the dissipation factor versus applied voltage is shown on Fig. 2, where curve 1 responds to good insulation, curve 2 responds to insulation with partial discharges. The critical value of the applied voltage is the initial voltage of partial discharges.

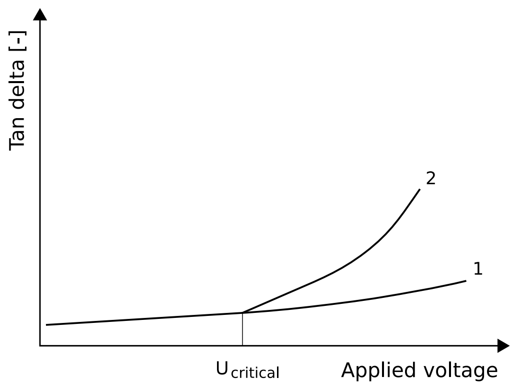

Fig. 2: Dissipation factor versus applied voltage.

2.3. Relative Permittivity

Relative permittivity ε_r is a characteristic material constant typical for every material, and describes the relationship of how much the capacitance of a capacitor changes when filled with a certain material C_x in relationship to a capacitor filled with air C_0. The relative permittivity expresses material skills to accumulation the electric charge. The following formula applies:

$$\varepsilon_r = \frac{C_x}{C_0} . \quad (2)$$

Relative permittivity is a macroscopic characteristic of the substances that depends on the microscopic properties of structure units, their polarizability α and dipole moment p of the material molecules and their speed in the electrical field [2] and [10]. It depends on temperature, frequency and applied voltage. Relative permittivity of liquids and solid materials is always more than 1.

3. Experimental Setup and Samples

This experiment is focused on measurement of properties of the oil paper insulation system after thermal ageing. The temperature of accelerated ageing test was 90 °C and there were chosen two time intervals of ageing. The first measurement was realized with new samples, the second one was realized after 750 hours of ageing, and the third one after 1500 hours of ageing. A transformer paper with 0.06 mm thickness and two types of impregnating oils were used for these purposes. The first type was natural sunflower oil and the second one was inhibited mineral oil ITO 100. The insulating oil, transformer paper and 10 grams of the copper wire were placed in the glass vessel during the thermal aging process.

3.1. Breakdown Voltage Measurement

The AC breakdown voltage was measured using two electrodes which were 25 mm diameter brass hemispherical types. AC breakdown voltage of mineral oil paper insulation and sunflower oil paper insulation were measured by the instrument High-Voltage DTS-60D. For each type of oil, five oil impregnated paper samples were tested, and the average value was calculated. The voltage was applied at a rise rate of 2 kV · s^{-1} until breakdown. The paper insulation was changed after each breakdown. There was a one-minute break between two measurements and the oil sample was mixed. Values of the electric breakdown strength were calculated according to Eq. (1).

3.2. Dissipation Factor and Relative Permittivity Measurement

The relative permittivity in dependence on voltage were measured with automatic Schering Bridge TETTEX AG. The measurement was realized at the room temperature of 20 °C and normal pressure. The applied voltage was increased from 0.2 kV to 2 kV with the step 0.2 kV at the frequency of 50 Hz.

4. Experimental Results and Discussion

The results of the measurement of AC breakdown voltage and the electrical breakdown strength are shown in Tab. 1 and Tab. 2. Then the average value was calculated according to the Eq. (3).

$$U_b = \frac{\sum_{i=1}^{n} U_{bi}}{n} . \quad (3)$$

Tab. 1: The values of the breakdown voltage U_b and the electric breakdown strength E_b for sunflower oil paper.

Number of measurement	**Before ageing**	**750 hours ageing at 90 °C**	**1500 hours ageing at 90 °C**
	U_b [kV]	U_b [kV]	U_b [kV]
1	22	24.5	23.1
2	21.8	22.5	23.2
3	21.4	23.3	20.9
4	19.6	22.6	21.4
5	20.7	24	24.5
Average	**21.1**	**23.38**	**22.62**
Number of measurement	**Before ageing**	**750 hours ageing at 90 °C**	**1500 hours ageing at 90 °C**
	E_b [kV/mm]	E_b [kV/mm]	E_b [kV/mm]
1	61.11	68.06	64.17
2	60.56	62.50	64.44
3	59.44	64.72	58.06
4	54.44	62.78	59.44
5	57.50	66.67	68.06
Average	**58.61**	**64.94**	**62.83**

Tab. 2: The values of the breakdown voltage U_b and the electric breakdown strength E_b for mineral oil paper.

Number of measurement	**Before ageing**	**750 hours ageing at 90 °C**	**1500 hours ageing at 90 °C**
	U_b [kV]	U_b [kV]	U_b [kV]
1	18	19.4	21.3
2	18	20.1	22
3	18.9	20.4	22
4	17.9	20.6	20.4
5	18.2	21.1	21.7
Average	**18.2**	**20.32**	**21.48**
Number of measurement	**Before ageing**	**750 hours ageing at 90 °C**	**1500 hours ageing at 90 °C**
	E_b [kV/mm]	E_b [kV/mm]	E_b [kV/mm]
1	50.00	53.89	59.17
2	50.00	55.83	61.11
3	52.50	56.67	61.11
4	49.72	57.22	56.67
5	50.56	58.61	60.28
Average	**50.56**	**56.44**	**59.67**

The AC breakdown voltage of natural esters is generally higher than the breakdown voltage of mineral oils. This is because sunflower oil has relative permittivity greater than transformer mineral oil. The initial average values of the breakdown voltage were 21.1 kV for the sunflower oil paper and 18.2 kV for the mineral oil paper. 750 hours of the thermal stress caused the growth of the average values of breakdown voltage from 21.1 to 23.38 kV for the sunflower oil paper, and from 18.2 to 20.32 kV for the mineral oil paper. After 1500-hour thermal aging the breakdown voltage for the sunflower oil paper declined slightly to the value 22.62 kV. This phenomenon is probably caused by hydrolysis. The breakdown voltage for the mineral oil paper increased to the value 21.48 kV. The electrical breakdown strength for these specimens corresponds with the situation like the breakdown voltage.

The voltage dependence on relative permittivity and dissipation factor for the sunflower oil paper are shown in Fig. 3 and Fig. 5, and for the mineral oil paper are shown in Fig. 4 and Fig. 6. The initial values of ε_r for the sunflower oil paper, due to its polar nature, are higher than those for the mineral oil paper. The values of relative permittivity are decreasing for mineral oil paper insulation after each degradation cycle. At the beginning of the thermal test the relative permittivity for sunflower oil paper in comparison with mineral oil has higher value due to the ability of natural ester to absorb moisture. The final value of ε_r after 1500-hour ageing is 2.2 for sunflower oil paper and 2.5 for mineral oil paper. This may be due to the drying of the oil.

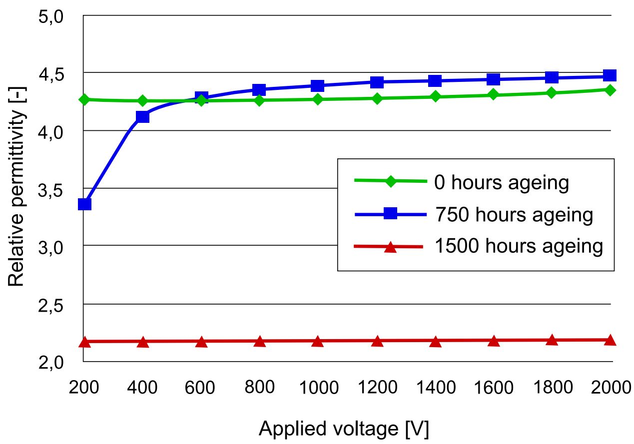

Fig. 3: Relative permittivity of the Kraft paper impregnated with a sunflower oil.

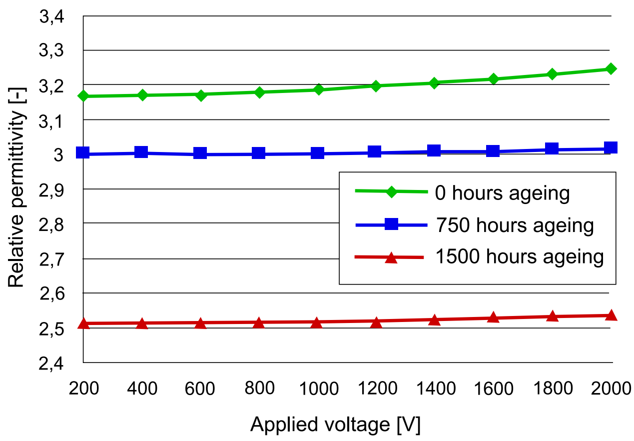

Fig. 4: Relative permittivity of the Kraft paper impregnated with a mineral oil.

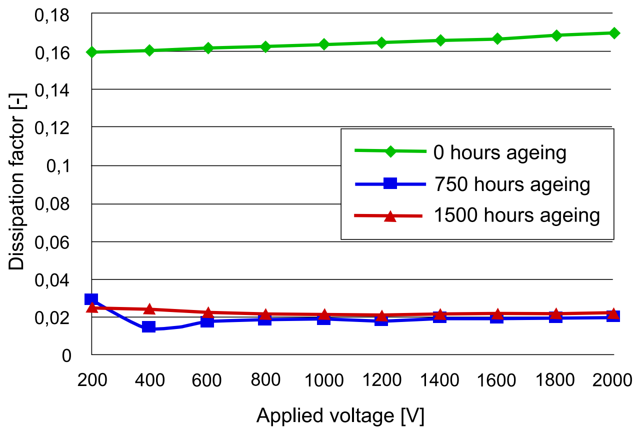

Fig. 5: Dissipation factor of Kraft paper impregnated with a sunflower oil.

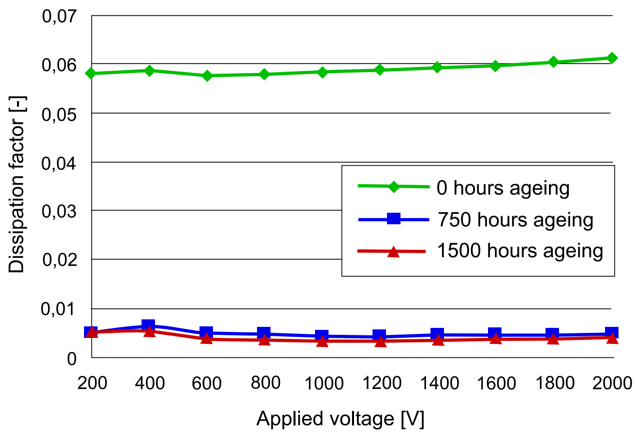

Fig. 6: Dissipation factor of Kraft paper impregnated with a mineral oil.

The dissipation factor has a very strong connection with the relative permittivity of the insulating material. The values of the dissipation factor significantly decreased for each sample. It can be noticed that the behaviour of samples at accelerated aging is very similar. This fact has a connection with moisture which is evaporated after thermal stress. The thermal ageing process caused that the dissipation factor of the samples decreased for each one. Higher dielectric losses were determined at the sunflower oil paper insulation. This status is caused by polar molecules which natural esters, like sunflower oil, contain. Initial values of tan delta were 0.16 for sunflower oil paper and 0.059 for mineral oil paper at 1 kV applied voltage. Temperature 90 °C and period of time 1500 hours caused that tan delta decreased to 0.02 and 0.004 respectively.

5. Conclusion

The aim of this paper was to compare the dielectric properties of commonly used transformer oil with natural ester in combination with transformer paper. All samples were subjected to accelerating of thermal aging at the temperature T = 90 °C in the time intervals of 750 h and 1500 h. This paper provides the readers with a view of the influence of thermal stress on the paper insulation impregnated by mineral oil ITO 100 in one case and natural ester - sunflower oil in another case. The following conclusions may be formulated.

The AC breakdown voltage of the paper impregnated with natural ester is higher than breakdown voltage of the paper impregnated with mineral oil. After 1500-hour thermal aging electrical breakdown strength is higher than before thermal stress for both specimens.

The values of relative permittivity are decreasing gradually for both mineral and natural ester oil paper insulation after each degradation cycle.

Dissipation factor fell down after 750-hour thermal aging for both specimens and remained on the same value during the rest of the thermal stress.

It can be visible from this experiment that the influence of the thermal stress on the dielectric properties of the paper impregnated by mineral oil or natural ester is very similar. Therefore, research and development in this area is much needed.

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