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Effect of Thermal Ageing on the Electrical Insulation Properties of the Oil-Paper Insulation

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Abstract: The article focuses on the electrical insulation properties of oil-paper insulation and its application in practice at AC voltage. It also discusses the effect of moisture and thermal ageing on the breakdown strength and breakdown voltage of oil-paper combinations. Measurements are made of the breakdown voltage and breakdown strength of liquid insulators and paper type KREMPEL-DPP, impregnated with two types of oils, SHELL Diala S4 ZX-I and Mogul Trafo CZ-A. The moisture content in the liquid insulants before and after thermal ageing is also measured.

Keywords: Insulation, transformer oil, impregnation paper, electrical breakdown strength.

1. Introduction

Nowadays, the oil-paper insulation system is one of the most widely used insulations in the power electrical engineering. This insulation is made up of solid and liquid components. The solid consists of insulating paper and the liquid consists of oil, which serves as an impregnant. Oil also serves as a cooling medium in transformers.

Oil-paper insulation is used in a number of electrical devices even with high power at voltage levels of HV and VHV. Impregnated paper has excellent insulating properties and an important place in the electric power industry. At high voltages, on the order of hundreds of kV, oil-paper insulation is the only insulator used [1].

The combination of oil and paper insulants is used in transformer to strip the windings. Together, these insulants have sufficient electrical properties. While paper has good mechanical strength, oil has the function of impregnant and coolant of the transformer. Both insulants have their negative properties but when they are combined, some of the bad properties are compensated, i.e., the properties of one insulator improve the properties of the other and vice versa [2]. Another use of this insulation is in power cables for voltages from 110 kV where the thickness of the impregnated paper is important. The thinner the insulating paper, the higher the electrical strength of the cable insulation [3]. Oil impregnated paper is also used in power capacitors. It is used in DC-link capacitors, in capacitors designed for power factor improvement in capacitors designed to improve power factor at a frequency of 50 Hz, etc. Mineral oil is used to impregnate the paper for this purpose.

2. Factors influencing the electrical insulation properties of the oil-paper insulation

A. Thermal stress of oil-paper insulation

In electrical equipment, during operation, insulators are often exposed to temperatures that differ significantly from room temperature (20 °C). The properties of insulants are substantially affected by such temperatures. High or low temperatures are caused by the ambient environment or by the electrical equipment itself due to electrical energy losses. For this reason, it is necessary to know what are the lowest and highest temperature a given insulation can withstand in relation to its application. According to these parameters, the insulation is selected to be suitable over the entire temperature range that the equipment can reach [3].

The highest temperature that can be considered for an insulation without any disturbance of its properties, taking into account transient thermal process in the equipment, is called the short-term thermal endurance. This, compared to the permanent thermal *e* (resistance to thermal ageing), is determined by the dimensional stability of the material. When selecting insulating materials for electrical equipment, it is necessary to include both of these values.

The consequences of increasing temperature are decreasing mechanical strength and decreasing modulus of elasticity of insulants. For the properties of liquid insulants, e.g., oil, its viscosity decreases and evaporation from the oil increases. As for the variation of electrical properties with increasing temperature, they deteriorate, the electrical resistance of the oil decreases and the tg δ increases. The electrical breakdown strength decreases along with the breakdown voltage. At temperatures lower than the rated operating temperature, these processes are reversed. The viscosity of the liquid insulants increases and the oil becomes thicker. The changes that occur with temperature variations are not permanent and the properties revert back to the optimum when the temperature is restored to the rated operating value [4], [5].

B. Electrical stress of oil-paper insulation

The electric field has indirect effects on the insulation. The only direct effect is the effect of DC voltage, and only on solid insulators of lower quality. However, we have observed from long-term practice that the indirect effect of electrical voltage is more important. Studying the reasons for thermal breakdowns resulted in measures, thanks to which we can prevent the temperature from permanently damaging the insulation. However, breakdown problems continued to occur, even though the risk of thermal breakdown was eliminated at operating voltage. During the insulation tests, a higher voltage than the subsequent operating voltage was used, but there was no breakdown. The breakthrough occurred after various lengths of time without any known causes. Later investigation revealed that the breakdown occurred as a discharge in the insulation cavities [6].

Solid insulations in most cases have small air cavities. Air cavities can be created during the production of the insulation itself, or they arose during the operating conditions inside the insulation, or between insulation and live parts. Under the action of the electric field, the air or other gas is stressed much more than the rest of the insulation. Air has a much lower electrical strength than solid or liquid insulation. This causes a breakdown in the air cavity of the insulation, even at low voltage. This voltage is much lower than the breakdown voltage of the entire insulation. We call this breakdown partial discharges because they did not travel the entire distance between the two electrodes [7].

The discharges have both direct and indirect effects on the cavities of the insulation, especially at locations that are adjacent to the cavities. These effects cause physical and chemical changes in the properties of the insulants. This process is also known as insulation ageing because the discharges often cause irreversible damage and deterioration of the electrical insulation properties of the insulator. These surges result in the breakdown of the entire insulation, even at voltage gradients lower than the electrical strength. For this reason, discharge in insulation has received attention [8].

C. Effect of moisture on the electrical breakdown strength of oil and paper insulation

The most serious cause of deterioration of insulation is water. It adversely affects all insulation systems and their dielectric characteristics. The worst effect on the insulation of electrical equipment is caused by the water content in the paper insulation of the equipment. Paper gets much wetter than oil and thus the water content of the paper is greater. To clarify, oil can contain 10 to 20 mg/kg of water, and at this content, up to 2 % of water by weight can be found in paper.

Oil contains water in three states: dissolved, emulsified and free.

The water content of the oil has a negative effect on the electrical strength of the oil. The higher the moisture content, the electrical breakdown strength decreases and hence the breakdown voltage assumes lower values [9].

Paper insulation can contain water in the following states: water in the form of vapor, water absorbed in monolayers, water absorbed in polymolecular layers, water condensed in capillaries, and free water.

In all states, except the first and fifth, water can be taken as absorbed into fibrous dielectrics. These three states depend on the relative humidity of the liquid and are conditioned by the law of absorption.

Thermal ageing of the paper and the presence of electrical stresses cause the formation of water and carbon oxides in the equipment. The fact that electrical equipment contains insulating paper or other solid insulating material increases the moisture and contaminants that pollute the electrical equipment and acts as an absorbent for polar contaminants and water [10].

At humidity below 4 %, the electrical breakdown strength of the paper appears to be nearly constant. As soon as the humidity starts to rise a significant decrease in the electrical breakdown strength is observed.

3. Measurement of the electrical breakdown strength of oil-impregnated paper insulation

A. Measuring the electrical breakdown voltage of oils

Two oils were considered for this measurement:

- Shell Diala S4 ZX-I
- Mogul Trafo CZ-A

The result of the measurement was a comparison of the breakdown voltage of the two oils. The measurements were performed on the measuring device Oil Dielectric Test Set DTS-60D. The measurement was repeated 10 times, always with a one-minute interval. After the measurement of one of the oils was completed, the vessel with electrodes was cleaned and the measurement on the second oil sample was carried out. The measurement was repeated before the oils were aged and after 1900 hours of ageing. In *Fig. 1* it is shown the electrode placement and shape.

Figure 1: Electrode placement and shape in the DTS-60D

B. Preparation of samples for measurement

Krempel insulating paper with a thickness of 0.075 mm and dimensions of 4.5x4.5 cm was used as a sample. Before the measurements were taken, it was placed in a dryer for 22 hours at 70 °C. The samples were then placed in cleaned, degreased and dried containers and impregnated with Shell Diala S4 ZX-I and Mogul Trafo CZ-A oils. The impregnated samples were aged for 1900 hours at 110 °C.

C. Procedure for measuring the breakdown voltage

The voltage increase was 2 kV/s until breakdown. The first measurement was on 1 layer of insulating paper, measurement was repeated 4 times. Gradually one layer of insulating paper was added at a time and 4 experiments were performed on each. The maximum number of layers was 6. The procedure was identical for the second type of oil. The ageing of both oils was carried out at 110 °C. Another measurement was taken after approximately 240 hours of ageing. The presence of moisture was detected with a Megger KF-LAB MKII.

4. Results of the experiments

The graphical dependence of the average values of the breakdown voltage is shown in *Fig. 2*. For each measurement, 10 tests were performed and the average value was calculated. From the results it is possible to observe the deterioration of the properties of both oils. When measured before ageing, it can be observed that Shell Diala S4 ZX-I oil has a higher value of the breakdown voltage than Mogul Trafo CZ-A. After 1900 hours, the deterioration is approximately the same for both oils. From *Fig. 2*, it can be seen that Shell Diala S4 ZX-I oil has higher electrical breakdown strength than Mogul Trafo CZ-A both before and after ageing. Voltage has been applied to the electrodes of the DTS-60D apparatus, and it has been observed, that the average value of the breakdown voltage in case of Mogul Trafo CZ-A was 8.77 kV and Shell Diala S4 ZX-I was 8.79 kV. Here it can be clearly seen that the deterioration is almost the same. From this point of view, it can be concluded that both oils handle thermal ageing in the same way.

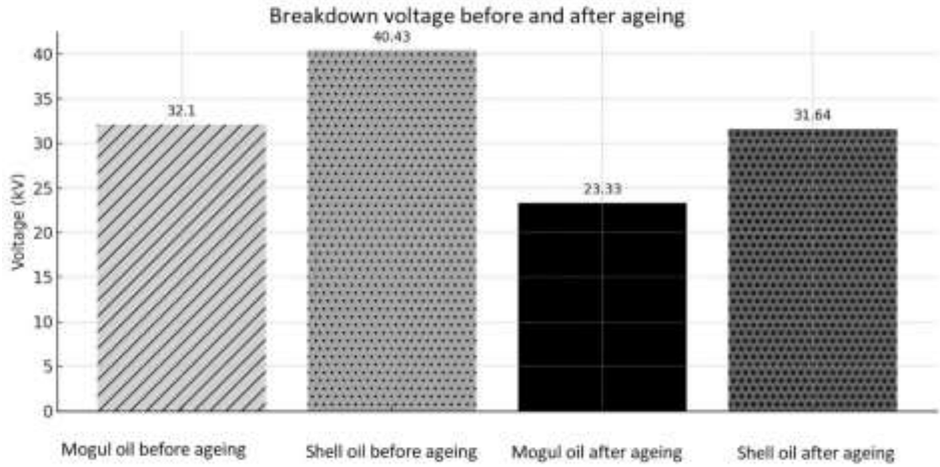

Figure 2: The graphical dependence of the electrical strength of the average values of the breakdown voltage

First, measurements were made on samples that were undried and dried. Both samples were impregnated with each of the oils. For the un-aged oil-paper insulation, it can be observed in *Fig. 3* and *Fig. 4* that the paper specimens impregnated with Shell Diala S4 ZX-I oil have higher values of impact strength than Mogul Trafo CZ-A, both for the not-dried and dried paper.

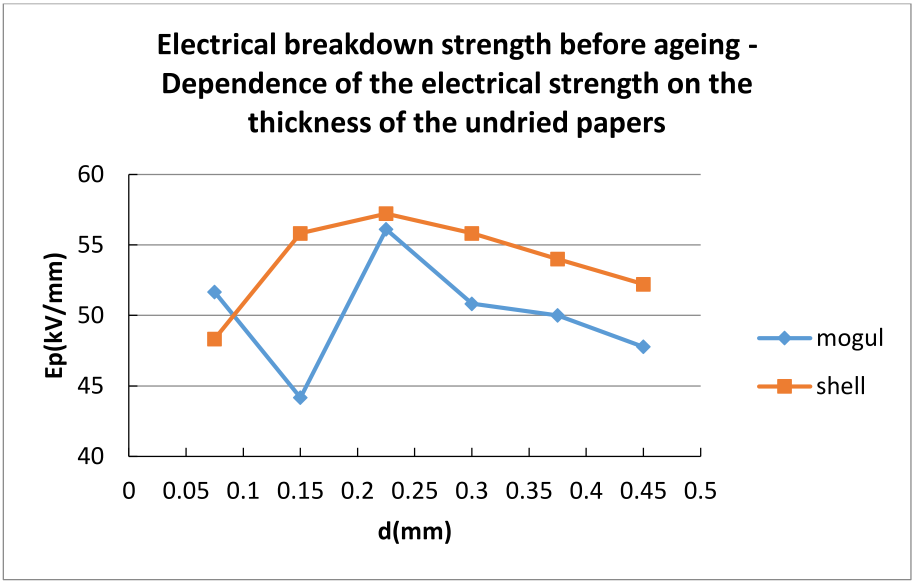

Figure 3: Graphical dependence of the electrical breakdown strength on the thickness of undried papers

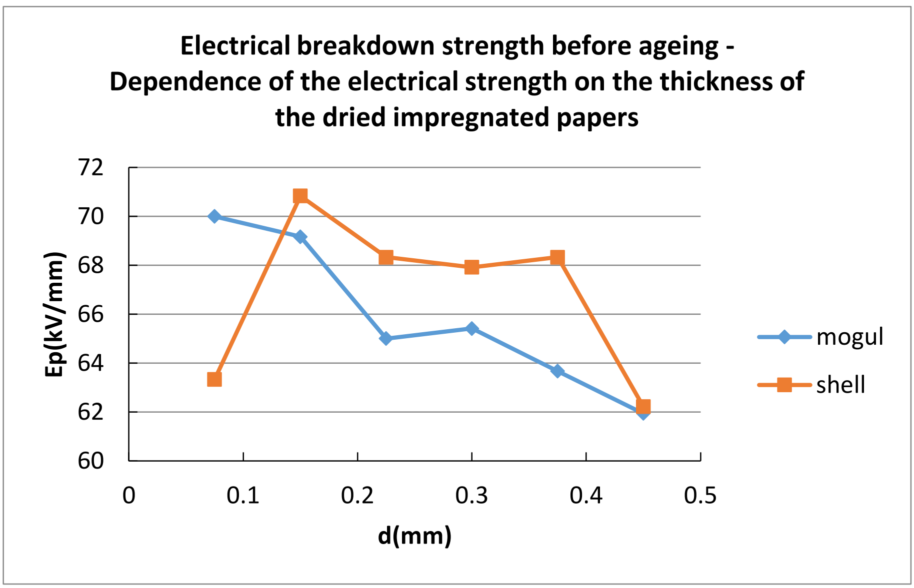

Figure 4: Graphical Dependence of electrical breakdown strength on the thickness of dried papers without ageing

Based on the results of the measurements, it was decided that only dried papers would be used in the next measurement as the magnitude of the breakdown stresses was much higher for dried than for undried samples. This statement is also evident from *Fig. 3* and *Fig. 4* where it can be clearly seen that the impact strength is higher for the dried papers with respect to the number of layers. After ageing, the Shell Diala S4 ZX-I sample has worse parameters. As can be seen in *Fig. 5* the values are not very different but Mogul Trafo CZ-A has slightly better impact strength.

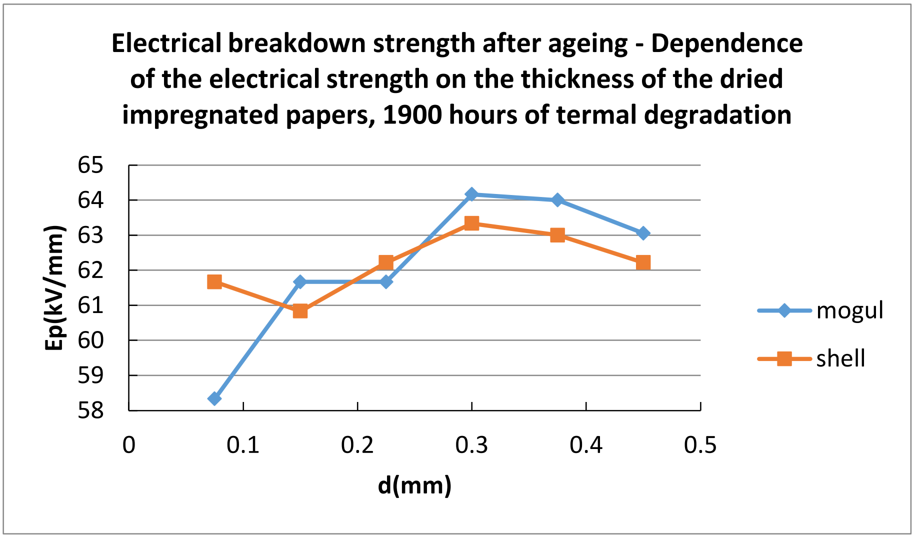

Figure 5: Graphical dependence of the electrical breakdown strength on the thickness of the dried papers after 1900 hours of ageing

It can be concluded that Shell Diala S4 ZX-I has better anti-ageing properties with increasing thickness of paper insulation and with dried papers. After 1900 hours of ageing, Shell Diala S4 ZX-I has a poorer electrical strength than Mogul Trafo CZ-A, with the exception of one and three layers of paper insulation. In the following graphs we have plotted the electrical breakdown strength versus ageing time for both types of oils. It is possible to notice a deterioration in properties with respect to ageing time.

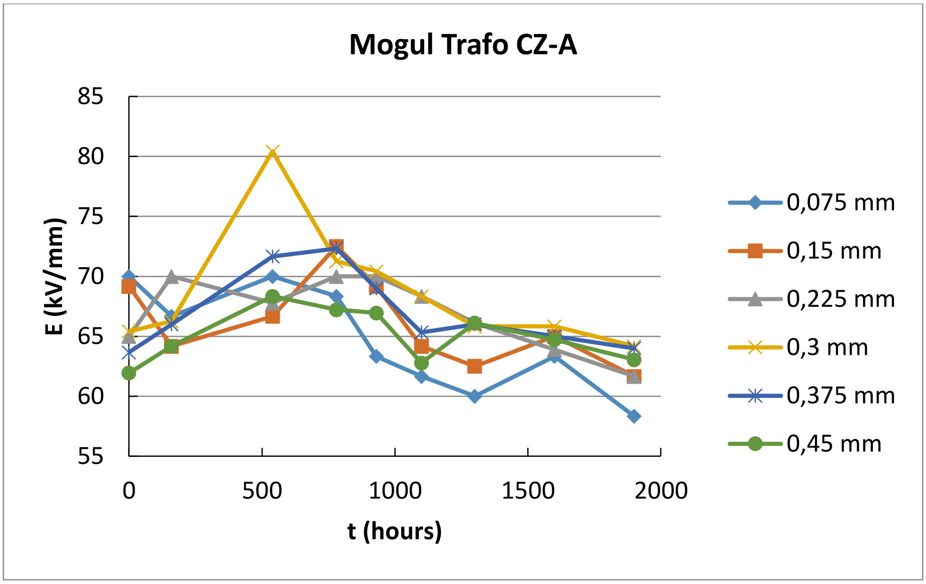

Figure 6: Graphical dependence of electrical breakdown strength on ageing time for Mogul Trafo CZ-A oil

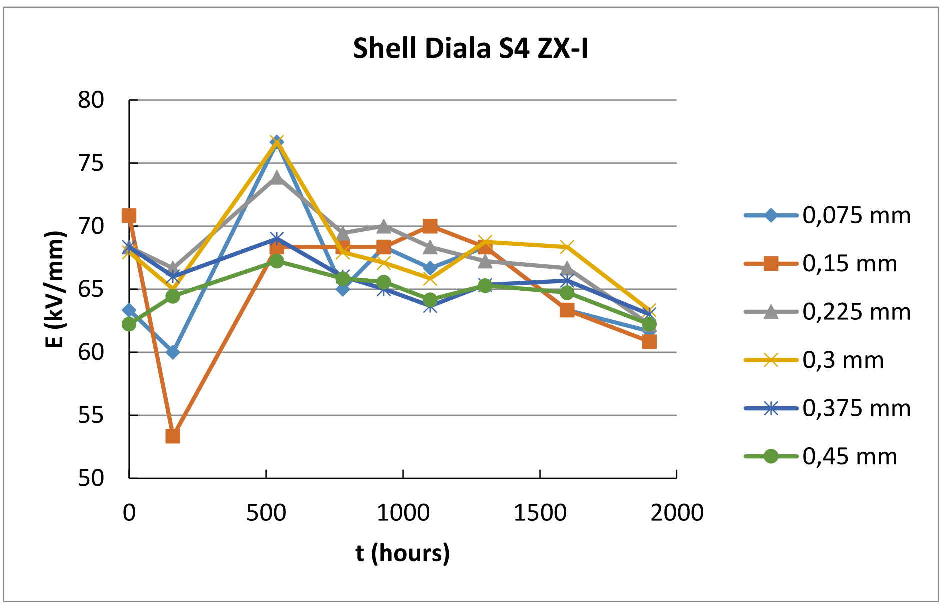

Figure 7: Graphical dependence of electrical breakdown strength on ageing time for Shell Diala S4 ZX-I oil

For further comparison of the oils, a thickness of 4 layers of insulating paper was chosen.

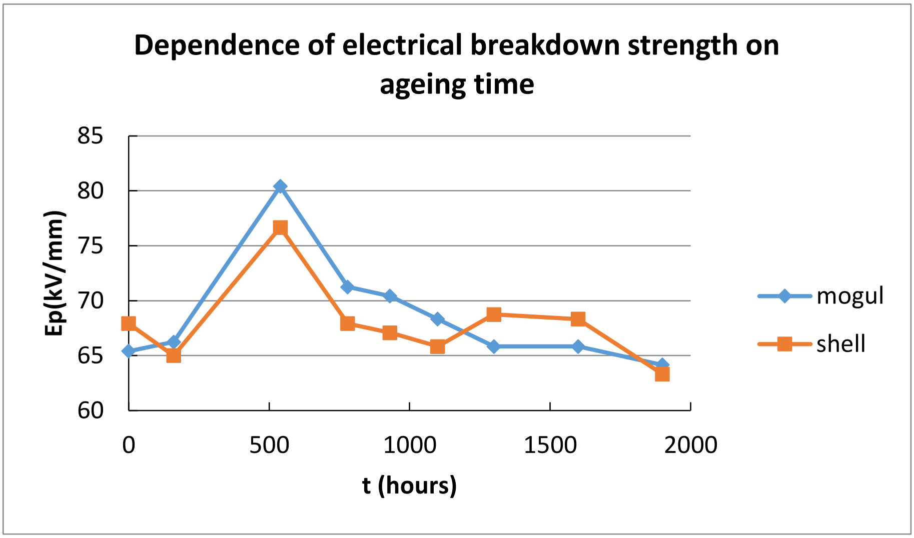

Figure 8: Graphical dependence of the electrical breakdown strength on the ageing time in case of 4 paper samples

In *Fig. 8* it can be seen how the breakdown strength of the two oils changes. Before ageing, it is confirmed, as mentioned above, that Shell Diala S4 ZX-I has a better value. However, this changes after about 150 hours and Mogul Trafo CZ-A has better properties. Both oils have an upward trend in terms of breakthrough strength up to about 500 hours of ageing. This improvement in values may be due to drying of the oil-paper insulation during thermal ageing. The values of the impact strength are not very different. After about 1200 hours of ageing, the breakpoint occurs again and the values of the impact stress are higher Shell Diala S4 ZX-I. At 1900 hours of ageing, these values are almost the same.A discoloration of the oils was observed during ageing, which was also due to the dissolution of the resin from the insulating paper. At about 1600 hours of ageing, higher oil density was observed, especially for Mogul Trafo CZ-A oil. After ageing, the density increased further due to processes caused by thermal stress.

On the following table are shown results from the measuring of the moisture. The presence of moisture was detected with a device Megger KF-LAB MKII. Moisture detection works on the principle of Karl Fischer titration, which is the standard method for determining the water content of various samples.

Table 1: Moisture content in the oils

Ageing time	No ageing	1600 hrs.	1900 hrs.	1900 hrs. at 80 °C
Mogul Trafo CZ-A	13.95 ppm	13.63 ppm	10.59 ppm	13.68 ppm
Shell Diala S4 ZX-I	12.78 ppm	12.38 ppm	11.62 ppm	13.87 ppm

5. Conclusion

In this paper, the electrical breakdown voltage was measured and the breakdown electrical strength of liquid insulators and paper impregnated with liquid insulator at AC voltage was calculated. Krempel paper with a thickness of 0.075 mm and two insulating mineral oils Mogul Trafo CZ-A and Shell Diala S4ZX-I were used for impregnating the paper. The breakdown voltage was measured for both dried and undried impregnated paper, then further measurements were performed on the dried paper sample due to the higher breakdown voltage value of 1.375 kV for one layer of paper. Subsequently, the samples were aged for 1900 hours and 9 measurements were performed. In the first measurement, the electrical strength of the selected oils without paper insulation was measured at AC voltage. The electrode distance was 2.5 mm. It can be seen from the measurements that after ageing, the properties of both oils deteriorated and the average value of the breakdown voltage decreased almost equally by about 8.8 kV. It can also be observed that Shell Diala S4 ZX-I oil has better value of the Mogul Trafo CZ-A both before and after ageing. From this it can be concluded that Shell Diala S4 ZX-I oil has better breakdown strength and hence better electrical insulation properties. When the impregnated paper is measured with both the oils, deterioration in properties is observed in case of Shell Diala S4 ZX-I oil. Before ageing, the paper impregnated with Shell Diala S4 ZX-I oil had a higher value of electrical breakdown strength than the paper impregnated with Mogul Trafo CZ-A oil. By approximately 500 hours of ageing, the values visibly increase. This may be due to the insulation system drying out. From this value onwards the breakdown voltage drops significantly for both oils. At 1200 hours of ageing, the breakdown values of Shell Diala S4 ZX-I are again higher than those of Mogul Trafo CZ-A. The differences between the values of the breakdown voltages of the two oils are not large, in the order of 1 to 2 kV. After ageing, when the oils are heated to 80°C, the values of moisture are higher due to the release of moisture from the oils. When we look at the individual oils, it is noticeable that Mogul Trafo CZ-A is better in terms of drying, because when comparing the values before and after ageing, the difference is 3.36 ppm. Shell Diala S4 ZX-I is quite a bit worse as the difference is only 1.16 ppm. When comparing the pre-ageing values of the oils, Shell Diala S4 ZX-I has a lower value of moisture.

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