International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:3, No:6, 2009

Ageing & Partial Discharge Patterns in oil-Impregnated Paper and Pressboard Insulation at High Temperature

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***Abstract*—**The power transformer is the most expensive, indispensable and arguably the most important equipment item in a power system Insulation failure in transformers can cause long term interruption to supply and loss of revenue and the condition assessment of the insulation is thus an important maintenance procedure. Oil-impregnated transformer insulation consists of mainly organic materials including mineral oil and cellulose-base paper and pressboard. The operating life of cellulose-based insulation, as with most organic insulation, depends heavily on its operating temperature rise above ambient. This paper reports results of a laboratory-based experimental investigation of partial discharge (PD) activity at high temperature in oil-impregnated insulation. The experiments reported here are part an on-going programme aimed at investigating the way in which insulation deterioration can be monitored and quantified by use of partial discharge diagnostics. Partial discharge patterns were recorded and analysed during increasing and decreasing phases of the temperature. The effect of ageing of the insulation on the PD patterns in oil and oil-impregnated insulation are also considered.

***Keywords*—**Ageing, high temperature, PD, oil-impregnated insulation

I. Introduction

THE power transformer is the most expensive and important item of capital equipment in the electric power transmission system and its long-term operational condition is thus of major concern to supply utility asset managers. The insulation within a power transformer consists primarily of organic dielectric materials, including mineral oil and cellulose-based materials such as paper and pressboard. These organic materials will suffer chemical change over the operating lifetime of the transformer and their insulating properties will deteriorate as a result. Paper in particular may deteriorate rapidly if the operating temperature is higher than the normal allowable levels in oil-impregnated insulation [1-3].

Modern computer-based partial discharge (PD) measurement techniques of electrical insulation will provide an instantaneous and time-resolved assessment of the insulation condition in most forms of equipment. In fact, PD monitoring is perhaps the most important tool available for the maintenance engineer to assess the condition of transformer insulation [4-6]. In conjunction with dissipation factor testing, PD monitoring is the one of the best method available for a combination of condition assessment and ageing [2].

This paper presents the results of an experimental investigation of partial discharge activity in oil-impregnated paper and pressboard configuration. The model was operated at elevated temperatures to simulate high temperature conditions such as may occur during abnormal (overload) operation of a transformer. As most transformer failures occur in the insulation, condition monitoring (preferably continuous and on-line) of transformer insulation is required to provide an early indication of any degradation that may be caused by abnormal electrical, thermal and mechanical stresses which may occur during operation. In order to recognize deterioration from PD patterns, it is necessary to catalogue and understand the correlation of PD patterns with the insulation condition [4-7].

A. Discharge Quantities

The analysis of the experimental results reported here is focused on the examination of peak and average partial discharge magnitude as well as the PD repetition rate. The peak discharge magnitude (q_m) is defined as "*the magnitude of the largest apparent charge recorded in a selected time interval*". The peak discharge magnitude is expressed in Pico coulombs:

$$q_m = \max[q_1, q_2, q_3, \cdots, q_n] \tag{1}$$

The average discharge magnitude (q_a) is defined as "*ratio between the sum of the measured discharge magnitude and the total number of PD pulses recorded in a selected time interval*". The average discharge magnitude is also expressed in Pico coulombs:

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$$q_a = \frac{1}{n}\sum_{i=1}^{n} q_i \tag{2}$$

According to the IEC 60270 Standard [7], the repetition rate (r) is defined as: "*ratio between the total number of PD pulses recorded in a selected time interval and the duration of this time interval*", and can be expressed mathematically:

$$r = \frac{n}{T} \tag{3}$$

Where n is the total number of discharges occurring within a selected time interval *T*.

The above PD parameters are calculated and displayed automatically almost in real time by a computer-based PD analysis system [6].

II. Experimental details

A. Test Configurations

The insulation system that was used in the work described here is designed to simulate the configurations and stress levels that occur in typical transformer insulation [2].

The test cell is made of glass containing the oil impregnated paper and pressboard insulation system. The glass cell is designed to withstand high temperature and it and the oil within is heated by thermostatically controlled heating tape wrapped around the lower part of the glass cell. The natural heat convection in the oil then forces the oil to circulate and transfer the heat throughout the sample. The maximum test temperature used during the experimental work was in the range 80-85 °C.

After reaching its maximum prescribed temperature, the heating source was disconnected and the oil allowed to cool naturally. The ambient temperature was kept within the range of 23.5-25.5°C. A fibre optic temperature sensor was used to monitor the insulation sample and oil temperature. The fibre sensor head was placed on the top surface of the paper/pressboard sample through a breathing hole on the top of the glass cell. Fig. 1 shows the test cell used in the experimental investigation.

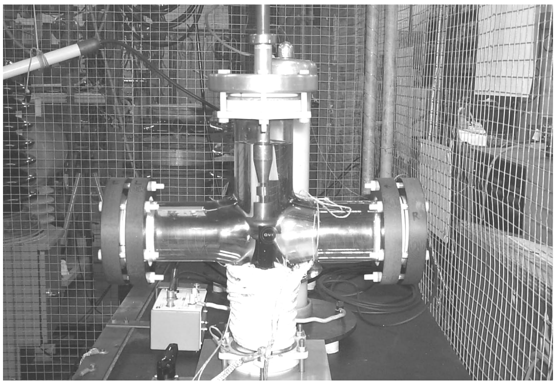

Fig. 1 The test cell

Fig. 2 shows the details of the insulation model configuration used. Oil-impregnated paper and pressboard insulate the high voltage (HV) and low voltage (LV) electrodes.

The insulation between the electrodes has three components. Immediately adjacent to the LV electrode are ten layers of Kraft paper each of thickness 0.06 mm, making a total thickness of paper equal to 0.6 mm. Immediately adjacent to the HV electrode are two layers of 0.25 mm thick crepe paper making a total thickness 0.5 mm. The third insulation component is a pressboard layer 3 mm thick sandwiched between the two paper layers. Overall, the Kraft paper, crepe paper and pressboard combination make up a 5cm^2 area covered by the electrodes.

The total separation between the HV electrode and LV electrode is approximately 4.1 mm. The HV and LV electrodes are bare, plane discs made from brass with disc diameter of 40 mm. The electrode configuration is large enough to generate a uniform electric field across the test sample. At the typical voltage used, 10 kV, the uniform electrical field acting on the insulation material between the electrodes will be 2.44 kV/ mm.

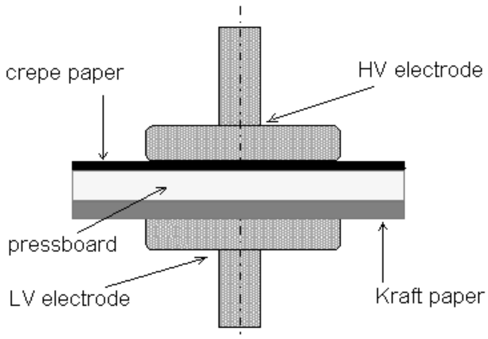

Fig. 2 Arrangement of the test sample

B. Measuring Equipment

PD activity in the insulation during the experiments was recorded using a computer-based analyser (CDA3). This system provides phase-resolved PD patterns of magnitude and number and their various statistical distributions for each half cycle of applied voltage. It also displays the IEC integrated quantities (discharge current, quadratic rate, and discharge power and repetition rate) [6]. The statistical moments for pattern characterisation (the mean, standard deviation, skewness and kurtosis of the PD patterns) are displayed on the computer monitor [6]. The circuit for PD measurement and calibration procedure follows the IEC-60270 Standard for partial discharge measurement [6, 7].

International Journal of Mechanical, Industrial and Aerospace Sciences
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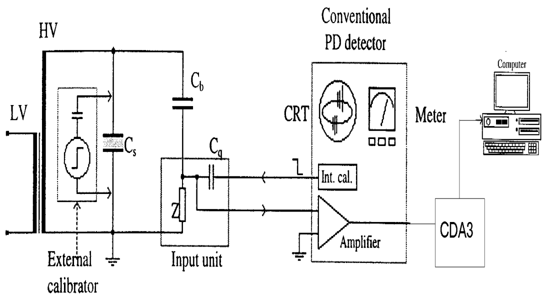

Fig. 3 Partial discharge measurement circuit

Fig. 3 shows the PD measurement circuit used. The CDA3 system is contained on a circuit board within a standard PC. The board interfaces the analogue output of a conventional discharge detector and the computer recording system. Cs denotes the capacitance of the test sample. The capacitance C_b represents a HV discharge-free coupling capacitor.

To prevent electrical interference in the measurements, the signal threshold of the CDA3 was set to reject background noise. In practice, the lower limit of PD detection was about 30 Pico Coulombs.

III. Results and Discussion

The experimental tests performed used a combination of thermal and electrical stress. The voltage applied to the model (10 kV) was designed to give operation at electrical stress typical of that of working transformers. The results reported here give PD activity characteristics for simulated thermal overload conditions in a transformer. The initial tests were done looking at the PD response when the insulation was subject to a short duration thermal cycle with PD activity monitored on both temperature increase and decrease during the cycle. The results for the new insulation used are also compared to results obtained on aged insulation in the same configuration, with the insulation being subject to ageing for some 5 months at the specified conditions of stress.

A. PDs with Increasing Temperature

In the initial test, the temperature of the sample was raised from ambient to 80-85°C and then allowed to cool back to ambient. It was observed that during increase of temperature from ambient to 60°C the peak discharge magnitude at the positive half-cycle was higher than the level during the negative half-cycle, as shown in Fig. 4.

In the temperature range from 60 to 70°C, [Fig. 5 shows PDs at 70°C] the PD repetition rate increased dramatically from 863pps [Fig. 4] to 4800pps [Fig. 5]. As the temperature reached the upper limit range of 80 to 85°C [Fig. 6 shows results at 81°C] the maximum PD level changed its behaviour and the peak PD magnitude on the negative half-cycle became larger than on the positive half-cycle. At the same time, the maximum and average discharge magnitude increased significantly. A significant increase in the repetition rate was also observed, as shown in Fig. 6.

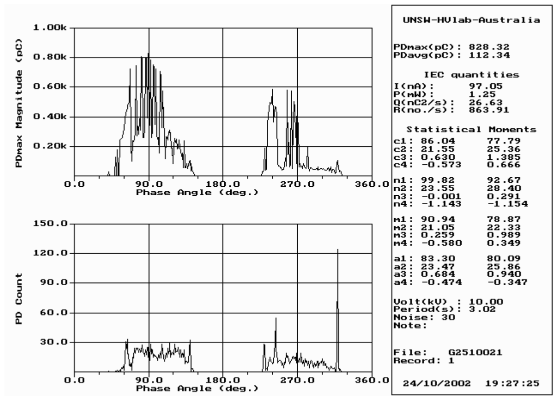

Fig. 4 PD pattern at 10 kV and 60°C temperature increasing

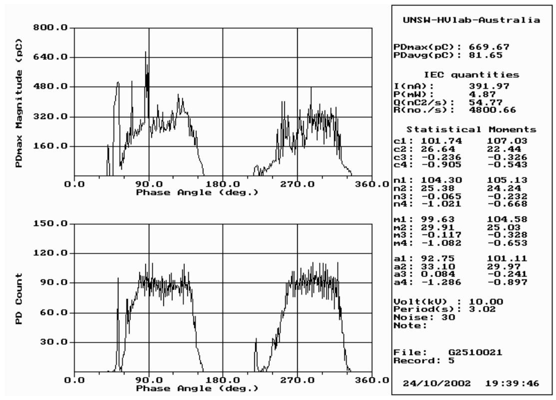

Fig. 5 PD pattern at 10 kV and 70°C temperature increasing

It can also be seen that there is a steady trend, with increasing temperature, to earlier PD inception on both the PD and repetition rate plots versus phase angle of the voltage waveform.

Following the simulated overload, the PD behavior was then investigated during the cooling part of the thermal cycle, with the heater off and the chamber allowed to cool naturally to ambient.

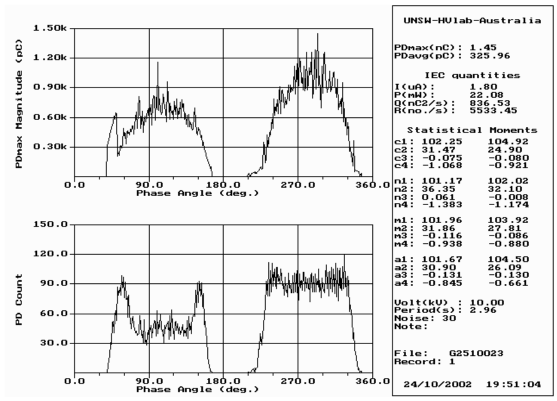

Fig. 6 PD pattern at 10 kV and 81°C temperature increasing

B. PDs with Decreasing Temperature

When the temperature is decreased from the peak level of 85°C back to 80°C, the largest peak PD magnitudes on both the positive and the negative half-cycles become almost equal (see Fig. 7). As the temperature was, then further decreased to 60°C, Fig. 8 and Fig. 9 show that the largest peak PD magnitude has again shifted to be again in the positive half-cycle. Fig. 8 and Fig. 9 depict the phase-resolved patterns of PDs at 70°C and 60°C.

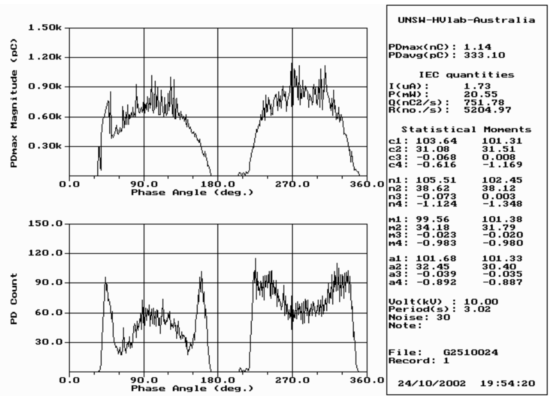

Fig. 7 PD pattern at 10 kV and 80°C temperature decreasing

It was also observed during the experiment that the PD magnitude and the PD repetition rate increased with increase of temperature between 60 to 85°C and when temperature decreased the repetition rate also decreased. It was also observed at 80°C was the temperature where the peak PD magnitudes for both positive and negative half-cycles were almost equal.

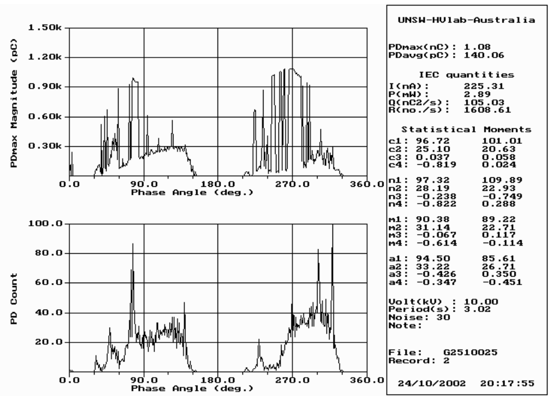

Fig. 8 PD pattern at 10 kV and 70°C temperature decreasing

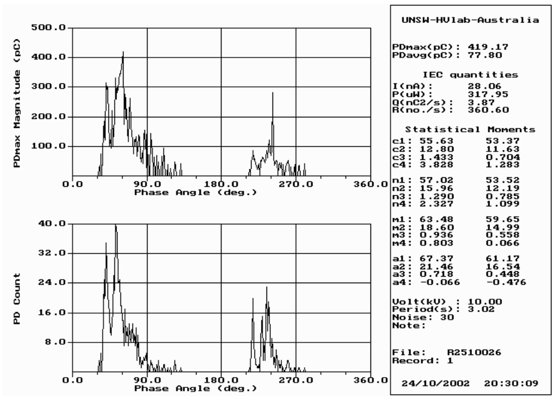

Fig. 9 PD pattern at 10 kV and 60°C temperature decreasing

C. Comparison with Previous Tests in a Steel Tank

It was also noted during the experiment that the PD patterns at 10kV, 80°C and 50Hz in the glass cell are somewhat similar to those monitored during previous tests in another insulation test configuration enclosed in a steel tank. In that work the test conditions used were 8kV, 80°C and 50Hz [1-3]. The patterns in Fig. 7 (in glass) and Fig. 10 (in steel [1-3]) can be compared. Although the voltage was different (the stress levels are 2.44 kV/mm in the glass and 1.95 kV/ mm in the steel tank). The general shapes of the patterns are similar, although there is some difference in the inception angles and the magnitudes are different, consistent with the different stress levels.

The insulation configuration between the HV and LV electrodes in the steel tank also contained kraft paper, crepe paper and pressboard and the total separation thickness between HV electrode and LV electrode was also 4.1mm, as in the glass. Thus the electric field would be the same for the same voltage.

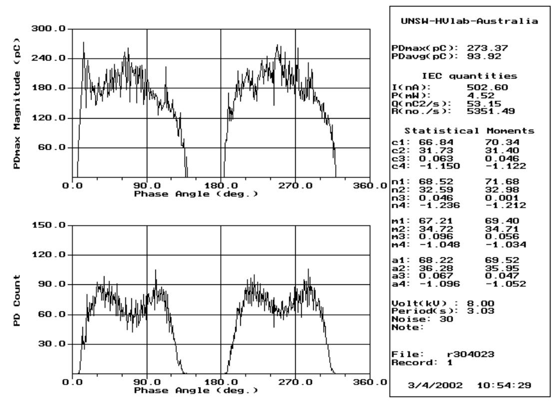

Fig. 10 PD pattern at 8 kV, 50 Hz and 50°C

D. Tests using Aged Insulation

The insulation structure was subjected to the voltage excitation for a total period of five months to investigate the effects of ageing on the oil-impregnated sample. At 80°C it was found that the peak PD magnitude had increased from

International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
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1.14nC to 2.0nC and the PD average has also increased. It was also noted that PD patterns in the aged sample had changed, with discharges on the positive half-cycle starting at about 5 degrees of voltage phase as compared to previous results where the discharges were very consistent in starting at about 30 degrees.

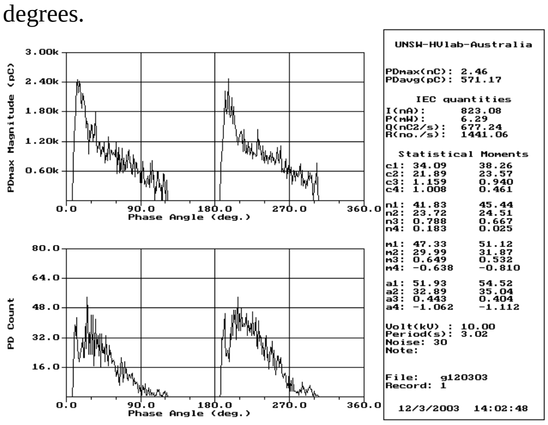

Fig. 11 PD pattern at 10 kV, 80°C after ageing for five months

Similarly, for the test on an aged sample, discharges on the negative half-cycle started at around 185 degrees compared with at 210 degrees in the previous test. Fig. 11 shows the phase-resolved pattern of peak PD magnitude and PD number distribution measured during the test using the aged insulation.

E. Ageing of Oil Impregnated Insulation

The change of colour of oil from clear to light brown was also observed during the ageing process caused due to thermal damage to cellulose materials and oxidation of oil. Fig. 12 and Fig. 13 show the colour change of the oil. The change of colour of the kraft paper, crepe paper and pressboard from light brown shade to dark brown was also observed during the ageing process. At high temperatures the cellulose polymer chains break up reduce in length and, as part of the degradation, form water especially in the presence of oxygen.

The excessive moisture, oxygen and temperature caused the oxidation that result in the change of colour of the cellulose material.

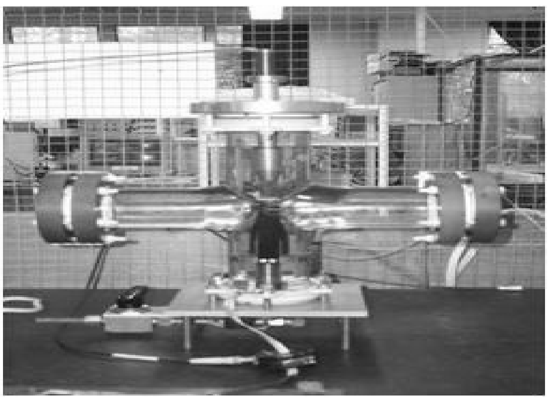

Fig. 12 Color of oil in glass cell before the ageing process

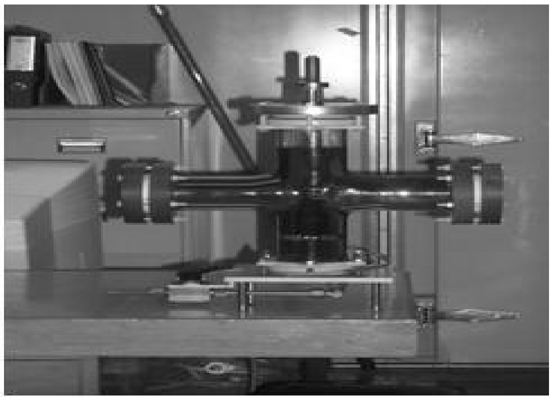

Fig. 13 Color of oil in glass cell after the ageing process caused oxidation of oil that result in darkening of oil color

The effects of ageing are also very obvious from the damage caused to the crepe paper, pressboard and kraft paper. Signs of water treeing can be seen on the crepe paper and significantly so on the pressboard. Electrical treeing can be seen on the kraft paper showing clear signs of black carbonised conducting paths causing burning and brittleness of the paper.

The water treeing is caused when water migrates to high stress areas and reduces the dielectric strength of the material and water treeing also produces third harmonics. No PD activity is present when the water trees are present. The water treeing is then followed by electrical treeing. In the electrical treeing mode the PD activity starts and causes black carbonised conducting paths ultimately leading to the failure of the insulation. Fig. 14 and Fig. 15 show the quality of cellulose material before and after the Ageing Process.

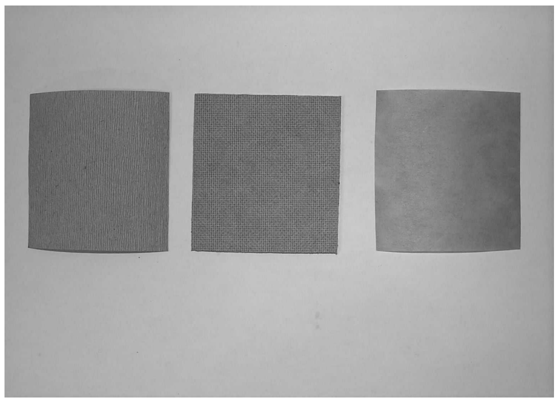

Fig. 14 Quality of crepe paper, pressboard and kraft paper before ageing; left is crepe paper, middle is pressboard and right is kraft paper

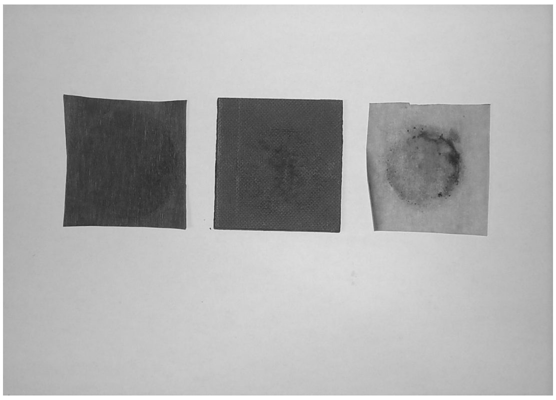

Fig. 15 Quality of crepe paper, pressboard and kraft paper after ageing; left is crepe paper, middle is pressboard and right is kraft paper with black marks showing clear signs of carbonised conducting paths causing burning and brittleness

IV. Conclusions

As long-term investigations are needed to investigate PD pattern analysis in oil-impregnated insulation at high temperature, a number of significant observations were noted during the increasing and decreasing temperature phases in the experiment.

- During simulated thermal overloading when temperature increased from ambient to 80-85°C the largest peak PD magnitude measured was initially on the positive half cycle, but then shifted from the positive to the negative half-cycle and the PD levels increased with increase of temperature of the insulation.
- During the cooling phase from 80-85°C to the ambient temperature the PDs with largest peak magnitude shifted back from the negative to the positive half-cycle. The PD levels decrease with the decrease of temperature during the cooling phase.
- The peak magnitude of the discharges and the PD repetition rate increases with increase of temperature and decreases with decrease of temperature.
- Similar test configurations result in similar partial discharge patterns at a same temperature stress level.
- The colour of the oil changed from clear to light brown with ageing due to thermal stress causing oxidation.
- The colour of the kraft paper, the crepe paper and the pressboard changed from the original light brown shade to dark brown with ageing. The ageing due to PD activity can cause a burning or carbonisation effect on both pressboard and paper and also caused the paper to become brittle through de-polymerisation.

The results of this investigation have shown the complexity involved in correlation of the effects of temperature on PD activity. This complexity may lead to problems in interpretation of PD measurements on transformers. Further work is required to elucidate the impact on PD activity so that definitive indicators of aging quantification can be derived.

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