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Investigating the impacts of ageing and moisture on dielectric response of oil/paper insulation systems

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Abstract: The oil/paper insulation system in a transformer degrades under various chemical, thermal and electromechanical stresses during its operation. Dielectric response measurements like the Return Voltage Measurement (RVM) and Polarisation and Depolarisation Current (PDC) measurement are currently being used for condition assessment of the insulation. In the current research project, the ageing condition and the moisture content of both paper and oil samples have been varied over a controlled range and their effects on the dielectric response measurements have been investigated. Experimental results are provided in this paper to demonstrate the effects of both ageing and moisture content of paper and oil on the RVM and PDC results.

1. Introduction

The insulation system in a power transformer degrades under normal operating conditions, in particular with higher temperature, higher moisture and oxygen. The remnant life of a transformer is significantly influenced by the condition of the oil-paper insulation. Currently, degradation of insulation in a transformer is monitored by sampling the oil and analysing for dissolved gases, furan content and by examining the change in the degree of polymerisation (DP) of cellulosic paper [1]. In current deregulated electricity markets, non-destructive diagnostic techniques are becoming more and more popular for condition-based maintenance of aged transformers.

The Return Voltage Measurement (RVM) technique [2-6] has been used for the last few years for the assessment of insulation condition in aged transformers. This technique was found to be sensitive to moisture and insulation ageing. RV measurements on transformers [2-3] as well as on artificially aged laboratory test samples [4-5] demonstrated the nature of insulation degradation and the deterioration of its electrical properties. It was also pointed out, however, that the RVM results often being the complex convoluted effect of both oil and paper – it is not possible to separately assess the condition of oil and paper.

In this context, the **P**olarisation and **D**epolarisation **C**urrent (PDC) measurement technique [6-8] promises to provide information about the paper and oil conditions separately. Both techniques (RVM and PDC) though being straight-forward, the interpretation of the results often becomes suspicious due to the effects of both oil and paper, their ageing status and moisture contents.

In the current research project, the authors have been investigating the effect of both ageing and moisture on the dielectric response measurements (RVM and PDC). Experiments have been performed on laboratory test samples with controlled moisture and ageing condition of both the oil and paper. Results of these tests along with suitable explanations and analyses are presented in this paper.

2. Experimental details

Moisture conditioning

The details of the moisture conditioning setup have been reported in [5]. The method was developed to control the moisture of insulation paper using Piper chart [9]. In this method, a set value of paper moisture level was achieved by controlling the pressure of water vapour and temperature inside a closed container for a long period of time. The test samples used for the purpose are a pair of paper-wrapped copper conductors impregnated with transformer oil [5].

Artificial ageing of the samples

To perform ageing experiments moisture conditioned conductor samples and oil were transferred from the conditioning vessel to the ageing ampoules after oil/paper equilibrium was achieved. The ampoules were subsequently placed in a controlled temperature oven for two selected periods of ageing: 120 and 240 days. The temperature of the oven was set to 95°C during the ageing period. After completion of the ageing according to the set period, the ampoules were taken out of the oven and placed into a humidity-controlled chamber. After cooling down, the aged samples and oil were transferred into the test cells for dielectric response measurements. The moisture contents of paper and oil after ageing were measured by the Karl Fischer titration method.

Dielectric response measurement system

Dielectric response measurements, RVM and PDC, were conducted with a computer controlled measurement system developed by the School of ITEE, University of Queensland [1-2, 4]. RVM parameter like the central time constant (CTC) were computed for all the test samples and paper and oil conductivities were calculated from the PDC test data. These values of CTC and conductivities are used for the assessment of the ageing and/or moisture condition of different test samples.

3. Results

In the present study, three different oil samples have been used. These oil samples have been obtained from field transformers and are summarised in Table 1. The paper samples with which the experiment was started were of 2% moisture content of different ageing conditions as shown in Table 2. However, during the course of the ageing process and also during the course of the experiment, when the different oils and different paper samples were paired together, the relative moisture contents of the oil and paper changed from their initial values. The actual values of the moisture contents of the oil and the paper samples as measured by Karl Fischer Titration method during the course of the experiments are shown in Table 2.

Table 1: Oil Specimens

Oil	Moisture Content (ppm)	Age (Years)
T0	9	New Oil
T1	23	34
T2	27	39

Table 2: Oil and paper samples for test

	Sample		Moisture	
	Paper	Oil	Paper (%)	Oil (ppm)
A	Dry Unaged	T0	1.1	9
B1	2% Unaged	T1	2.9	26
B2	2% Unaged	T2	3.0	33
C	2% 120 Days Aged	120 Days Aged	2.6	14
C1	2% 120 Days Aged	T1	3.3	26
C2	2% 120 Days Aged	T2	3.3	31
D1	2% 240 Days Aged	T1	3.1	25
D2	2% 240 Days Aged	T2	3.2	31

As can be seen from Table 2, whenever paper and oil of different moisture contents are added together, depending upon the temperature and their individual moisture saturation levels, there is always a re-distribution of the moisture between the oil and the paper till equilibrium is attained. All these experiments were performed at a controlled temperature of $25^0C \pm 2^0C$.

Paper ageing and moisture

The samples B1, C1 and D1 have the same oil (T1) in them, whereas the papers have different ageing and moisture conditions. Figure 1 shows the RV spectra corresponding to these three samples and also the dry and unaged sample A, for reference. It is observed from Figure 1 that the peaks of the RV spectra occur at lower times for samples with higher paper moisture and ageing. The plots for C1 and D1 are close to each other as their paper moisture contents are not too different. The values of the central time constants (CTC) are summarised for all the samples in Table 3.

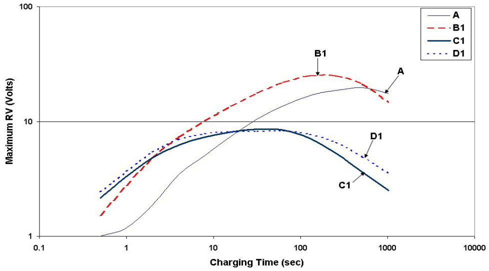

Figure 1: RV spectra for samples with different paper ageing and moisture but with the same oil T1.

Similar plots are obtained for samples B2, C2 and D2, as shown in Figure 2, where the T2 oil has been used. Once again, the RV spectra for C2 and D2 lie close to each other as they have similar values of paper moisture contents.

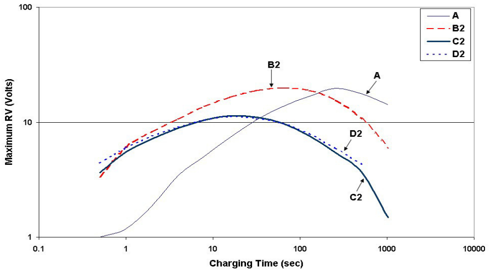

Figure 2: RV spectra for samples with different paper ageing and moisture but with the same oil T2.

The polarisation and depolarisation currents for the set of samples A, B2, C2 and D2 are plotted in Figure 3 and Figure 4 respectively.

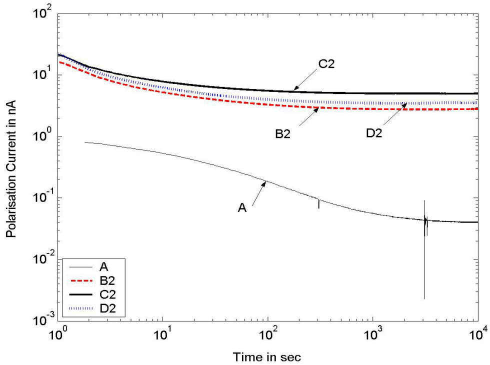

Figure 3: Polarisation currents for different paper ageing and moisture but with the same oil T2.

As seen in Figure 3, the polarisation currents for aged and moist paper samples B2, C2 and D2 are higher than the dry and unaged reference sample A. The relative positions of the polarisation currents for B2, C2 and D2 are dependent on both the moisture and ageing. Higher the ageing and/or moisture, higher will be the value of the polarisation current. Since the oil condition is the same in all the three cases, as suggested by [7-8], the initial values of the currents corresponding to B2, C2 and D2 are very close to each other. The difference is mainly in after 100 sec, when the effect of paper ageing and/or moisture shows up in the values of the currents. C2 having the highest amount of moisture in paper lies on the top. B2, corresponding to the unaged paper sample lies at the bottom of the three. The D2 sample, though more aged than B2 and C2, lies in-between B2 and C2 since its paper moisture content, as shown in Table2, is lower than that of C2. The differences in the current values are however not too much since all these samples B2, C2 and D2 have paper moisture content values quite close to each other.

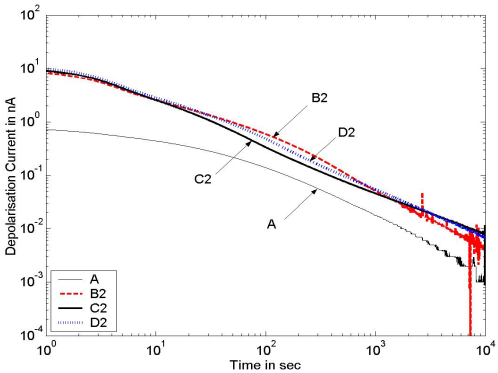

Figure 4: Depolarisation currents for different paper ageing and moisture but with the same oil T2.

As expected, the depolarisation currents for the aged and/or moist samples B2, C2 and D2 lie above the reference sample A. The difference between the depolarisation currents for B2, C2 and D2 are, however, not significant since their moisture contents are quite close. Only a very close look at Figure 6 will reveal the difference between the depolarisation currents of B2, C2 and D2 at the final stage. Values of paper and oil conductivities calculated from these polarisation and depolarisation currents are presented in Table 3.

Oil ageing and moisture

The samples C, C1 and C2 have papers of same ageing condition and the paper moisture values are also quite close. The oils in those samples are however, of different ageing and moisture conditions. Figure 5 shows the polarisation spectra corresponding to these three samples and also the dry and unaged sample A, for reference.

The RV spectra plot of Figure 5 shows that the samples with lower moisture content and/or ageing have higher values of central time constant. These values are also summarised in Table 3.

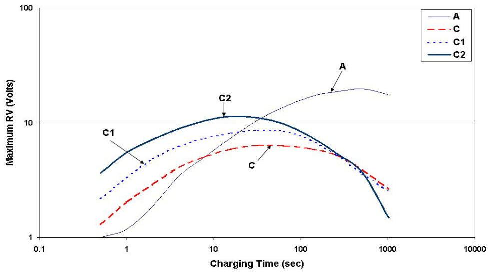

Figure 5: RV spectra for samples with different oil ageing and moisture.

The polarisation and depolarisation currents for the set of samples C, C1 and C2 are plotted in Figure 6 and figure 7 respectively. The currents for sample A are also included as a reference.

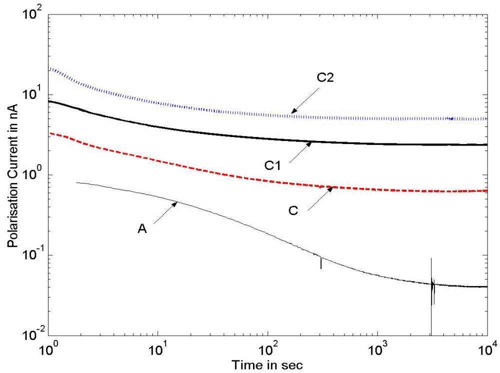

Figure 6: Polarisation currents for different Oil ageing and moistures

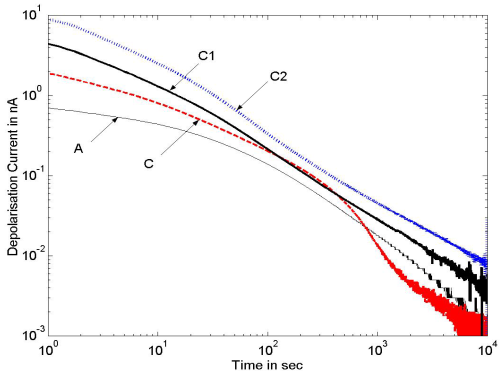

Figure 7: Depolarisation currents for different Oil ageing and moistures

It is evident from Figures 6 and 7, that the condition of oil affects the initial parts of the polarisation and depolarisation currents. These deviations in the initial magnitudes were not present in Figures 3 or 4 – where the oil condition was the same for the three samples. Sample C having the least value of oil ageing and moisture lies at the bottom – followed by samples C1 and C2 respectively. As seen from Table 2, C2 has the most severe oil ageing and moisture. The long-time values of the polarisation and depolarisation currents however, depend on the paper ageing and/or moisture. Though all of C, C1 and C2 have the same paper ageing period of 120 days, since C2 has the highest value of paper moisture, the polarisation and depolarisation current plots at longer time for C2 lies above those for C1 and C respectively. The currents for the reference sample A lie below all three samples C, C1 and C2. The conductivity values calculated from these polarisation and depolarisation currents are shown in Table 3. As expected, C2 is having the highest conductivity among the three samples C, C1 and C2.

Table 3: Summary of Dielectric Measurements

Sample	CTC (sec)	Conductivity (pS/m)	
		Oil	Paper
A	912	0.165	0.058
B1	174	1.17	1.12
B2	68	11.63	4.44
C	69	1.92	0.97
C1	46	5.46	3.04
C2	22	15.79	7.26
D1	77	3.2	1.53
D2	24	12.38	4.32

4. Discussions

From the above results, the following general observations can be made:

- Whenever oil and paper of different moisture levels are put together, depending upon the operating temperature and their individual moisture saturation levels, there is always a transition of moisture between the two till they come into equilibrium. This observation is supported by the fact that, though 2% initial moisture were set in the paper samples used in the experiment, after impregnating with oils of different moisture contents, the moisture contents of the paper deviated from the initial value till equilibrium is reached.
- The effects of paper ageing or moisture are indistinguishable on the RV spectra. A high moisture or ageing of paper tend to bring down the central time constant to lower values.
- A high ageing and/or moisture in oil tend to lower down the CTC of the RV spectra. The RV spectra is a convoluted effect of the oil-paper ageing and moisture and it is difficult to distinguish the individual effects of oil-paper ageing and/or moisture on RV spectra.
- The polarisation and depolarisation current magnitudes are significantly controlled by the paper and oil moisture contents. Higher moisture content in oil increases the initial magnitude of the polarisation and depolarisation currents, whereas higher moisture content in the paper tends to increase the final magnitude of the polarisation and depolarisation currents. These magnitudes are very sensitive to moisture and these are reflected in the calculated values of the conductivities of oil and paper.
- The PDC technique can, however separate out the effects of oil and paper condition – oil condition mainly affecting the initial phases of the polarisation and depolarisation currents, whereas the final values of the polarisation and depolarisation currents are dependent upon mainly on the state of the paper insulation.

5. Conclusions

Dielectric diagnostic tests for condition assessment of transformer insulation have become more popular than ever due to the demand of non-destructive diagnostic techniques for condition based maintenance in the current deregulated power industries. This paper presents results and analysis from a series of experiments conducted with transformer oil and paper insulation at different moisture and ageing conditions. The results show a definite influence of the ageing and/or moisture on both the RV and PDC measurements. Whereas the RV measurement results are a convoluted effect of both the oil and the paper conditions, the PDC measurement is able to distinguish between the condition of oil and paper separately.

6. References

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