Impact of the Condition of Oil on the Polarisation based Diagnostics for Assessing the Condition of Transformers Insulation

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Abstract—The oil/paper insulation system in a transformer degrades under various chemical, thermal and electromechanical stresses. Among the newer dielectric response measurements, Polarisation and Depolarisation Current (PDC) measurement has the strength to monitor the quality of oil and papers conditions separately on the overall diagnostic results. 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. Particular emphasis has been given to use different oil samples from field transformers. Experimental results are described in this paper to demonstrate the effects of both ageing and moisture content of oil on PDC results. A mathematical tool has also been used to model the equivalent circuit of polarisation process to monitor the impact of oil on diagnostics.

***Index Terms*—Power transformer, polarisation depolarisation current measurement, oil conductivity, ageing of transformer, dielectric diagnostics**

I. Introduction

OIL immersed paper and pressboard insulation are still the traditional insulation for power transformers. Solid insulations of transformers are made from pure cellulose without any binder. When the insulating material is in the form of thin layers of paper they are used for wrapping the conductors of the winding. They are used to insulate the windings from the earthed parts. Pressboards are thicker than paper and is used to mechanically separate discs or layers from each other. The solid insulation (paper, pressboard, transformerboard) used in transformers are manufactured from unbleached sulphate cellulose. Alpha cellulose required for paper manufacture is a high polymer carbohydrate chain consisting of approximately 2000 glucose units.

Transformer oil is used as a dielectric and as a coolant medium. The windings are cooled by the circulation of oil over their surfaces. The oil consists of a mixture of hydrocarbon compounds with different structure. The composition of transformer oil can vary due to degree of refinement and due to the differences that occur between oils taken from different geographical locations.

The paper and oil insulation used in transformers normally degrade with time. The degradation depends on thermal, oxidative hydrolytic, electrical and mechanical conditions within the transformer. The temperature of the insulation in a particular transformer depends on its loading history and on the ambient operating conditions. The temperature of the oil-cellulose dielectric is the critical ageing parameter for the changes in the mechanical, chemical and electrical properties of the material. Oxygen dissolved in the oil is a major contributory factor in accelerating the rate of degradation of the solid insulation and the oil, particularly in the presence of moisture and under conditions of high operating temperatures.

The ageing process of cellulose materials has been monitored by many techniques. Dissolved Gas Analysis (DGA) [1], Degree of Polymerization (DP) measurement [2, 3] and Furan analysis [4] are very commonly used by electric utilities. Other recently developed techniques such as Gel Permeation Chromatography (GPC) for studying the molecular weight distribution of cellulose are also suggested for assessment of solid insulation ageing [5]. Oil condition can be assessed by periodically sampling the oil and testing for parameters such as breakdown strength, acidity, moisture content etc.

Recently, Recovery Voltage Measurement (RVM) technique [6, 7] is being used for the assessment of the condition of the composite oil-paper insulation system. Though RVM has the advantage of being a non-destructive diagnostic technique, its use is constrained by complicated interpretation scheme and also by the fact that RVM can only assess the overall condition of the insulation without emphasizing on oil or paper condition separately.

On the other hand, Polarisation and Depolarisation Current (PDC) measurement technique [8] promises to separately identify the conditions of oil and paper insulation inside the transformer, without having to open the lid for paper sampling.

In this context, a study on the effect of oil and paper condition (ageing and moisture) on the PDC test results seems pertinent. The present paper thus describes a set of controlled experiments performed with different oil and paper conditions under normal and accelerated ageing conditions. An attempt has been made to correlate the PDC test results with the

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actual moisture content and ageing condition of the oil and paper insulation. The experimental results obtained have been compared with simulation results obtained from an insulation system model earlier presented in a paper [15].

II. Theory and Technique of PDC Measurement [14]

For a homogeneous material, the field strength *E(t)* can be considered as generated by an external voltage *U(t),* then the current through a test object with geometric capacitance C_0 (measured capacitance at or near power frequency, divided by ε_r) can be written as:

$$i(t) = C_0\left[\frac{\sigma}{\varepsilon_0}U(t) + \varepsilon_r\frac{dU(t)}{dt} + \frac{d}{dt}\int_0^t f(t-\tau).U(\tau)d\tau\right] \qquad (1)$$

The test object can be a single dielectric material or an arrangement of several dielectric materials in series or in parallel. For more than one dielectric material, σ, ε_r and *f(t)* represent, respectively, composite conductivity, relative permittivity and dielectric response function of this heterogeneous test object. The response function *f(t)* describes the fundamental memory property of the dielectric system and can provide significant information about the insulating material [9]. The function *f(t)* can be determined experimentally as the response of the dielectric to a step-function charging field [9].

Assuming that the test object is totally discharged and that a step voltage is applied with the following characteristics:

$$U(t) = \begin{cases} 0 & t \langle 0 \\ U_0 & 0 \underline{\langle} t \underline{\langle} t_c \\ 0 & t \rangle t_c \end{cases} \qquad (2)$$

This will give zero current for times before t = 0, and so called polarisation currents for times $0 \le t \le t_c$. The polarisation current is built up in two parts – one part is related to the conductivity of the test object and the other is related to the activation of the different polarisation processes within the test object. The polarisation (charging) current through the object can thus be expressed as:

$$i_p(t) = C_0 U_0\left[\frac{\sigma}{\varepsilon_0} + f(t)\right] \qquad (3)$$

Once the step voltage is replaced by a short circuit, a depolarisation current is built up. The depolarisation current is expressed as:

$$i_d(t) = -C_0 U_0\left[f(t) - f(t+t_c)\right] \qquad (4)$$

Where t_c is the time during which the voltage has been applied to the test object.

The principle of measurement of polarisation and depolarisation current is based on application of a DC voltage across a test object for a long time (e.g.10000 sec). During this time, the current, arising from the activation of the polarisation process with different time constants corresponding to different insulation materials and due to the conductivity of the object is measured. Then the voltage is removed and the object is short circuited. The previously activated polarisation process now gives rise to the discharging current in the opposite direction, where no contribution of the conductivity is present. The schematic diagram of the PDC measuring set-up is shown in Fig.1. Fig.2 shows the typical nature of these currents due to a step charging voltage U_0.

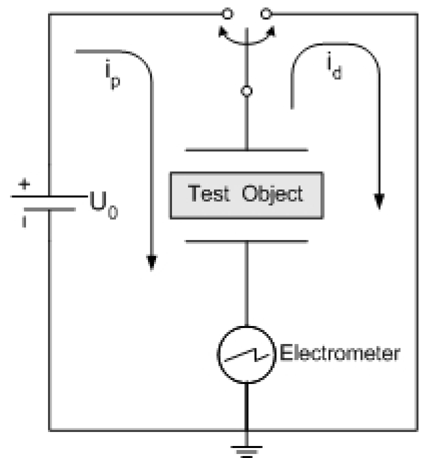

Fig.1. Basic PDC measuring circuit

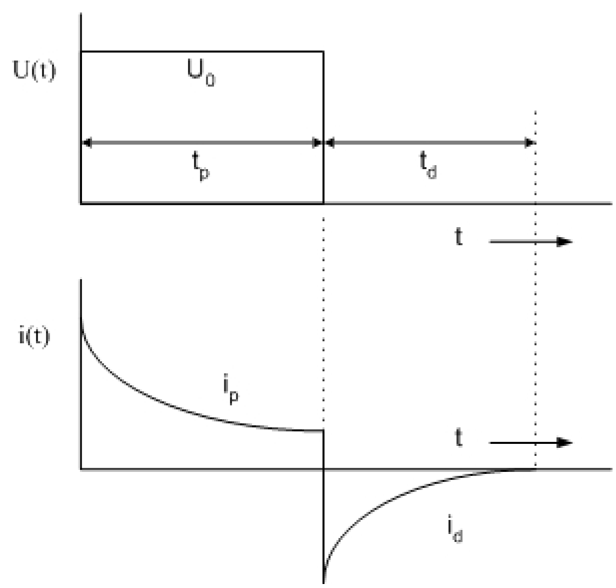

Fig.2. Waveform of polarisation and depolarisation currents

Charging and discharging currents (i.e. polarisation and depolarisation currents) are influenced by the properties of the insulating materials as well as by the geometric structure of the insulating system [10].

III. Experimental Details

A. Moisture conditioning

The details of the moisture conditioning setup have been reported in [11]. The method was developed to control the moisture of insulation paper using Piper chart [12]. 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 [11].

B. 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 a selected period of ageing of 240 days. The temperature of the oven was set to 95^{o}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.

C. PDC measurement system

The PDC measurement was conducted with a computer controlled measurement system developed by the School of ITEE, University of Queensland [13-14]. Paper and oil conductivities were calculated from the PDC test data. These values of conductivities are used for the assessment of the ageing and/or moisture condition of the oil and paper insulation of different test samples.

IV. Results

In the present study, three different oil samples have been used. One is new oil and the other two oil samples have been obtained from field transformers and are summarized in Table 1. The paper samples with which the experiment was started were of 2% moisture content of un-aged condition 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 the 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. A second set of 2% moisture content paper samples were artificially aged for 240 days at 95^{o}C in a closed chamber. After the ageing period was over, the paper samples were immersed in the oil samples T0, T1 and T2 and the PDC tests were carried out once again.

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	2.8	26
B2	2% Unaged	T2	3.0	33
C1	2% 240 Days Aged	T1	3.1	25
C2	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^{0}C ± 2^{0}C.

A. Oil ageing and moisture

The samples B1 and B2 have papers of same ageing condition (no ageing) and the paper moisture values are also quite close. The oils in those samples are however, of different ageing and moisture conditions. The polarisation and depolarisation currents for the set of samples B1 and B2 are plotted in Fig. 3 and Fig.4 respectively. The currents for sample A are also included as a reference.

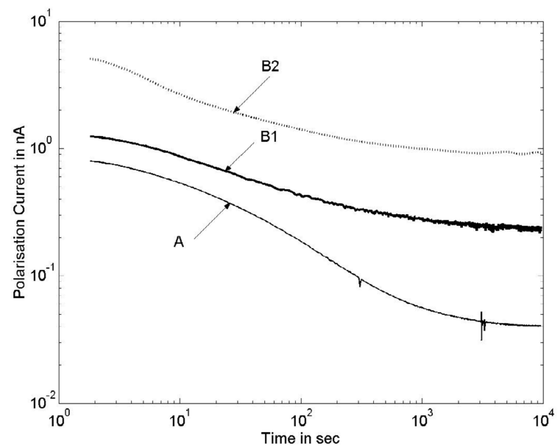

Fig.3. Polarisation currents for samples B1 and B2

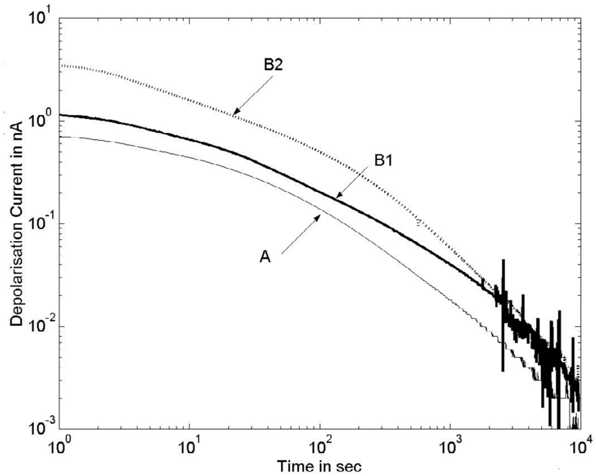

Fig.4. Depolarisation currents for samples B1 and B2

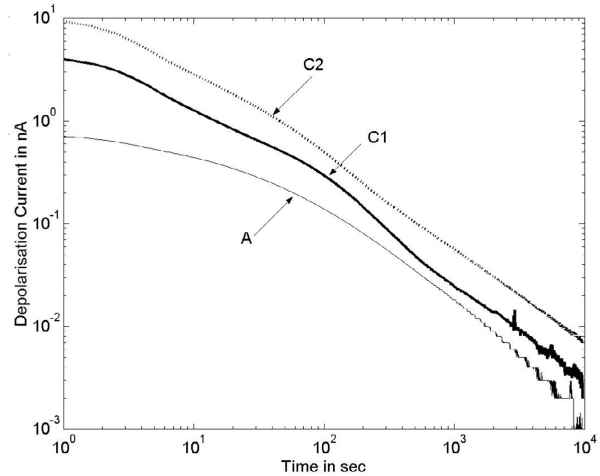

Fig.7. Depolarisation currents for different Oil ageing and moistures

As seen in Fig.3 and Fig.4, sample A having the least value of oil ageing and moisture lies at the bottom – followed by samples B1 and B2 respectively. The magnitudes of these currents are related to the oil/paper moisture contents [14]. Higher the moisture content, higher will be the current levels. Oil conductivity values obtained from the initial values of the polarisation and depolarisation currents using the method described in [14] are presented in Table 3. As expected, B2 is having the highest conductivity among the three samples A, B1 and B2.

TABLE 3 OIL CONDUCTIVITY

Sample	Oil Conductivity (pS/m)
A	0.165
B1	1.17
B2	11.63
C1	3.2
C2	12.38

Similar plots for the samples C1 and C2 are shown in Fig.5 and Fig.6 respectively. Similar conclusions can be drawn for the samples C1 and C2 also and their oil conductivity values are also included in Table 3.

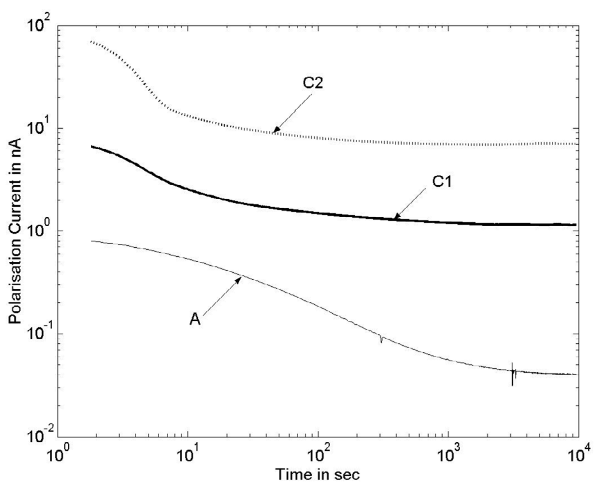

Fig.6.Polarisation currents for different Oil ageing and moistures

As seen from Table 3, B2 has more severe oil ageing and moisture contents among A, B1 and B2. Similarly, C2 has the worst condition of oil ageing and moisture condition as compared to C1 and A. PDC measurements results and their analyses provided sufficient information about the conditions of oil. We have shown previously that PDC measurement also provides information about paper ageing and hence an estimation of paper conductivity. However, the focus of this paper is on the impact of oil condition on the overall diagnostic results.

V. STUDIES OF INSULATION MODEL

The polarisation and relaxation mechanisms in a dielectric material can be modelled by a parallel arrangement of branches each containing a series connection of resistor and capacitor as shown in the circuit of Fig. 8 [15-16]. These dipoles, represented as R_i-C_i, are randomly distributed, and have associated time constants given by $\tau_i=R_iC_i$. Apart from the polarisation current, conduction current flows in the insulation in the presence of an electric field. The conduction current in the insulation is due to the insulation resistance R_0 as shown in Fig. 8. C_0 represents the geometric capacitance of the insulation system.

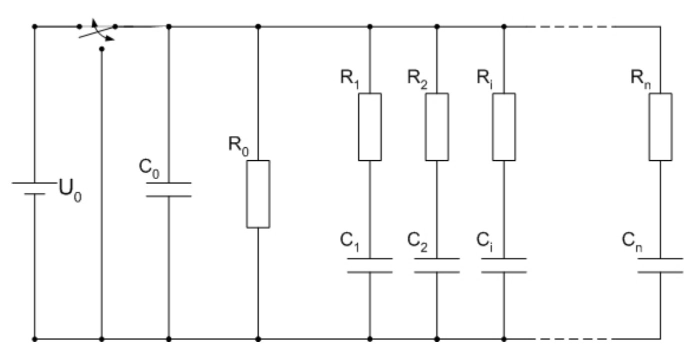

Fig. 8. Equivalent circuit to model a linear dielectric material

The values of the parallel branch resistors and capacitors R_i and C_i, i.e. the polarisation parameters and their associated time constants are related to the condition of the oil and paper insulation [15]. As described in [15], the variation in the values of R_i and C_i for the smaller time constants shifts the initial values of polarisation and depolarisation currents. Since the initial parts of these relaxation currents are related to the oil condition, it can be interpreted that the values of R_i and C_i for the smaller time constant branches are governed by the condition of the oil. A better condition of oil tends to increase the value of R_i-s and decrease the value of C_i-s for the smaller time constant branches and thereby reduce the magnitude of initial portion of polarisation and depolarisation currents. On the other hand, aged and moist oil will increase the initial magnitudes of polarisation and depolarisation currents as a result of decrease in R_i-s and increase in C_i-s for the smaller time constant branches.

Given the oil-paper insulation arrangement, and the polarisation and depolarisation currents, the values of the model parameters (R_i-C_i) can be obtained by a parametric curve fitting routine described in [15]. These values of the model parameters for the lower time constant branches corresponding to the condition of the oil, for the test samples A, B1, B2, C1 and C2 are summarized in Table 4. R_i values are given in G-Ohm and C_i values are given in pF.

TABLE 4. MODEL PARAMETER VALUES FOR DIFFERENT TEST SAMPLES

Branch	Parameter Values									
	A		B1		B2		C1		C2	
	R_i	C_i	R_i	C_i	R_i	C_i	R_i	C_i	R_i	C_i
1	13	135	9.3	370	6.6	770	8.9	350	6.9	690
2	3.3	54	4.2	100	3.7	190	3.9	140	3.4	160
3	2.2	19	1.3	82	2.3	81	1.0	140	2.1	87
4	2.4	4	0.4	89	1.1	63	0.3	81	1.0	26

As can be seen from Table 4, samples B2 and C2, having the most aged and moist oils, have lower values of R_i and higher values of C_i than the other samples. The dry un-aged reference sample A has the highest values of R_i and lowest values of C_i as compared to all other samples. These results confirm the observation that a poor quality of oil decreases the model parameter R_i of first few branches (branches with lower time constants) and increases the values of C_i for the same branches. This finding is simply complementary to what has been shown previously by the estimation of oil conductivity.

VI. CONCLUSIONS

Dielectric diagnostic tests for condition assessment of transformer insulation have been widely used in recent time, as condition based maintenance gets widely accepted in the current deregulated power industries. This paper presents results and analysis from a series of experiments conducted with different transformer oil condition with same paper insulation at two different ageing conditions.

The results show a definite influence of the oil condition on the PDC measurement results. PDC measurement is able to distinguish between the condition of oil and paper separately. This finding also confirms that condition of oil has a significant impact on the dielectric response based diagnostics. Hence, oil condition must be considered to estimate the ageing/moisture condition of composite insulation of transformer.

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VIII. BIOGRAPHIES

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