CONDITION MONITORING OF TRANSFORMER INSULATION BY POLARISATION AND DEPOLARISATION CURRENT MEASUREMENTS

T. K. Saha* Senior Member, P. Purkait Member, Z. T. Yao member IEEE
*Email: saha@itee.uq.edu.au
School of Information Technology and Electrical engineering
University of Queensland, Brisbane, QLD – 4072, Australia

Abstract

The measurement and evaluation of the 'dielectric response' is one possible way of diagnosing a transformers insulation condition. Moisture and ageing strongly influence the dielectric properties of oil/cellulose insulation systems. In our recent research project, dielectric measurement was used for assessing the condition of oil/paper insulation. The **P**olarisation and **D**epolarisation **C**urrent (PDC) analysis is a non-destructive dielectric testing method for determining the conductivity and moisture content of insulation materials in a transformer. On the basis of this analysis one can decide upon further actions. This paper presents a description of the PDC technique with the physical and mathematical background and some results of dielectric response measurements of several transformers. Data analysis and interpretation of the field test results are also presented in this paper.

1. INTRODUCTION

Ageing of the oil/paper insulation system of power transformers is influenced by various stresses -thermal, electromechanical and chemical. Thermal stress leads to a major degradation process of both oil and cellulose paper. Under all these stresses, the paper becomes brittle and the durability against mechanical stress is strongly reduced. The process of breaking cellulose molecule chains produces water in the solid insulation, which acts as a catalyst for further breakdown. Further, the breakdown voltage of the insulating oil and paper is reduced with increasing moisture content of the oil. The conductivity of a material is a property, which can be directly related to the moisture content. Thus the knowledge about the conductivity and hence the moisture contents of the oil and the solid insulation material can be used as an important basis for onsite drying and oil reclamations.

A paper/pressboard insulation system is very hygroscopic and can still contain moisture, even if the oil has been dried. There are indirect methods available to estimate moisture content of paper. However, to date paper ageing and moisture can only be reliably measured by paper samples collected at critical locations (leads, outer winding etc.) and analysing in the laboratory [1]. Therefore solid insulation components are examined by opening the transformer and taking samples from the insulation. Obviously, this is not possible in most cases. Up to now there is no commonly accepted method for a non-destructive evaluation of solid insulation. Therefore, there is a great demand in using dielectric diagnostic methods to relate to insulation properties.

Time domain dielectric measurements based on polarisation/depolarisation current measurement and return voltage measurement have gained significant importance over the last ten years. Particularly, there has been growing interest in the condition assessment of transformer insulation by the Return Voltage Method (RVM). In our previous and current research projects we have extensively used the return voltage method for analysing the condition of aged oil/paper insulation.

In reference [5] Gafvert et al. recommend polarisation current measurement as the preferred method since the properties of oil and paper can be separately assessed from the experimental results. The authors explained that return voltage measurement results are convoluted by two constituents and it is difficult to separate the oil and paper impacts. Gafvert et al. in reference [1] also emphasised that return voltage curves are strongly influenced by the oil conductivity.

Polarisation/depolarisation current measurements are being used more and more for diagnostic insulation testing of motors, generators, cables and recently transformers. Hassig et al [2] mentioned the Polarisation Depolarisation Current (PDC) method as a user friendly method for assessing the integral condition of the oil-cellulose insulation system of a transformer.

Alff et al [3], in their paper described the development of a novel type of equipment based on polarisation/depolarisation current measurements, which is designed for on-site tests of high voltage power apparatus. They presented some examples of on-site measurements on power transformers and demonstrated the interpretation of the results.

Houhanessian et al [4] presented results of polarisation/depolarisation current measurements of pressboard samples at different moisture content and temperature. They also demonstrated how the moisture content of pressboard could be quantified from evaluation of the polarisation/depolarisation current measurements of power transformers.

Gafvert et al [5] reported their findings on time domain polarisation/depolarisation current measurements used to assess the quality of the insulation systems of a number of power transformers.

Leibfried et al [6] demonstrated the application of the PDC technique on new and aged power transformers for assessment of the insulation condition and moisture content in solid insulation.

Frimpong et al [7] reported measurements and modelling of polarisation and depolarisation currents in a composite oil/paper insulation system. They also showed the influence of material properties like conductivity on the dielectric response.

In recent times we have been investigating the PDC measurement technique for separation of moisture and ageing impacts on transformer insulation degradation. PDC tests have been performed on a number of aged transformers in field environment. These findings and their analysis are reported in this paper. PDC can provide information about the conductivity of oil and paper separately. The analysis of conductivity will also be reported in this paper.

2. BASIC THEORY OF DIELECTRIC RESPONSE

The basic theory of dielectric response as it pertains to the analysis described in this paper, has been developed in [8].

Assuming a homogeneous electric field *E(t)* is applied to the dielectric material, the current density through the surface of the material can be written as:

$$J(t) = \sigma E(t) + \frac{dD(t)}{dt} \qquad (1)$$

The current density *J(t)* is the sum of the conduction current and the displacement current, where σ is the DC conductivity and *D(t)* is the electric displacement as given below:

$$D(t) = \varepsilon_0 \varepsilon_r E(t) + \Delta P(t) \qquad (2)$$

ε_0 and ε_r are respectively, the permittivity of vacuum and of the dielectric material. *P(t)* is the dielectric polarisation and is related to the response function *f(t)* of the material by the relationship:

$$\Delta P(t) = \varepsilon_0 \int_0^{\infty} f(t-\tau).E(\tau)d\tau \qquad (3)$$

2.1 Polarisation and Depolarisation Currents

One way, in the time domain, to investigate the slow polarisation process for a dielectric material is to measure polarisation and depolarisation currents. Combining (2) and (3), (1) can be re-written as:

$$J(t) = \sigma E(t) + \varepsilon_0 \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt}\int_0^t f(t-\tau).E(\tau)d\tau \qquad (4)$$

For a homogeneous material, the field strength *E(t)* can be considered as generated by an external voltage *U(t)*, the current through a test object with geometric capacitance C_0 can be written as:

$$i(t) = C_0\left[\frac{\sigma}{\varepsilon_0}U(t) + \varepsilon \frac{dU(t)}{dt} + \frac{d}{dt}\int_0^t f(t-\tau).U(\tau)d\tau\right] \qquad (5)$$

The test object can be a single dielectric material or an arrangement of several dielectric materials in series or in parallel. In such a case σ, ε_r and *f(t)* represent, respectively, a composite conductivity, relative permittivity and dielectric response function of this heterogeneous test object. Assuming that the test object is totally discharged and that a step voltage is applied with the following characteristics:

$$U(t) = \begin{cases} 0 & t < 0 \\ U_0 & 0 \le t \le t_c \\ 0 & t > t_c \end{cases} \qquad (6)$$

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:

$$i_p(t) = C_0 U_0 \left[\frac{\sigma}{\varepsilon_0} + f(t) \right] \tag{7}$$

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

$$i_d(t) = -C_0 U_0 \left[f(t) - f(t + t_c) \right] \tag{8}$$

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

2.2 Dielectric Response Function Estimation

It has been shown [8-10] that, for oil/cellulose insulation systems the "general response function" can be expressed as:

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m} \tag{9}$$

with A, $t_0 > 0$, $m > n > 0$ and $m > 1$

In order to estimate the dielectric response function *f(t)* from a depolarisation current measurement it is assumed that the dielectric response function is a continuously decreasing function in time, then if the polarisation period is sufficiently long, so that $f(t + t_c) \cong 0$, the dielectric response function *f(t)* is proportional to the depolarisation current. Thus from (8)

$$f(t) \approx \frac{-i_d(t)}{C_0 U_0} \tag{10}$$

The parameters of *f(t)* are obtained from a non-linear least square fit into (10).

2.3 Estimation of the Conductivity

From the measurements of polarisation and depolarisation currents, it is possible to estimate the DC conductivity σ, of the test object. If the test object is charged for a sufficiently long time so that $f(t + t_c) \cong 0$, (7) and (8) can be combined to express the DC conductivity as:

$$\sigma \approx \frac{\varepsilon_0}{C_0 U_0} \left(i_p(t) - i_d(t) \right) \tag{11}$$

3. PDC Measurement

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 (~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 polarisation/depolarisation of previously activated polarisation process now gives rise to the discharging current in the opposite direction, where no contribution of the conductivity is present. Figure 1 shows schematically, the nature of these currents due to a step charging voltage.

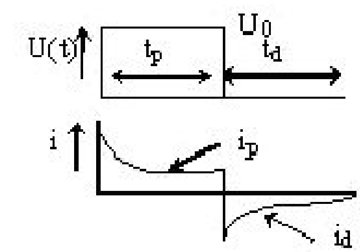

Figure 1. Waveform of Polarisation/Depolarisation Currents

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 [11].

At present there are a couple of commercially available PDC analysers available in the market. PDC-Analyser-3205 [6] is the commercial version of the instrument described in [3]. The authors in [3] described the operation and application of a compact, portable instrument for measuring polarisation and depolarisation currents. It comprises a charging voltage source, a current measuring circuit and a computer for timing and recording the measurements as well as displaying graphically the measured values.

The Automatic Recovery Voltage Meter RVM-5462 from TETTEX instruments, incorporates a sensitive electrometer with inbuilt high voltage DC source for measuring charging and discharging current measurements..

The Interfacial Polarisation Spectra (IPS) measurement equipment [12-14] developed at the School of Information Technology and Electrical Engineering, University of Queensland, has the capability of measuring the Polarisation/Depolarisation currents. The system is equipped with a computer, a GPIB Card, a high resistance Electrometer with a built in DC charging voltage source (software controllable up to 1000 volts), a 16-channel with PCAC2 switch module power control interface (Control 488/16) and two high voltage relays.

The required software has been developed in the LabView environment to control this hardware system. The user friendly interface of the developed software enables the operator to choose the voltage and time for charging and discharging. Once the operator sets the system into operation the measurement system becomes fully automated. The measurement data can be stored in the computer for future analysis.

4. ONSITE PDC MEASUREMENTS

PDC measurement results and analyses are presented in the following sections for a number of transformers as summarised in Table 1. For the purpose of better understanding, they have been categorised into two groups A and B. The first group (A) consists of two aged transformers and the second group (B) consists of a single transformer, on which PDC measurements have been carried out before and after oil reclamation. Polarisation currents for the transformers are plotted in Figures 2 and 3. Depolarisation currents for the transformers are plotted in Figures 4 and 5.

5. ANALYSIS OF PDC MEASUREMENTS

The initial predominant exponential shape of the polarisation/depolarisation currents of a transformer are due to the exponential time dependence of the polarisation and depolarisation currents generated by the series arrangements of the oil ducts and the paper/pressboard insulation barriers. The initial time dependence of polarisation/depolarisation currents is very sensitive to the conductivity of the oil. The moisture content and conductivity of the pressboard influences mainly the shape of the currents at long time range (i.e. DC stationary current).

The predominant influence of oil conductivity on the initial amplitudes of polarisation/depolarisation currents can be used to estimate the oil conductivity of a transformer even without performing direct conductivity measurements on its oil sample. In the same way, an estimation of the conductivity of the paper can be obtained from the long term values of the polarisation and depolarisation currents.

Table 1. Transformer Details

Transformer.	**MVA**	**Volt (kV)**	**Type**	**Year of Manuf.**	**Service Record**
A1	7	66/11	Y/Δ	1968	Lightly loaded
A2	30	132/66/1	Y/Y/Δ	1966	Suspected
B1	100	330/132/16	Y/Y/Δ	1966	Before Oil Change
B2	100	330/132/16	Y/Y/Δ	1966	After Oil Change

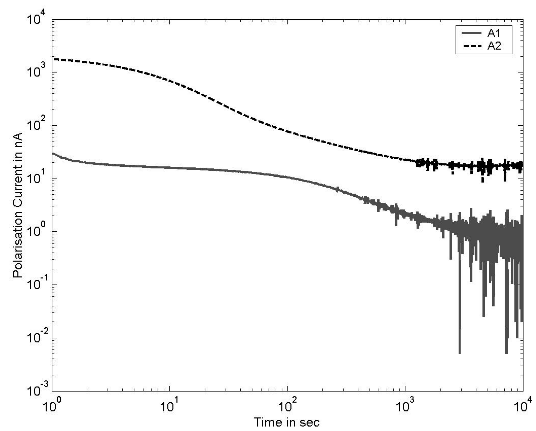

Figure 2. Polarisation Current for A1 and A2

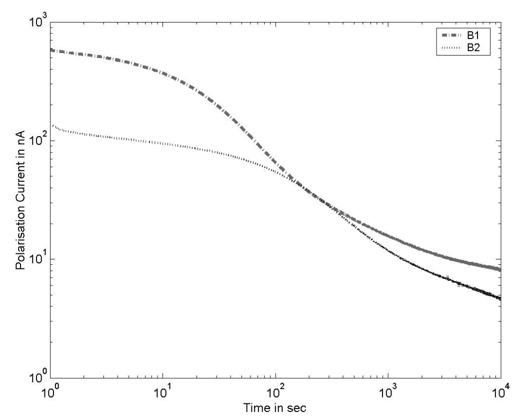

Figure 3. . Polarisation Current for B1 and B2

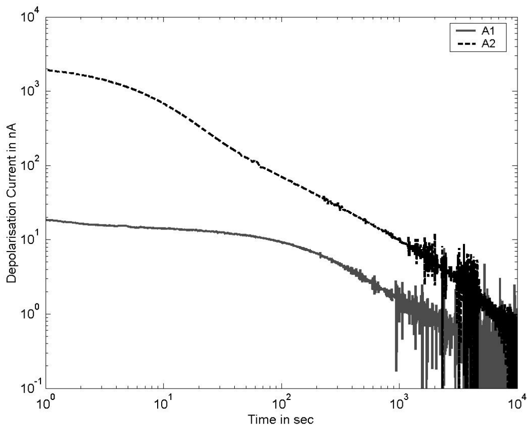

Figure 4. . Depolarisation Current for A1 and A2

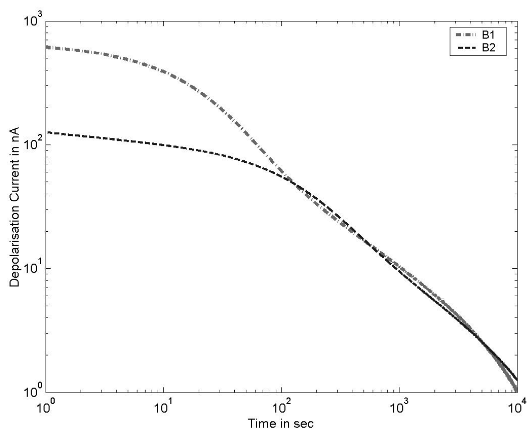

Figure 5. . Depolarisation Current for B1 and B2

It is evident from Figures 2 and 4 that both polarisation and depolarisation currents for A2 are higher than those of A1. Transformers with poor insulation condition normally have higher values of polarisation/depolarisation currents. Transformer A2 was suspected of having advanced insulation ageing due to the fact that one of the companion transformers of this group failed in service. A1 was relatively lightly loaded during its service life – it is expected that the ageing condition of the insulation in A1 was better than A2. This is evident from the polarisation/depolarisation current plots. A flatter initial part of both polarisation and depolarisation currents for A1, as compared to A2 indicate that the moisture content in oil for A1 is lower than that in A2. Conductivity values for both oil and paper have been calculated from the measured polarisation/depolarisation currents and are presented in Table 2.

Corresponding depolarisation currents have been used to model the "response function" of each transformer. A software package has been developed to fit the depolarisation current in parametric form to obtain the *f(t)*. Based on *f(t)* and other geometric information (e.g. capacitance between insulation) the software is used to calculate conductivities of oil and paper.

The conductivity values of both oil and paper are lower for A1 than those of A2 – indicating a more degraded condition of insulation in A2.

Figure 3 and Figure 5 represent the polarisation and depolarisation current plots for another transformer before and after oil reclamation. Both the polarisation and depolarisation currents have a higher value during the initial period for B1 than B2. The initial part of the polarisation/depolarisation currents for B1 also has an earlier inflection. These indicate that after oil reclamation, the moisture content in the oil is reduced – which is also confirmed by the DGA results of B1 and B2 presented in Table 3. However, the final parts of the polarisation/depolarisation currents do not have much difference – which is indicative of the fact that the paper ageing condition has not been improved by a great amount after the oil reclamation.

Table 2. Oil and Paper Conductivities

Transformer	Oil Conductivity (S/m)	Paper Conductivity (S/m)
A1	2.36×10^{-13}	0.9×10^{-14}
A2	15.4×10^{-13}	22.6×10^{-14}
B1	10.1×10^{-13}	17.6×10^{-14}
B2	6.25×10^{-13}	8.53×10^{-14}

Table 3. DGA and Furan Analysis Results

Transformer	Moisture in Oil (ppm)	Moisture in Paper (%)	2-furfuraldehyde μg/g
A1	-	-	0.02
A2	-	-	1.03
B1	28	5.4	1.9
B2	10	1.4	0.26

As expected, the furan contents of A1 (lightly loaded) and B2 (after oil change) are much lower than those of A2 (suspect aged transformer) and B1 (before oil change). It can be noted that refurbishment of oil has reduced the moisture content of both the oil and the paper. Furan content has been reduced significantly by the oil reclamation process. This also suggests that oil reclamation improves the insulation condition. However, it would be interesting to monitor how quickly the ageing products of paper reappear in the oil sample.

6. CONCLUSIONS

A number of transformers have recently been tested for polarisation/depolarisation current measurements. Our findings suggest that polarisation/depolarisation current measurement can accurately estimate the moisture and general ageing status of insulation. The PDC measurement is capable of estimating the oil/paper condition by conductivity calculations. Oil reclamation reduced moisture content of insulation and a significant reduction of furan content. Transformers ageing by-products are mostly polar in nature and are always bound to the paper surface. So it is expected that ageing products of paper would be back in the oil in a future time depending on other operating conditions inside the transformer. Hence the evidence of reduction of ageing by-products is not guaranteed by a single test. Further tests in the future could be useful for a better estimation of ageing.

8. REFERENCES

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