

The Sixth International Power Engineering Conference
(IPEC2003), 27-29 November 2003, Singapore

INVESTIGATING SOME IMPORTANT PARAMETERS OF THE PDC MEASUREMENT TECHNIQUE FOR THE INSULATION CONDITION ASSESSMENT OF POWER TRANSFORMER

T. K. Saha and **P. Purkait**

University of Queensland
Australia

Abstract

The need for economic, reliable and effective delivery of electric power has led to the search for new, efficient and effective methods for diagnosing the insulation of the HV equipments in the industries all over the world. One of the methods currently being investigated as a potential non-destructive diagnostic tool for condition monitoring of the oil-paper insulation of power transformers is the Polarisation and Depolarisation Current (PDC) measurement. This paper starts with a theoretical and physical description of the PDC technique. Several practical aspects of the technique have been discussed in the paper along with corresponding experimental and field test results.

Keywords

Condition Monitoring, Depolarisation Current, Insulation Assessment, Polarisation Current, Transformer Insulation.

1 INTRODUCTION

In recent years there has been growing interest in the condition monitoring of transformer insulation. Primarily this is due to the increasing aged population of transformers in utilities around the world. A large proportion of existing transformers are approaching the end of their design life and insulation degradation continues to be a major concern for these transformers.

Moisture and ageing strongly influence the dielectric properties of oil/paper insulation system of power transformer. To assess the reliability of insulation it is necessary to know the moisture content of the oil and the paper. Oil specimen tests generally can not provide any conclusive information since oil/paper moisture equilibrium is temperature dependent and takes a long time to stabilise. Paper specimen tests (e.g. by Karl-Fischer Titration) are not suitable for non-destructive and quick-check measurements of in-service equipments.

In recent years additional methods to assess insulation systems have been promoted in addition to the classical

insulation resistance and power frequency loss factor measurements. Dielectric diagnostic measurements based on polarisation and depolarisation current measurements and return voltage measurements have gained significant importance over the last several years [1].

The Polarisation and Depolarisation Current (PDC) analysis is a non-destructive dielectric testing method for determining the conductivity and moisture content of insulation materials in a transformer [2-4]. PDC can provide information about the characteristic Response Function of the dielectric and the conductivities of oil and paper. On the basis of this analysis it is possible to take further actions like oil-refurbishment or drying or replacement of the transformer. This paper presents a description of the PDC technique with the physical and mathematical explanations. The different physical parameters and practical considerations of the technique are discussed along with supporting experimental and field test results on transformers. These parameters have been identified by the authors from their experience with the actual on-site measurements over the years.

2 PDC MEASUREMENT

2.1 Theoretical Background

Consider that a totally discharged dielectric test object is subjected to a step voltage with the following characteristics:

$$U(t) = \begin{cases} 0 & t < 0 \\ U_0 & 0 \leq t \leq t_p \\ 0 & t > t_p \end{cases} \quad (1)$$

This will give zero current for times before $t = 0$, and so called polarisation currents for times $0 \leq t \leq t_p$. 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:

$$i_p(t) = C_0 U_0 \left[\frac{\sigma}{\epsilon_0} + f(t) \right] \quad (2)$$

where σ is the DC conductivity, ϵ_0 is the permittivity of vacuum, $f(t)$ is the response function and C_0 is the geometric capacitance (measured capacitance divided by relative permittivity of the dielectric material) of the dielectric material.

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

$$i_d(t) = -C_0 U_0 [f(t) - f(t + t_p)] \quad (3)$$

2.2 Dielectric Response Function Estimation

It has been shown [5-6] that, for oil/cellulose insulation systems the “general response function” can be expressed in parametric form as:

$$f(t) = \frac{A}{\left(\frac{t}{t_0}\right)^n + \left(\frac{t}{t_0}\right)^m} \quad (4)$$

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 $f(t + t_p) \cong 0$, the dielectric response function $f(t)$ is proportional to the depolarisation current. Thus from (3)

$$f(t) \approx \frac{-i_d(t)}{C_0 U_0} \quad (5)$$

The parameters of $f(t)$ are obtained from a non-linear least square fit into (5).

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 $f(t + t_p) \cong 0$, (2) and (3) can be combined to express the DC conductivity of the composite dielectric as:

$$\sigma \approx \frac{\epsilon_0}{C_0 U_0} (i_p(t) - i_d(t)) \quad (6)$$

Conductivity for a given insulation system thus, is found to be dependent upon the difference between the polarisation and depolarisation current values. This composite conductivity, in practice, is the convolution of the conductivities of the oil and the paper that make up the insulation structure. The conductivity will depend on the relative amount of oil and paper and the geometry of their arrangements inside the transformer.

2.4 Measurement Technique

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 polarisation current is measured. Then the voltage source is removed and the object is short circuited. The previously activated polarisation process now gives rise to the depolarisation current in the opposite direction. The schematic diagram of the PDC measuring set-up is shown in Figure 1. Figure 2 shows the typical nature of these currents due to a step charging voltage U_0 .

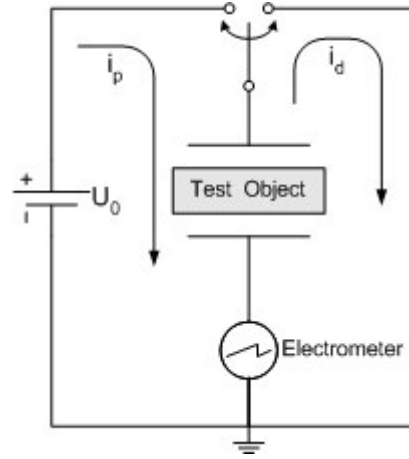


Figure 1. Basic PDC measuring circuit

The Interfacial Polarisation Spectra (IPS) measurement equipment [7] 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, a 16-channel with PCAC2 switch module power control interface (Control 488/16) and two high voltage relays. 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.

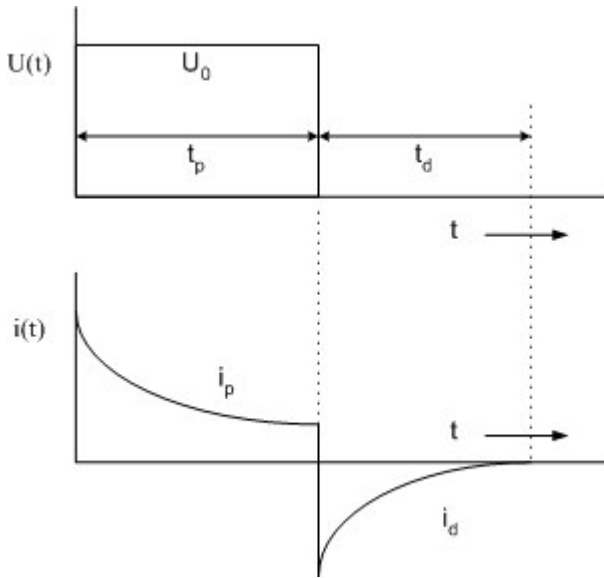


Figure 2. Waveform of polarisation and depolarisation currents

The following sections will point out some practical considerations for the PDC measurement. The different physical parameters involved during the measurement procedure are discussed with relevant experimental and field test results on actual transformers.

3 PHYSICAL PARAMETERS

The authors of this paper have been investigating the PDC technique for transformer insulation condition assessment for the last few years. In course of the different on-site measurements and laboratory experiments, the influence of different physical parameters on the PDC measurement has been studied. These include the amplitude of the excitation voltage, charging and discharging periods and environmental influences like the temperature variation and the effect of noise and interference.

3.1 Excitation Voltage Amplitude

During the PDC tests, it is often very convenient to make the assumption of linearity of the dielectric in order to simplify the analysis of the results of measurements. However, it remains an experimental fact that very few systems are truly linear in the presence of high electric field. At higher charging voltage (high field) charge movements may take place on a significant scale [5].

Figure 3 shows the influence of an increase of charging voltage level from 500V to 1000V on a 100kVA transformer. To simplify the comparison, currents obtained with 500V charging voltage are multiplied by 2. The results show that the actual amplitude of depolarisation current for 1000V is lower. This non-linearity is caused by too high excitation voltage. This will in turn give rise to error in the computation of the

dielectric response function from (5) and the conductivities from (6). The polarisation currents, however, are close to each other. Similar findings were reported by Houhanessian et al in [8].

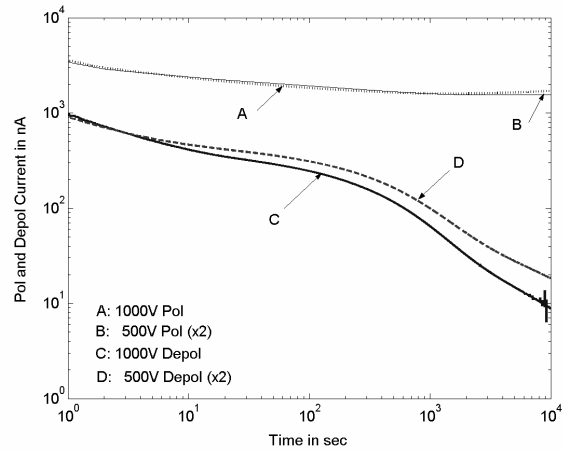


Figure 3. Relaxation currents at different excitation voltages (scaled to the same level for comparison)

According to Jonscher [5], if the amplitude of the field is raised sufficiently, a complete crossing over of the polarisation and depolarisation currents at short times may be observed. The phenomena of crossing over is due to the injection of space charge into the dielectric during the charging process, leading to gradual accumulation of excess charge near one or both electrodes, according to the nature of the interface. When the field is removed abruptly at the commencement of the discharge process, the initial depolarisation current consists of the true depolarisation current along with the current due to the withdrawal of the previously injected charges superimposed on it. Figure 4 depicts such case corresponding to a 30MVA transformer where the crossing over of the depolarisation and polarisation currents at small time is observed.

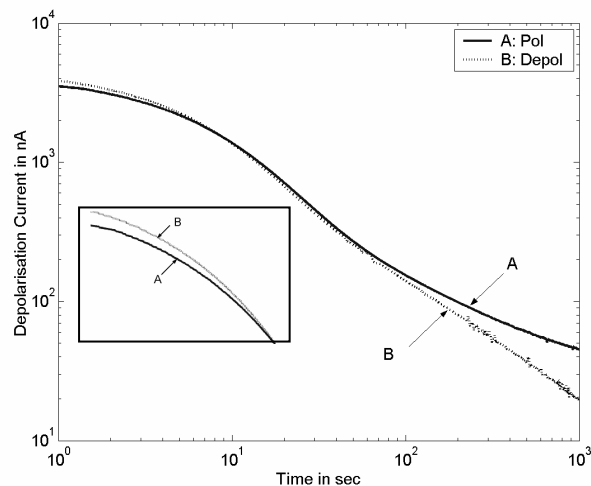


Figure 4. Crossing over of Depolarisation and Polarisation current; Inset shows the initial period in an enlarged scale

Therefore, it is important to stay within a linear dielectric domain by performing the relaxation current measurements with low charging voltages.

3.2 Charging and Discharging Periods

In order to study the discharge characteristics of a material with a view to accurately determine its dielectric response, it is necessary to charge the material prior to the beginning of the discharge process for at least ten times longer than the maximum desired time of the discharge measurement [5-6]. The depolarisation current at times that are short compared to the preceding charging time follow the genuine characteristics expected of the material in question, but at times long compared with the charging time, the slope of the logarithmic plot of the depolarisation current becomes much steeper than the genuine characteristics. Figure 5 is a plot for the two dielectric response functions $f(t)$ calculated for a 70MVA transformer – at charging to discharging time ratios of 10:1 and 1:1 respectively.

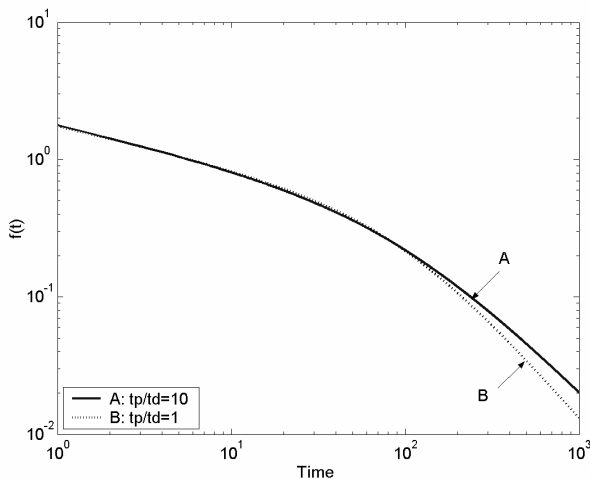


Figure 5. Dielectric response function $f(t)$ at different ratios of charging and discharging times t_p and t_d .

Apart from the serious errors that may arise if this condition is not fulfilled, these requirements mean that the time taken for an experiment is much longer than the actual measuring time itself.

The same conditions apply to the opposite process of polarisation current measurement: the material must be thoroughly discharged for at least ten times as long as it is intended to measure the polarisation current for [5]. If the material is not fully discharged before starting a new cycle of measurement, the charges remaining from the previous measurement may introduce errors into the current measurement. This effect is more severe in new transformers where the magnitudes of the relaxation currents are quite low themselves. This is often referred to as the ‘memory effect’. Figure 6 shows such a condition when the transformer is charged again without discharging for sufficiently long time. The apparently higher magnitude of the polarisation and depolarisation

current is due to the ‘memory effect’ i.e. due to the influence of previous measurements. As observed in Figure 6, the difference in the magnitudes of the two depolarisation currents is, however, more prominent than the corresponding differences in the polarisation currents. This may result in erroneous calculation of response function and conductivities.

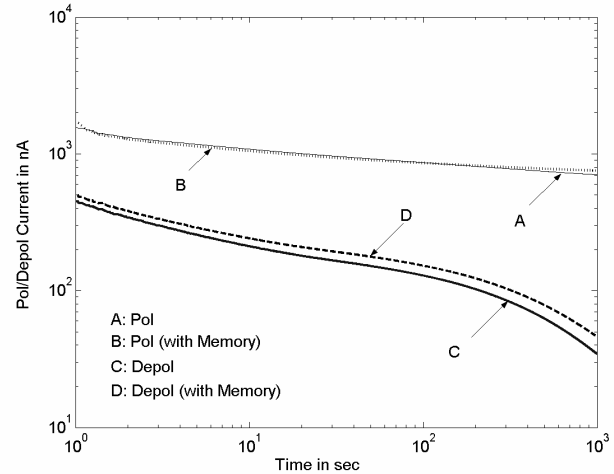


Figure 6. Polarisation and depolarisation currents with and without adequate pre-discharging

It is thus evident that in order to obtain correct estimation of the dielectric response or the conductivities from the polarisation and depolarisation currents, it is essential to short the transformer to ground for sufficiently long time before conducting the test. It is also recommended that the charging time be at least ten times longer than the intended discharging time in one cycle of measurement.

3.3 Noise and Interference

Due to the inherently high values of the insulation resistance of the oil and the paper, the polarisation and depolarisation currents in normal transformers are very small – in the range of nA. The measurements of these small currents can be affected by induced ac currents, electromagnetic interferences and electrostatic induction from the nearby high voltage installations. In actual field test conditions, these interfering objects are unavoidable. These effects are also aggravated by wind and humidity in open substations. Long test leads connecting the bushings to the testing instrument also add up to the problem of interference. It has also been observed during on-site measurements that too much people movement close to the measurement set-up may introduce noise in the measurement. It is also recommended that the transformer under test should in no way be touched from outside while the testing is going on, otherwise, spurious signals may get injected into the measurement. Figure 7 displays the polarisation and depolarisation currents of a 7MVA transformer tested in the field with extremely windy condition and with close proximity to live overhead bus-bars and other live transformers.

Apart from the obvious and practicable precautions to reduce the interference in the field, the situation can be improved by the use of filters. These filters can be either analogue filters integrated with the measurement system or may be software implemented digital filters. Analogue filtering, however, should be kept to a minimum as the capacitors needed for the filters would exhibit dielectric relaxation phenomena much like the insulation to be diagnosed – thereby introducing unwanted error. Digital filtering consists of notch filtering at mains supply frequency and low pass filtering. Digital filtering has the advantage for this application is that filter quality is independent of the signal amplitude and the filter properties can be easily adjusted by the software.

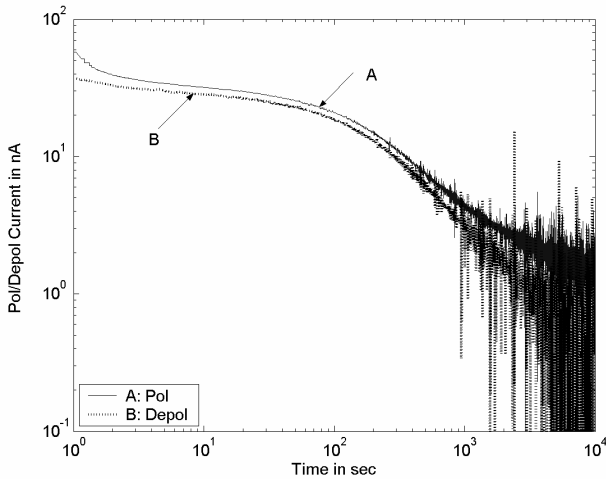


Figure 7. Polarisation and Depolarisation currents in the presence of noise

In the PDC measuring equipment developed by the authors, software based digital filters have been implemented to reduce the noise from the measured relaxation current signals. Figure 8 shows the polarisation and depolarisation currents of the same transformer as in Figure 7, but after the signals are processed by a digital filter.

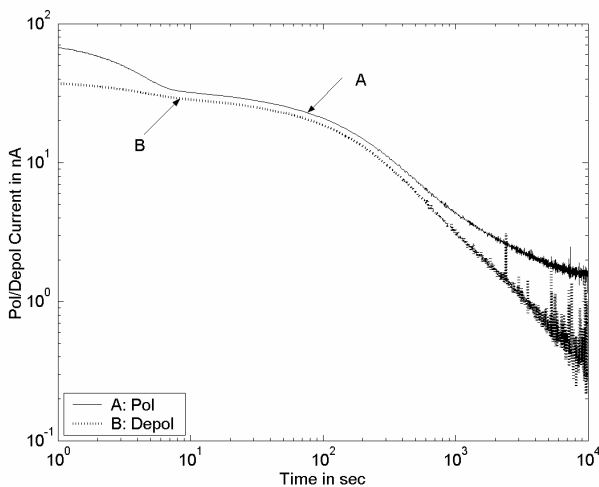


Figure 8. Polarisation and Depolarisation currents after filtering out noise

It is thus evident that the effect of noise can be greatly reduced by the use of suitable filters. Otherwise too much noise added up to the relaxation current data may lead to faulty computation of the response function and the conductivities. Also interpretation of the polarisation and depolarisation current plots become confusing if there is too much noise.

3.4 Temperature Instability

It is often experienced in actual field testing that the transformer to be tested was previously connected to the grid and was in operating condition. During normal operating condition, the temperature inside a transformer may reach a value much higher than the ambient, depending upon the loading condition. For the testing purpose, if a transformer is taken out of service, it must be given adequate time for the temperature to settle down to ambient condition before commencing the actual PDC testing.

During thermal transition complex dynamic processes occur as temperature gradients develop. Temperature transitions disturb the moisture equilibrium of the system, causing the initiation of moisture mass transfer processes. Transformer oil and paper/pressboard are very dissimilar materials, in that the former is hydrophobic and the latter is hydrophilic. As a consequence, almost all of the moisture present in the system resides in the pressboard. As the temperature changes, moisture will move into or out of the paper/pressboard via diffusion. [9]. It is thus evident that unless the temperature is stable and the oil-paper have attained equilibrium, any dielectric test done in-between will not reflect the true condition of the insulation.

Figure 9 is a plot for the PDC test on a transformer where test have been done while the transformer was under the process of cooling down. Before the start of the test, the transformer was running at a temperature of 60°C. The transformer was then switched off from the source and allowed to cool down to the ambient temperature of 23°C. The PDC measurement was done during this cooling-down process. The plot of Figure 9 also contains the polarisation and depolarisation currents at normal ambient condition of 23°C, for comparison.

It was pointed out in [10], that if a thermal step is applied to one or other of the sides of the sample, there is a thermal wave diffusion into the material. The expansion which appears, generates a slight displacement of the charges placed in the bulk of the material. This causes the appearance of a current in the external circuit. This current may interfere with the polarisation and depolarisation currents under measurement giving rise to unwanted errors. This observation is well supported by the plots of Figure 9. The polarisation and depolarisation currents corresponding to the case when the transformer temperature was under transition are higher than their ambient temperature counterparts. This may result in

erroneous calculation of the response function and the conductivities.

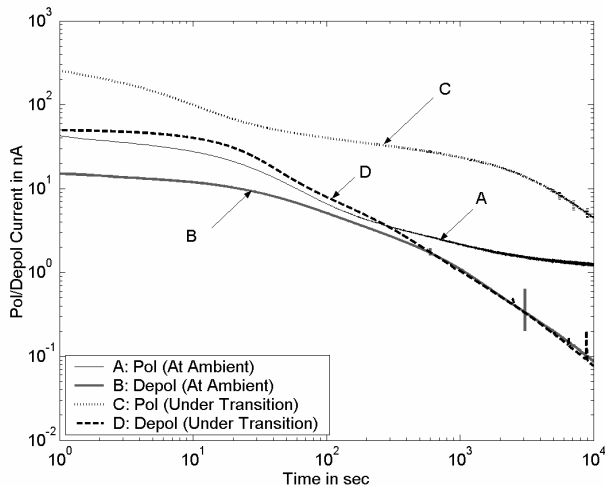


Figure 9. Polarisation and depolarisation current plots for transformer under temperature transition

Thus it is essential to allow sufficient time for the transformer temperature to settle down to ambient before commencing the actual PDC test.

4 CONCLUSIONS

PDC test is fast emerging as an effective non-destructive dielectric diagnostic testing method for high voltage transformer insulation. It has the potential of determining the ageing and moisture conditions of oil and paper insulations inside the transformer. The theoretical and practical backgrounds of the PDC technique have been introduced in this paper. It was intended to present in this paper, some important practical and physical aspects of the PDC technique when referred to actual on-site testing. The following points need to be kept in mind while conducting PDC test on outdoor transformers in substations:

- Excitation voltage amplitude
- Charging/discharging periods
- Shorting period before starting the test
- Noise and interference
- Temperature stability

It is essential that these points be addressed properly while analysing the PDC results for correct assessment of the insulation condition. One or more of these physical parameters may affect the results and pollute the sensitive relaxation currents.

5 REFERENCES

[1] M. Darveniza, T.K.Saha D. J.T. Hill and T.T.Le. Investigations into Effective Methods for Assessing the Condition of Insulation in Aged Power transformers. *IEEE Transactions on Power Delivery*, vol 13, no.4, pp.1214-1223, 1998.

[2] G. Frimpong, U. Gafvert and J. Fuhr .Measurement and Modelling of Dielectric Response of Composite Oil/Paper Insulation . *Proc. 5th International Conference on Properties and Applications of Dielectric Materials*, Korea, pp. 86-89, 1997.

[3] J.J. Alff, Van Der. Houhanessian, W.S. Zaengl and A.J. Kachler .A Novel, Compact Instrument for the Measurement and Evaluation of Polarisation/Depolarisation Currents Conceived for On-Site Diagnosis of Electric Power Apparatus. *Conference Record of the 2000 IEEE International Symposium on Electrical Insulation* , USA, pp.161-167, 2000.

[4] T. Leibfried and A.J. Kachler .Insulation Diagnostics on Power Transformers Using the Polarisation and Depolarisation Current (PDC) Analysis. *Conference Record of the 2002 IEEE International Symposium on Electrical Insulation*, USA, pp.170-173, 2002.

[5] A. K. Jonscher .Dielectric Relaxation in Solids. Chelsea Dielectric Press, 1983.

[6] U. Gafvert and E. Ildstad .Modelling Return Voltage Measurement of Multi-Layer Insulation Systems. *Proc. 4th International Conference on Properties and Applications of Dielectric Materials*, AUS, Paper 4234, pp. 123-126, 1994.

[7] T. K. Saha, M. Darveniza, D. J. T. Hill and T. T. Le. Electrical and Chemical Diagnostics of Transformers Insulation. Part-A. Aged Transformer Samples. *IEEE Transactions on Power Delivery*, vol. 12, pp. 1547-1554, 1997.

[8] V. D. Houhanessian and W. S. Zaengl .Application of Relaxation Current Measurements to On-Site Diagnosis of Power Transformers. *IEEE Annual Report – Conference on Electrical Insulation and Dielectric Phenomena*, Minneapolis, pp. 45-51, 1997.

[9] Y. Sheiretov and M. Zahn .Dielectrometry Measurements of Moisture Dynamics in Oil-Impregnated Pressboard. *IEEE Trans. Dielectrics and Electrical Insulation*, vol. 2, no. 3, pp. 329-351, 1995.

[10] S. Agnel and A. Toureille .Study of the Ageing of Impregnated Paper of High Power Capacitors Using the Thermal Step Method and the Thermally Stimulated Currents. *IEEE Annual Report – Conference on Electrical Insulation and Dielectric Phenomena*, pp. 190-193, 1996.