Some Precautions for the Field Users of PDC Measurement for Transformer Insulation Condition Assessment

T. K. Saha, *Senior Member, IEEE*, and P. Purkait, *Member, IEEE*

***Abstract*-- The need for economic, reliable and effective delivery of electric power has lead 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. These physical considerations can be used as 'precautions' for the potential field users of the PDC technique for insulation condition assessment of transformers.**

***Index Terms*—Condition Monitoring, Depolarisation Current, Insulation Assessment, Noise, PDC Measurement, Polarisation Current, Temperature, Transformer Insulation.**

I. Introduction

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 condition of the oil and the paper separately.

In recent years, new 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 [2-5]. PDC can provide information about the *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. It is recommended that the field-users of the PDC technique should carefully address these issues while conducting the test and also during analysis of the results.

II. PDC Measurement

A. Theoretical Background

When a step voltage of magnitude U_0 is applied to an initially discharged dielectric, the polarisation current flowing through it is given by (1). The process is summarised in Fig.1.

$$i_p(t) = C_0 U_0 \left[\frac{\sigma}{\varepsilon_0} + f(t) \right] \quad (1)$$

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.

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

$$i_d(t) = -C_0 U_0 \left[f(t) - f(t + t_p) \right] \quad (2)$$

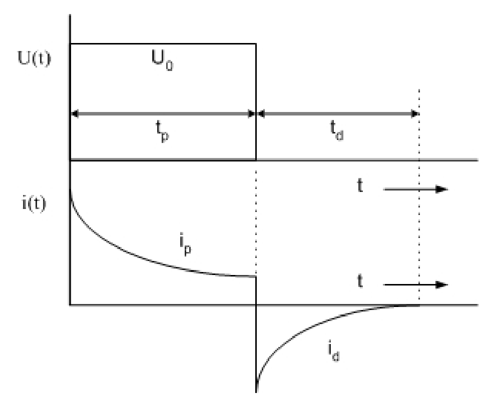

Fig. 1. Waveform of polarisation and depolarisation currents

T. K. Saha (e-mail: saha@itee.uq.edu.au) and P. Purkait (e-mail: praj@ieee.org) are with the School of Information Technology and Electrical Engineering, University of Queensland, Qld – 4072, Australia.

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B. Dielectric Response Function

It has been shown [6-8] that, for oil/cellulose insulation systems the 'dielectric response function' can be expressed in parametric form as:

$$f(t)=\frac{A}{\left(\frac{t}{t_0}\right)^n+\left(\frac{t}{t_0}\right)^m} \qquad (3)$$

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 (2), the dielectric response function *f(t)* can be approximated as:

$$f(t)\approx\frac{-i_d(t)}{C_0U_0} \qquad (4)$$

C. 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 $f(t + t_p) \cong 0$, (1) and (2) can be combined to express the DC conductivity of the composite dielectric as:

$$\sigma\approx\frac{\varepsilon_0}{C_0U_0}\left(i_p(t)-i_d(t)\right) \qquad (5)$$

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.

III. Practical Aspects and Physical Parameters

In course of different on-site measurements and laboratory experiments, the influence of different physical parameters on the PDC measurement has been studied. These include the measuring circuit requirements, amplitude of the excitation voltage, charging and discharging periods and environmental influences like the temperature variation and the effects of noise and interference.

A. Measuring Circuit

The basic circuit arrangement for the measurement of PDC of insulation consists of a high voltage source for charging the insulation and a sensitive current measuring device. It is recommended [3] to use the 'two active electrodes' technique for the measurement. According to this technique, the insulation to be analysed is connected between two electrodes. One of the electrodes is marked as the 'excitation electrode' and the test voltage is applied to it referenced to ground while the current is measured along a line connected between the second 'sensing electrode' and ground. With such a 'two active electrode' arrangement, effects of stray capacitances of the insulation to ground and also cable capacitances can be reduced to a minimum.

Transformers have a variety of possible connections including single-phase, three-phase, three-phase star, three-phase delta, with or without tertiary winding, with or without tap winding and even three-phase and single-phase autotransformers. The basic idea is to assess the condition of the bulk insulation consisting of paper and oil between the windings. Thus, for all different transformer configurations, the insulation to be diagnosed need to be connected as the dielectric between the two electrodes of the measuring unit. Fig.2 demonstrates the recommended connections at the transformer terminals for different types of transformers.

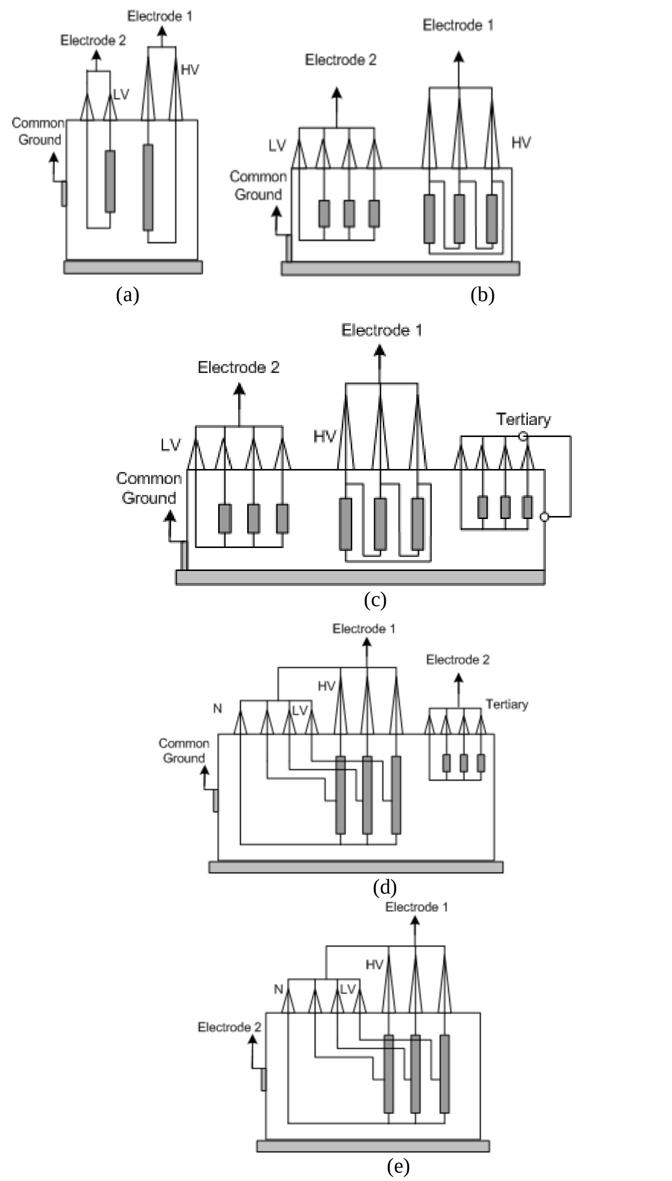

Fig. 2. Different transformer terminal connections for PDC test (a) single-phase two-winding transformer; (b) three-phase transformer with star connected low voltage (LV) winding with neutral and delta connected high voltage (HV) winding; (c) three-phase transformer with star-connected tertiary winding; (d)

three-phase auto-transformer with tertiary winding; (e) three-phase auto-transformer without tertiary winding.

There may be some more arrangements of transformer windings possible, which are nothing but different combinations of those shown in Fig.2.

The high voltage source to be used for exciting the insulation should be free of drift and disturbances. The voltage source must also be stable during its transient switching to the capacitive load of the insulation. The in-built high voltage source in the Keithley Electrometer model 6517A [10] is used for measurements and this satisfies these requirements to a great extent. The most sensitive and expensive part of the PDC measuring equipment is the current measuring device. Normally the polarisation and depolarisation currents are very small (often several nano-amperes) and the values for different test objects can range over several decades. The Keithley Electrometer Model 6517A has a very sensitive and accurate current measuring circuit that can be programmed to read such small currents varying over a wide range.

B. Temperature Instability

Transformer oil and paper/pressboard are very dissimilar materials, in that the former is hydrophobic and the latter is hydrophilic. As the temperature changes, there will be migration of moisture between oil and paper/pressboard via diffusion. [11]. It is thus evident that unless the temperature is stable and the oil-paper has attained equilibrium, any dielectric test done in-between will not reflect the true condition of the insulation.

It has been reported by [2-8] and several other researchers that the relaxation currents are very sensitive to the temperature. This phenomenon has been attributed to the increased mobility of the charge carriers during the polarisation/depolarisation process at elevated temperatures. This dependence of the relaxation currents on temperature may seriously affect the PDC measurement results during field-testing in more than one ways.

It is often experienced in actual filed 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 much higher than the ambient, depending upon the loading condition. For the PDC measurement 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.

Fig.3 is a plot for the PDC test on a transformer where PDC measurement has 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 60^0C. The transformer was then switched off from the supply and allowed to cool down to the ambient temperature of 23^0C. The PDC measurement was done during this cooling-down process. The plot of Fig.3 contains the polarisation and depolarisation currents at normal ambient condition of 23^0C, for comparison.

It was pointed out in [12] that if a thermal step is applied to one or other of the sides of the sample, due to displacement of the charges a current appear in the external circuit. This current interferes with the polarisation and depolarisation currents under measurement giving rise to unwanted errors. As seen in Fig.3, 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.

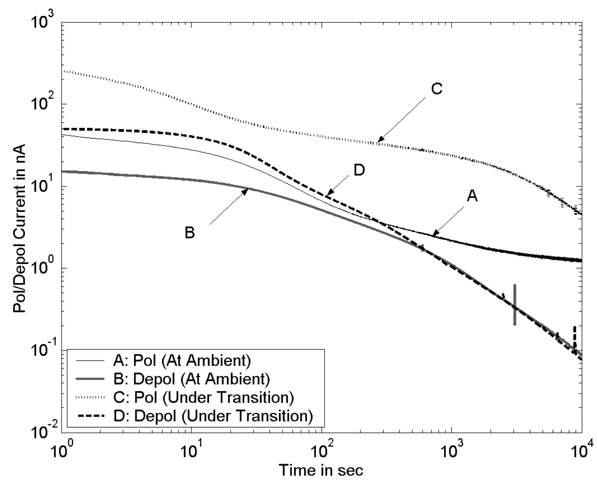

Fig.3. Polarisation and depolarisation current plots for transformer under downward transition of temperature

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

An opposite kind of temperature transition effect on the PDC measurement can be observed while field-testing in open substations where the ambient temperature itself varies widely during the day. The ambient temperature may start with 18-20^0C in the morning and may increase to 30-35^0C in the mid-day. In effect, the temperature inside the transformer tank will also go up. This may have a noticeable impact on the PDC measurement. Both the polarisation and depolarisation currents being very sensitive to temperature variations – this kind of temperature variation during the measurement period itself may introduce some unwanted variations in the currents. An experiment was performed in the laboratory with the test transformer being put inside a temperature controlled chamber. The PDC test was started at 20^0C and then the chamber temperature was increased at a steady rate of 2^0C per hour up to 30^0C while the test was going on. Fig. 4 shows the polarisation and depolarisation currents in the case with the temperature around the transformer tank rising steadily from 20^0C to 30^0C during the test. Fig. 4 also includes the polarisation and depolarisation currents when the same transformer was tested at a constant temperature of 20^0C.

It is observed in Fig. 4 that, both the polarisation and depolarisation currents with the temperature under upward transition are higher than their lower temperature counterparts. It is thus clear from the Fig. 4 that any dielectric response function and conductivity computed from the polarisation and depolarisation currents obtained under such temperature transition during the PDC measurement will be erroneous.

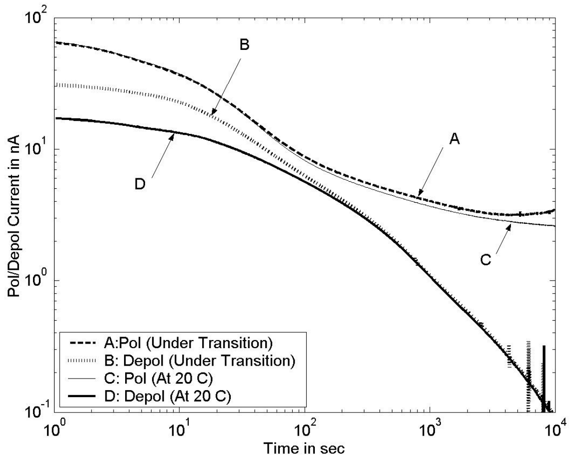

Fig.4. Polarisation and depolarisation current plots for transformer under upward transition of temperature

It is thus apparent that the interpretation of the PDC test results should be done with sufficient attention being given to such temperature variations during the measurement itself. The authors are currently working upon possible ways of correctly interpreting the PDC results in the presence of temperature variation – experiments and simulations are being performed at controlled temperature conditions.

C. 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 [6] that affects the linearity properties.

Fig.5 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 and the conductivities. The polarisation currents, however, are close to each other. Similar findings were reported by Houhanessian *et al* in [7].

According to Jonscher [6], 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 due to the injection of excess space charges into the dielectric during the charging process. Fig. 6 shows such a case corresponding to a 30 MVA transformer where there is a complete crossing over of the depolarisation and polarisation currents at small time.

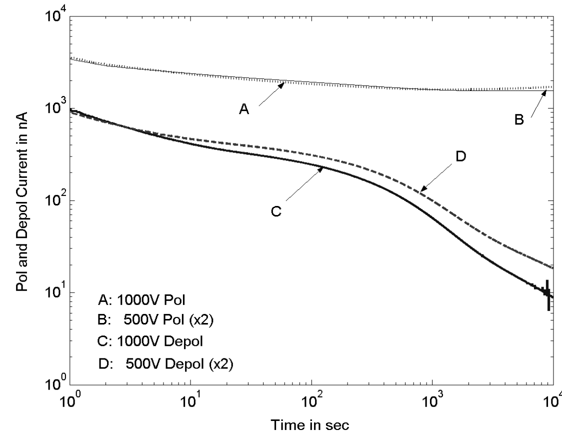

Fig. 5. Relaxation currents at different excitation voltages (scaled to the same level for comparison)

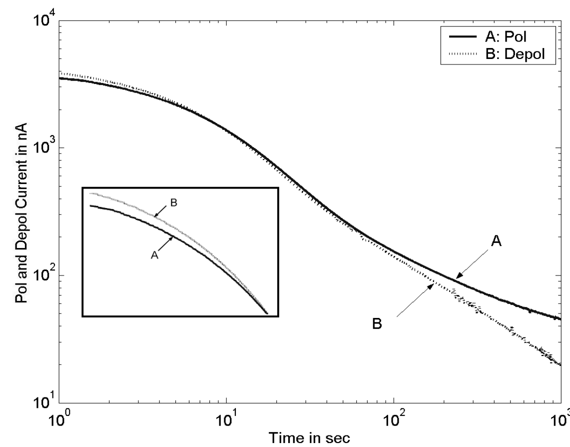

Fig. 6. Crossing over of depolarisation and polarisation currents; Inset shows the initial period in an enlarged scale

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

D. 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 [6-8]. 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. Fig.7 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.

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 [6].

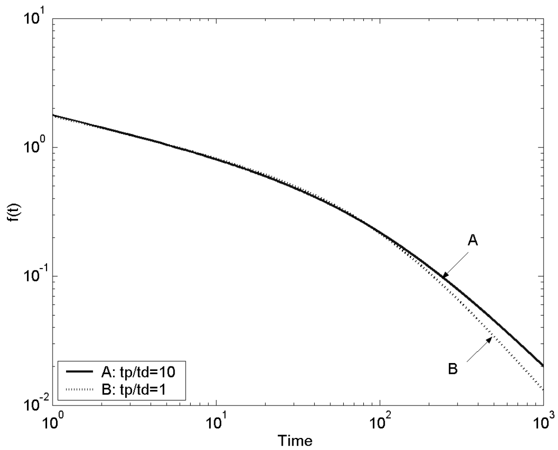

Fig.7. Dielectric response function f(t) at different ratios of charging and discharging times t_p and t_d.

This effect is more severe in new transformers where the magnitudes of the relaxation currents are quite low. This is often referred as the 'memory effect'. Fig.8 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. This may result in erroneous calculation of response function and conductivities. As observed in Fig.8, the difference in the magnitudes of the two depolarisation currents is, however, more prominent than the corresponding differences in the polarisation currents.

These requirements, however, often need to be sacrificed due to constraint of the practically available testing times. A compromise thus needs to be made between the charging/discharging periods and the actually available total testing time.

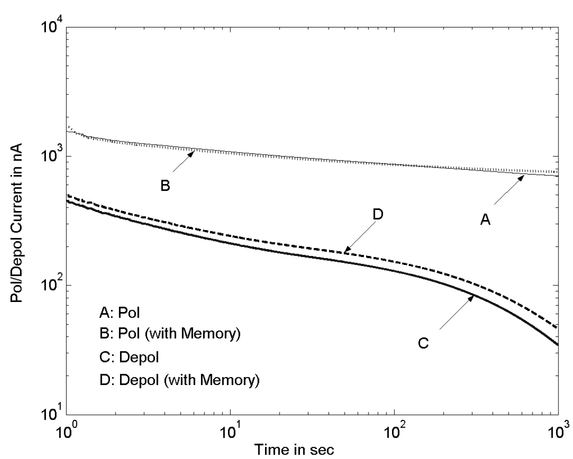

Fig.8. Polarisation and depolarisation currents with and without adequate pre-discharging

E. Noise and Interference

The polarisation and depolarisation currents in normal transformers are very small – in the range of 10^{-9}A. 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. Fig.9 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 busbars and other live transformers.

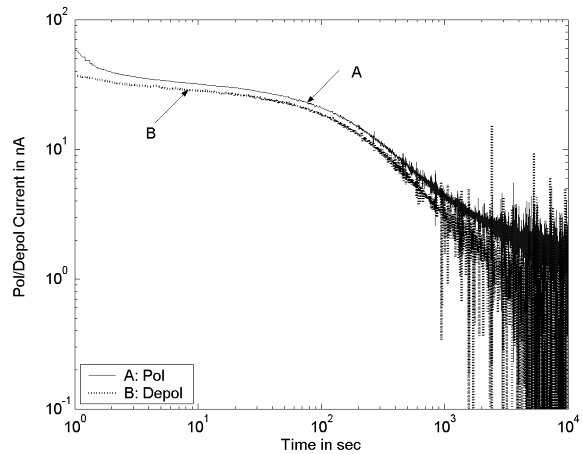

Fig.9. Polarisation and depolarisation currents in the presence of noise

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 can be used.

In the PDC measuring equipment developed by the authors [1, 5, 9], software based digital filters have been implemented to reduce the noise from the measured relaxation current signals. Fig.10 shows the polarisation and depolarisation currents of the same transformer as in Fig.9, but after the signals are processed by a digital filter.

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 might lead to faulty computation of the response function and the conductivities. Also interpretation of the polarisation and depolarisation current plots becomes confusing if there is too much noise.

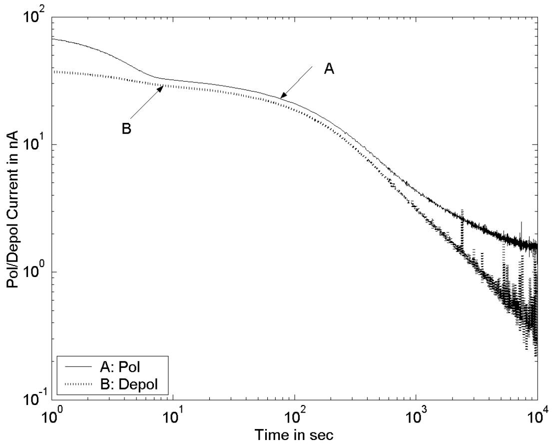

Fig. 10. Polarisation and depolarisation currents after filtering out noise

IV. 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 in 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:

- Measuring system requirements and configurations
- Temperature variations during the test
- Excitation voltage amplitude
- Charging/discharging and shorting periods
- Noise and interference

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 corrupt the sensitive relaxation currents.

V. References

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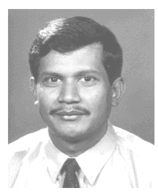
VI. Biographies



Tapan K. Saha was born in Bangladesh and came to Australia in 1989. Dr. Saha is a senior lecturer in the school of Information Technology and Electrical Engineering, University of Queensland, Australia. Before joining the University of Queensland in 1996, he taught at the Bangladesh University of Engineering and Technology, Dhaka, Bangladesh for three and half years and then at James Cook University of North Queensland, Townsville, Australia for two and half years. He is a senior member of IEEE and Fellow of the Institution of Engineers, Australia. His research interests include power systems, power quality and condition monitoring of electrical plants.

Prithwiraj Purkait was born in Kolkata, India in 1973. He obtained his B.E.E., M.E.E. and PhD degrees from Jadavpur University, Kolkata, India in 1996, 1999 and 2002 respectively. He worked with M/s Crompton Greaves Ltd , Mumbai , India as a Design Engineer for one year. Presently Dr. Purkait holds the post of lecturer in the department of Electronics and Instrumentation Engineering in Haldia Institute of Technology, Haldia, India. He is currently involved in post-doctoral research in the University of Queensland, Australia. His current research includes transformer insulation condition assessment techniques and advanced signal processing applications in High Voltage Engineering.