How Confident are we with Polarisation Based Diagnostics for Transformer Condition Assessment?

Tapan K Saha, Jing Haur Yew, Andrew Thomas
School of Information Technology & Electrical Engineering
University of Queensland
St. Lucia, Brisbane, Australia
saha@itee.uq.edu.au

ABSTRACT

Preventative diagnosis of transformers has become an important issue in recent times in order to improve the reliability of electric power systems. A number of diagnostic techniques such as Return Voltage (RV), Polarization/Depolarisation Current (PDC) and Dielectric Dissipation Factor (tan •) measurements at low frequency are currently available for practicing engineers. This paper outlines the summary of these techniques and a case study with all these measurements. Then the difficulties with the interpretation techniques are highlighted along with the recommendation of an expert system previously developed by the first author of this paper.

1. INTRODUCTION

Transformers are one of the most important components of electric power transmission and distribution systems. Many transformers around the world have now been in operation for several decades. During the course of operation, the transformer insulation undergoes degradation due to thermal, chemical, electrical and mechanical stresses. Traditionally, transformer insulation quality checks have been based on Dissolved Gas Analysis (DGA). During the last decade, furan analysis by High Performance Liquid Chromatography (HPLC) has been more frequently used to monitor paper insulation degradation [1]. Dielectric diagnosis techniques based on time domain measurements such as Return Voltage Measurement (RVM) [2, 3] and Polarisation and Depolarisation Current (PDC) [5, 6, 7] measurement techniques have been in use since 1990's. On the other hand, in frequency domain dissipation factor measurement at low frequency (in the range of 1 mHz to 1 kHz) has become popular in recent years [4, 8].

The RVM technique is simple to perform and can provide an indication of the overall condition of the oil-paper insulation [9, 10]. However, the correct interpretation of the RVM results needs a substantial amount of expertise [12]. Moreover, RVM results are found to be affected by the geometry of the insulation system, temperature, ageing by-products and moisture. To supplement the RVM technique, PDC is currently being investigated by several researchers around the globe [11]. Once again, correct interpretations of PDC method is only possible after adequate experience and after taking care of all parameters affecting the test results. Although dissipation factor is independent of transformer geometry, moisture and ageing condition assessment based on frequency domain measurement is not simple either.

Our research group have been working for the last fifteen years with RVM and PDC techniques. Many transformers have been tested under open substation conditions to investigate the effects of all possible parameters on the RVM and PDC test results. With hundreds of test results, it still remained a big task to correctly interpret a transformer's condition. To understand the whole interpretation process, it is essential that the test results be adequately correlated to the basic physical properties of the insulation system. In recent times, we have started using the frequency domain dissipation factor measurement as well.

This paper will report progress and findings made by our research group regarding the polarization measurement techniques and their interpretation schemes for condition assessment of transformer insulation. The paper will also point out some recommendations using the developed expert system.

2. THEORY OF POLARISATION MEASUREMENTS

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:

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

Where ε_0 is the vacuum permittivity and ε_r is the relative permittivity of the insulation at power frequency (typically 4.5 for cellulose paper/pressboard and 2.2 for transformer hydrocarbon oil). *P(t)* is the dielectric polarisation and is related to the response function *f(t)* of the material by the relationship:

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

The response function *f(t)* describes the fundamental memory property of the dielectric system and can provide significant information about the insulating material. The function *f(t)* can be determined experimentally as the response of the dielectric to a step-function charging field.

2.1 Polarisation and Depolarisation Currents [11]

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

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

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 (measured capacitance at or near power frequency, divided by ε_r) can be written as:

$$i(t) = C_0 \left[\begin{array}{l} \dfrac{\sigma}{\varepsilon_0} U(t) + \varepsilon_r \dfrac{dU(t)}{dt} \\ + \dfrac{d}{dt} \displaystyle\int_0^t f(t-\tau).U(\tau)\,d\tau \end{array} \right] \qquad (5)$$

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 the 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:

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

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

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

Where t_c is the time during which the voltage has been applied to the test object. Figure 1 shows the typical nature of these currents due to a step charging voltage U_0.

2.2 Estimation of the Conductivity [11]

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 of the composite dielectric as:

$$\sigma \approx \frac{\varepsilon_0}{C_0 U_0} \left(i_p(t) - i_d(t) \right) \qquad (9)$$

The average conductivity for a given insulation system thus, is found to be dependent upon the difference between the polarisation and depolarisation current values. For a linear dielectric, it is expected that the difference between the polarisation and depolarisation current is equal to the time-independent direct current. However, practical dielectric systems (such as transformer) inevitably have certain non linearity in their dielectric response. As a result, the difference between the polarisation and depolarisation current is found to vary with time depending upon the condition of the oil and paper. The conductivity of the dielectric computed using (9) will thus be dependent on time. This composite conductivity, in practice, is the convolution of the conductivities of the oil and the paper that make up the insulation structure.

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.

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.

Dielectric properties of an insulating material change with moisture, ageing and contamination products. The conductivities of both oil and paper in a transformer can change over a wide range during the operation of the transformer depending upon the operating conditions. In order to assess the state of the insulation system by the analysis of dielectric response characteristics, it is therefore important to understand the influence of various dielectric properties on the dielectric response measurements.

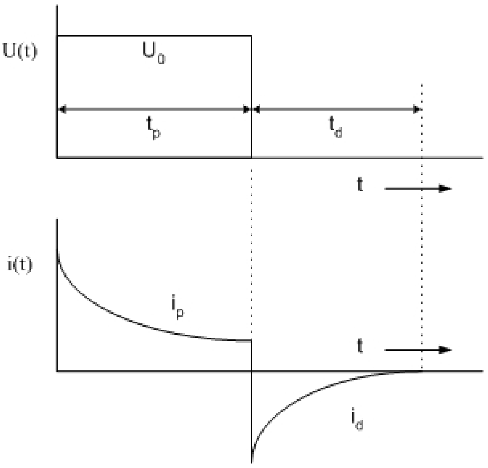


Figure 1 polarisation and depolarisation currents

A software based modelling tool has been developed for the numerical solution of the equations described in Section 2 for determination of the various dielectric responses.

2.3 Return Voltage Measurement

Three steps are followed during the return voltage measurement.

(a) During the initial charging period a step voltage is applied for time $0 \le t \le t_1$. In this time the charging current $i_{pol}(t)$ given by (7) will flow.

(b) At time $t \ge t_1$, the insulation is then grounded (short circuited) for a subsequent time period $t_1 \le t \le t_2$, now the current $i_{depol}(t)$ given by equation (8) flows.

(c) At $t=t_2$ ground (short circuit) is removed from the insulation and a voltmeter is connected across it.

Depending on how long the test object is grounded, t_2, some of the previously polarised molecules get totally relaxed and some do not. The polarisation processes which were not totally relaxed during the grounding period will relax and give rise to a return voltage across the electrodes of the insulation. Figure 2 shows the waveform of a return voltage. The return voltage U_r can be expressed with the following equations.

$$i_r(t) = \sigma U_r(t) + \varepsilon_0\varepsilon_r \frac{dU_r(t)}{dt} + \varepsilon_0 U_0\big(f(t) - f(t-t_1)\big) + \varepsilon_0 \frac{d}{dt}\int_{t2}^{t} f(t-\tau)U_r(\tau)d\tau \qquad (10)$$

for $t_2 < t < \infty$ and $U_r(t=t_2) = 0$

with the current $i_r(t)$ being zero during the voltage measurement (open circuit), (10) can be re-written as:

$$\sigma U_r(t) + \varepsilon_0\varepsilon_r \frac{dU_r(t)}{dt} + \varepsilon_0 U_0\big(f(t) - f(t-t_1)\big) + \varepsilon_0 \frac{d}{dt}\int_{t2}^{t} f(t-\tau)U_r(\tau)d\tau = 0 \qquad (11)$$

In return voltage measurements this charging/discharging sequence is continued until the peak of the maximum return voltage is achieved. Traditionally the ratio of charging to discharging time is maintained at two. Three key parameters are very often described to assess the condition of moisture and ageing in a transformer. These are:- peak maximum return voltage, initial slope and the corresponding time to reach the peak maximum return voltage. A number of authors have described a simple relationship between the peak maximum return voltage and its time to reach the peak, with the moisture content [2,3]. In [13] Gafvert et al. recommend polarisation current measurement as the preferred time-domain diagnostic method since the properties of oil and paper can be separately assessed from the experimental results. The authors explain that return voltage measurement results are convoluted by two constituents and it is difficult to separate the oil and paper impacts. Gafvert et al. emphasises that return voltage curves are strongly influenced by the oil conductivity. The authors suggest that the oil conductivity and geometry of the insulation strongly affects the central time constant.

2.4 Dielectric Response in Frequency Domain

Frequency domain dielectric spectroscopy (FDS) measurement is a refined version of the capacitance and dissipation factor measurement performed usually for a single power frequency.

With the measurement of the complex capacitance and the dissipation factor in relation to frequency *f*, it is possible to distinguish between the different polarization mechanisms in the frequency spectra. The expression for the capacitance is:

$$C = \varepsilon \cdot \frac{A}{w} \qquad (12)$$

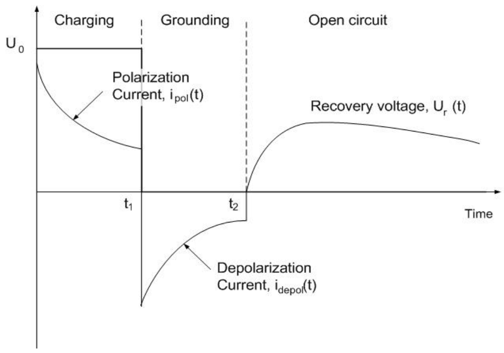


Figure 2 Return voltage principle

Where A is plate area of the capacitance, ε is permittivity and w is the distance between two plates. If the applied voltage is an alternating signal at a frequency • , then the measured capacitance is a complex quantity whose real and imaginary parts correspond directly to the real and imaginary components of the complex permittivity.

$$C(\mathrm{w}) = C'(\mathrm{w}) - iC''(\mathrm{w})$$
$$= (A/w)\cdot\left(\mathrm{e}'(\mathrm{w}) - i\mathrm{e}''(\mathrm{w})\right) \qquad (13)$$

C’(•) corresponds to the ordinary capacitance, while the imaginary component C’’(•) represents the dielectric loss component.

The tangent of the loss angle δ, the dissipation factor is given by the relation :

$$\tan\mathrm{d} = \frac{C''(\mathrm{w})}{C'(\mathrm{w})} = \frac{\mathrm{e}''(\mathrm{w})}{\mathrm{e}'(\mathrm{w})} \qquad (14)$$

For the measurement of the dissipation factor, a sinusoidal voltage of variable frequency is used; this voltage is applied to the shorted high voltage winding of the transformer. On the shorted low voltage winding the current is measured. The transformer tank is grounded. The range of the measured frequencies starts at 0.001 Hz and goes to 1000 Hz. One practical advantage with the dissipation factor (tan•) is that it is independent of the geometry. This makes it possible to study tan• when the geometry of the test sample is not known. A number of methodologies are currently in use to interpret the condition of moisture from the tan• measurement.

Gafvert et al. [8] presented dielectric spectroscopy in time and frequency domain for a number of power transformers from a nuclear power station. The authors used low frequency dielectric spectroscopy, polarisation/depolarisation current and return voltage spectra measurements. Significant differences in RV results were detected by change in oil quality and moisture content of the solid insulation. The authors while comparing the time-domain versus frequency-domain diagnostic methods suggest that low frequency dielectric spectroscopy measurement of capacitance and dissipation factor in the frequency range 0.1 mHz to 1 kHz is the best measurement method for fieldwork. Their findings suggest that the RVM method is useful but more sensitive to systematic errors than the other two methods. RVM is a high impedance input method, and hence leakage current on the bushings can easily corrupt the measurement.

3. CASE STUDY

To show the complexity and the difficulty in analysing test results from the polarisation based measurements, a laboratory transformer was tested with three diagnostic techniques.

The measurement includes:-

(i) Polarisation and depolarisation current measurements at 100 and 200 Volts DC

(ii) Return voltage measurements at 100 and 200 Volts DC

(iii) Dissipation factor measurements at 100 and 200 Volts variable frequency (1mHz to 1 kHz)

The first two measurements were performed by the equipment developed at the School of Information Technology and Electrical Engineering, University of Queensland [10-11]. Frequency domain dissipation factor measurement was performed by the IDA-200 commercial equipment [14]. The tested transformer (year of manufacture 1962) is 100kVA, 3 phase Delta-Star, 10.5 kV HV and 415 V LV and Oil immersed natural cooled.

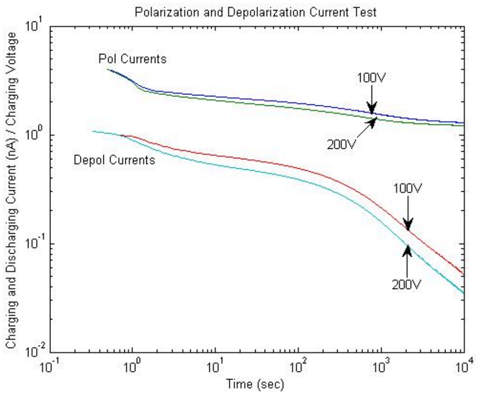


Figure 3 Polarisation and Depolarisation currents at 100 and 200 V DC

Polarisation and depolarisation currents were measured for this transformer at two different charging voltages (100 and 200 Volt DC). These currents were normalised with charging voltage and shown in Figure 3. The measured currents were reasonably larger for a small distribution transformer. Another point to note is that the currents at 200 volt was not 2 times the currents at 100 volt. Higher values of polarization and depolarization currents can be attributed to higher conductivity, higher moisture content and an advanced ageing state of the insulation.

The initial period of the polarization/depolarization current are found to be governed by the oil properties and the long time values of these currents are primarily determined by the paper/pressboard condition [11]. Though the condition of both oil and paper can thus be separately estimated, it still appears to be difficult to quantify the exact degree of ageing from the PDC measurements. Conductivities of oil and paper insulation were calculated based on these assumptions [11]. Conductivity of paper and oil was found to be 1×10^{-11} S/m and 1×10^{-10} S/m respectively. These conductivities are very high compared to the conductivities of unaged and dry oil-paper insulation. Moisture and ageing estimation based on the conductivity and other diagnosis results will be performed in the later part of this section with the help of our developed expert systems tool.

RV measurements at two charging voltages on this transformer are plotted versus the charging time and are shown in Figure 4. The peak of the maximum RV occurred for few hundred second charging time. The time to reach the maximum return voltage is commonly known as the central time constant (CTC). Figure 5 shows the plot of maximum RV against the corresponding central time constant. This shows that the transformer peak maximum return voltage reaches in a very short time (within few tens of seconds).

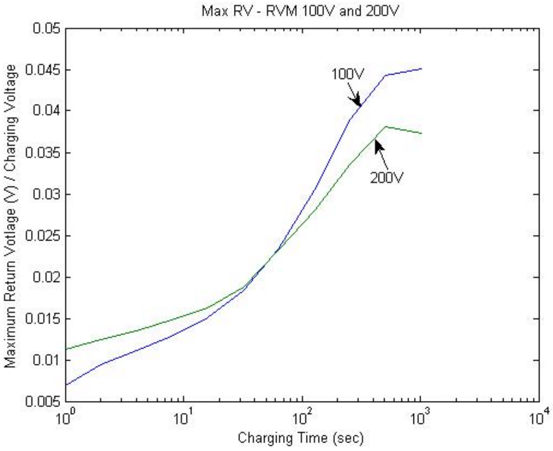


Figure 4 Maximum return voltage versus charging time at 100 and 200 V DC

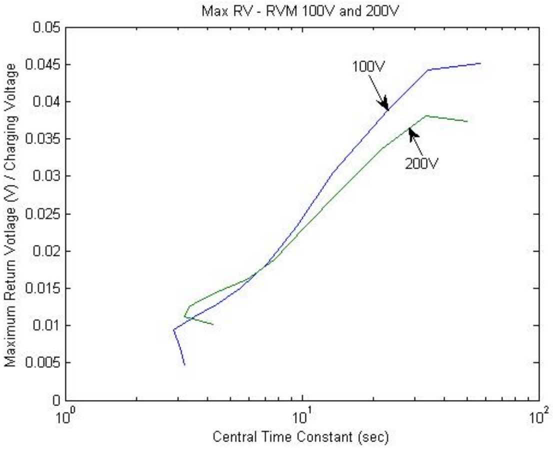


Figure 5 Maximum return voltage versus central time constant at 100 and 200 V DC

Normally for a very aged and moist transformer this central time constant is few to tens of seconds, while for a very good insulation condition and relatively dry transformer, this CTC will be hundreds to thousands of seconds. CTC depends on the geometry, moisture and ageing condition of the transformer. Without knowing the geometry of the transformer, a simple interpretation could be very erroneous. Temperature during the RV measurement plays a significant role in the CTC value. Hence, to interpret the RV/PDC results, an expert system was developed in our research work, which will be discussed in the later part of this section. It is to be noted that RV maximum values at 200 Volt charging were not twice the values obtained at 100 V charging. A similar phenomenon was observed at PDC measurements.

Figure 6 shows the dissipation factor versus frequency (1 mHz to 1 kHz) at 100 and 200 Volt. The dissipation factor values of this transformer were very high. There was a small difference in peak value of the dissipation factor between two applied voltages. Other than that, the dissipation factor graphs were overlapping throughout the remaining frequency range.

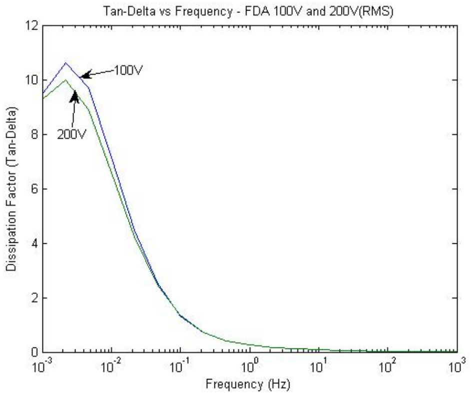
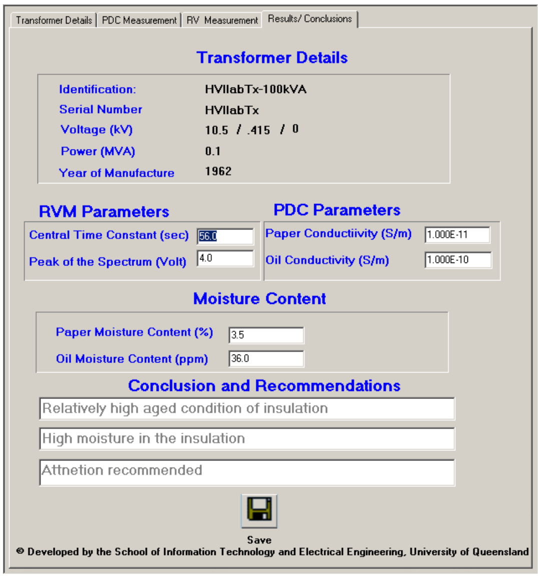


Figure 6 Dissipation factor measurements at 100 and 200 V at variable frequency

As can be seen from Figure 6, the Maxwell-Wagner type peak is observed in the low frequency range. This phenomenon is due to the pressboards which act as a barrier for the ionic charge carriers in the oil as well as the surface charges that were accumulated on the solid surface [8]. Therefore, the conductivity of the oil and the amount of the board in the duct determines the position of this peak [8]. The modelling done by Gafvert et al [8] shows that the lower the oil conductivity is, the lower frequency the peak will occur at. A general trend of high moisture and high ageing condition was observed from all three diagnostics.



Transformer Details

Identification: HVlabTx-100kVA
Serial Number HVlabTx
Voltage (kV) 10.5 / .415 / 0
Power (MVA) 0.1
Year of Manufacture 1962

RVM Parameters

Central Time Constant (sec) 56.0
Peak of the Spectrum (Volt) 4.0

PDC Parameters

Paper Conductiivity (S/m) 1.000E-11
Oil Conductivity (S/m) 1.000E-10

Moisture Content

Paper Moisture Content (%) 3.5
Oil Moisture Content (ppm) 36.0

Conclusion and Recommendations

Relatively high aged condition of insulation

High moisture in the insulation

Attnetion recommended

© Developed by the School of Information Technology and Electrical Engineering, University of Queensland

A

Figure 7 Expert system output based on PDC and RV results

However, to get a clear picture about the condition of this transformer a thorough understanding of these methods is required. In our previous work, an expert system (ES) for transformer insulation diagnosis based on the ageing mechanism of insulation system and service experiences was constructed. The developed expert system tool aimed at assisting the user to obtain unambiguous, reliable, and quick decision in insulation condition assessment of transformers using the RVM and the PDC techniques [12].

By means of this expert system, even an inexperienced user is able to valuate competently the state of the transformer insulation system and the equipment's behaviour in further operations. An example of the application of the ES is presented in Figure 7 to demonstrate that the expert system can provide reliable and effective insulation diagnosis. Based on the PDC/RV diagnosis results, the expert system predicts 3.5% moisture content in solid insulation with very high conductivities for both paper and oil. This also predicts high ageing in the oil-paper insulation system. This finding has been correlated with traditional chemical analysis of oil and paper. However, this was not the study matter of this paper.

4. CONCLUSIONS

Dielectric diagnosis techniques RVM, PDC and FDS have now been established as non-destructive dielectric diagnosis techniques for transformer insulation condition assessment. Polarization and depolarization currents are strongly influenced by the conductivity, moisture contents and ageing status of the oil and the paper. Though the condition of both oil and paper can thus be separately estimated, it still appears to be difficult to quantify the exact degree of ageing from the PDC measurements.

RVM and FDS have also been used by many engineers and researchers around the world. However, their popularity has not been as well spread as anticipated due to the requirement of the expertise for their evaluation and analysis. In particular a number of factors need to be understood. An expert system tool for transformer insulation condition assessment based on the RVM and PDC techniques has been used in this paper. The ES is demonstrated to perform insulation diagnosis in an effective and reliable manner. The ES is expected to be useful to even inexperienced maintenance engineers for quick and reliable insulation condition assessment of transformers based on the dielectric response measurements.

REFERENCES

[1] M. Darveniza, D. J. T. Hill, T. T. Le and T. K. Saha, ‘‘Investigations into Effective Methods for Assessing the Condition of Insulation in Aged Power Transformers’’, IEEE Trans. Power Delivery, Vol, 13, pp. 1214_1223, 1998

[2] A. Bognar, L. Kalocsai, G. Csepes, E. Nemeth, and J. Schmidt, “Dielectric tests of high voltage oil paper insulating systems (In particular transformer insulation) using DC dielectrometrics,” in *Proc. CIGRE, 33rd Session*, Paris, France, 1990, 15/33–08.

[3] G. Csepes, I. Hamos, I. Brooks, and V. Karius, “Practical foundations of the RVM (Recovery voltage method for oil/paper insulation diagnosis),” in *Proc. IEEE Conf., Elect. Insul. Dielectric Phenomena*, 1998, pp. 345–355

[4] E. Ildstad, U. Gafvert and P. Tharning, ‘‘Relation between Return Voltage and Other Methods for Measurements of Dielectric Response’’, IEEE Intern. Sympos. Electr. Insul., USA, pp. 25_28, 1994

[5] J. J. Alff, Vahe 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’’, IEEE Intern. Sympos. Electr. Insul., USA, pp. 161_167, 2000.

[6] M. Hassig, R. Braunlich, R. Gysi, J. J. Alff, Vahe Der. Houhanessian and W. S. Zaengl, ‘‘On-site Applications of Advanced Diagnosis Methods for Quality Assessment of Insulation of Power Transformers’’, IEEE Conf. Electr. Insul. Dielectr. Phenomena, USA, pp. 441_447, 2001

[7] Vahe Der. Houhanessian and W. S. Zaengl, ‘‘Time Domain Measurements of Dielectric Response in Oil-Paper Insulation Systems’’, IEEE Intern. Sympos. Electr. Insul., Canada, Vol. 1, pp. 47_52, 1996

[8] U. Gafvert, L. Adeen, M. Tapper, P. Ghasemi and B. Jonsson, ‘‘Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostics of Power Transformers’’, IEEE 6th International Conference on Properties and Applications of Dielectric Materials, China, Vol. 2, pp. 825_830, 2000.

[9] T. K. Saha, ‘‘Review of Time Domain Polarisation Measurements for Assessing Insulation Condition in Aged Transformers’’, IEEE Trans. Power Delivery, Vol. 18, No. 4, October 2003, pp. 1293-1301

[10] 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.

[11] T. K. Saha and P. Purkait, “Investigation of polarization and depolarization current measurements for the assessment of oil-paper insulation of aged transformers”, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 11, Issue: 1, Feb. 2004, Pages: 144 – 154.

[12]. T. K. Saha and P. Purkait, “Investigation of an Expert System for Condition Assessment of transformer insulation Based on Dielectric response measurements”, IEEE Transactions on Power Delivery, Vol. 19, No. 3, July 2004, pp. 1127-1134.

[13] U. Gafvert, G. Frimpong, and J. Fuhr, ‘‘Modelling of Dielectric Measurements on Power Transformers’’, Intern. Conference on Large HV Electric Systems, CIGRE, Paris, France, Paper No. 15-103, 1998.

[14] GE Energy Services, “IDA 200™, Insulation Diagnostics System”.