An Attempt to Correlate Time & Frequency Domain Polarisation Measurements for the Insulation Diagnosis of Power Transformer

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***Abstract*-- The insulation system of power transformers (oil and paper/pressboard) generally change their dielectric properties during the life of the transformer and dielectric measurements have therefore been applied to assess the quality or state of ageing of the system. Both time domain and frequency domain dielectric diagnosis techniques have recently gained popularity in providing information on the condition of transformer oil-paper insulation. The present paper aims at deriving a correlation between these two methods of diagnosis. Simulation results along with actual field test results have demonstrated a direct correlation between the time and frequency domain tools for insulation diagnosis.**

***Index Terms*—transformer insulation, dielectric diagnosis, polarisation/depolarisation current, frequency domain spectroscopy, dissipation factor, complex capacitance.**

I. Introduction

A major challenge facing electric utility engineers today is to use electrical equipment in a way that meets system requirements yet also maximises the equipments useful life. Proper monitoring and on-site diagnosis can extend the useful life of electrical equipment. So there has been an urge to direct priority attention of research into improved diagnostic techniques for determining the condition of the insulation in aged transformers. Modern dielectric diagnosis, supplemented with advanced modelling and analysis tools promise to offer accurate and reliable methods for assessing the condition of the insulation.

The condition of oil/paper insulation system in a power transformer is degraded by the electrical, thermal and environmental stresses during its operation. Time domain polarisation measurements [1-5] and frequency domain spectroscopy (FDS) [6-11] measurements are examples of dielectric response measurements that have been used in recent times for diagnosis of power transformers insulation condition. Though different research groups have been involved in independent development of time and frequency domain diagnostic tools separately, there has been always an urge to establish correlation between the two techniques for obtaining a more correct and reliable diagnosis outcome. This paper attempts to bridge this gap and thereby introduces a comprehensive dielectric diagnosis routine involving a correlation between the time and frequency domain diagnosis techniques.

This paper reports development of a model of the insulation structure of transformers based on the polarisation and depolarisation current measurements in time domain. The model takes into account the geometry of the transformer and the influence of the properties of the constituent materials (oil and paper). The model parameters have been identified using a curve-fitting procedure as described in [12]. Frequency domain measurement parameters-such as dissipation factor and complex capacitance can be estimated from the identified model components by using simple mathematical formulations.

A correlation has been attempted between the time-domain and frequency-domain results regarding diagnosis of the state of insulation. Simulation results have been supported with actual field test results to illustrate the correlation between time and frequency domain diagnostic techniques.

II. Theoretical Background and Physical Model Implementation

The dielectric measurements can be performed either in "time-domain" or in "frequency-domain".

- In time-domain, a step voltage is applied to the test sample and the response of the dielectric material is analysed.
- In frequency-domain, a sinusoidal voltage of variable frequency is applied and the response of the dielectric is determined from the amplitude and phase of the current flowing through the test sample.

A. Time Domain Polarisation Measurements

If an insulation system with geometrical capacitance C_0 (measured capacitance divided by ε_r, the relative permittivity of the composite insulation system), composite conductivity σ and dielectric response function *f(t)* is exposed to a step voltage of magnitude U_0, the polarisation current through the insulation system can be derived as:

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

Once the step voltage is removed and the insulation system

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is shorted to ground, the depolarisation current can be written as:

$$i_{depol}(t) = -C_0 \cdot U_0 \cdot \left[f(t) - f(t+t_p) \right] \tag{2}$$

Where t_p is the duration of the time during which the voltage had been applied to the test object. If the polarisation time is sufficiently long, so that $f(t+t_p)\approx 0$ the response function is proportional to the depolarisation current.

$$i_{depol}(t) = -C_0 \cdot U_0 \cdot f(t) \tag{3}$$

From these two equations (1) and (3) of the polarisation and depolarisation currents the dielectric response function *f(t)* and the composite conductivity σ can be determined.

Fig. 1 shows the nature of the polarisation current after applying a DC voltage U_0 and of the depolarisation current during the short circuit.

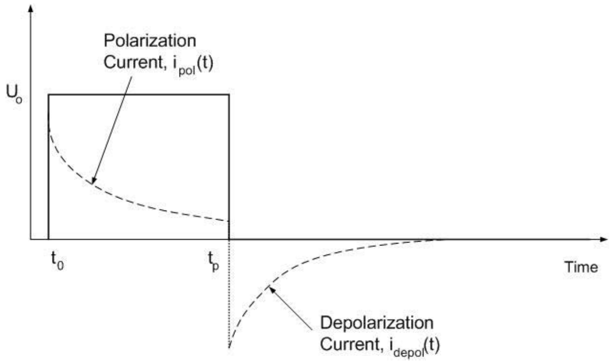

Fig. 1 Principle of relaxation current measurement

Earlier researchers [1-5] have reported that the initial parts of the polarisation and depolarisation currents are sensitive to the condition of the oil, whereas the final long-term values of these currents are influenced by the condition of the solid insulation (paper). In other words, the initial higher magnitude of the conduction current is due to the higher mobility of the charge carriers in the liquid dielectric (oil). This initial part of the response is found to die down after some time and the steady conduction current due to the less mobile charge carriers in the solid insulation (paper/pressboard) becomes predominant.

B. Frequency Domain Dielectric Spectroscopy (FDS)

This technique is a generalization of the capacitance and dissipation factor (tanδ) measurements usually done at power frequency. A sinusoidal signal is applied to the high voltage bushing and current is measured at the low voltage terminal. The tank and core are connected to ground. A frequency range between 1 mHz to 1kHz is most commonly used. The supply voltage may range from 5 to 200 volts (RMS). With the measurement of the dissipation factor and the complex capacitance in relation to frequency, it is possible to distinguish between the different polarization mechanisms in the frequency spectra.

1) Dissipation Factor [19, 20]:

When a sinusoidal voltage is applied across an insulation, a current will flow with a certain phase angel φ. The dissipation angle δ describes the angle between the complex conductance Y_C and the imaginary axis. If φ = 90° that means angle δ = 0 degree, the insulation material would have no loss. The tangent of the angle δ is called the "dissipation factor".

$$\tan\delta = \frac{\text{Real part of Impedance}}{\text{Imaginary part of Impedance}} \tag{4}$$

2) Complex Capacitance:

The expression for the capacitance is:

$$C = \varepsilon \cdot \frac{A}{w} \tag{5}$$

Where A is the plate area of the capacitance, ε is the permittivity and w is distance between two plates.

If the applied voltage is an alternating signal at a frequency ω, 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:

$$C(\omega) = C'(\omega) - jC''(\omega) = (A/w)\cdot\left(\varepsilon'(\omega) - j\varepsilon''(\omega)\right) \tag{6}$$

C'(ω) corresponds to the ordinary capacitance, while the imaginary component C''(ω) represents the dielectric loss component. The tangent of the loss angle δ the dissipation factor is given by the relation:

$$\tan\delta = \frac{C'(\omega)}{C''(\omega)} \tag{6a}$$

C. Relations between Time and Frequency Domains:

The information obtained in either frequency or time domain is theoretically equivalent if the dielectric material can be described as a linear system. Then the following relation between frequency and time domain responses is valid:

$$\chi(\omega) = \chi'(\omega) - j.\chi''(\omega) = \int_0^\infty f(t).e^{-j\omega} dt \tag{7}$$

Where χ(ω) is the frequency dependent complex susceptibility and *f(t)* is the dielectric response function characterizing the dielectric response characteristics of the material. The theoretical background of the numerical calculations can be found elsewhere [9, 10].

III. Modelling Of Transformer Oil-Paper Insulation Using Extended Debye Model (RC Circuit Equivalents)

Over the last few years, several researchers [13-20] have proposed a number of equivalent circuits for modelling the transformer oil/paper insulation system for better understanding of the dielectric response. In essence, all the models proposed so far have been derived from an extended Debye approach based on a simple RC-model.

The polarisation processes inside the oil-paper insulation structure can be modelled by a parallel arrangement of branches each containing a series connection of resistor and capacitor as shown in the circuit of Fig. 2. These dipoles, represented as R_i-C_i, are randomly distributed, and have associated time constants given by $\tau_i=R_iC_i$. Apart from the polarization current, conduction current flows in the insulation in the presence of an electric field. The conduction current in the insulation is due to the insulation resistance R_0 as shown in Fig. 2. C_0 represents the geometric capacitance of the insulation system.

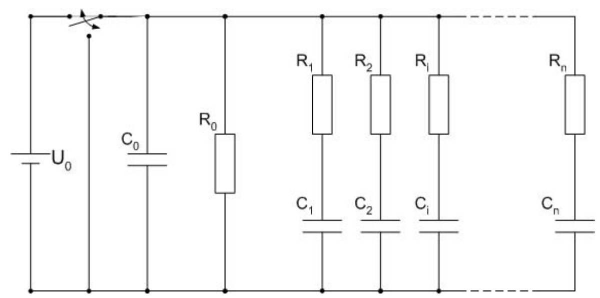

Fig. 2 Equivalent circuit to model a linear dielectric material

A. Identification of the Model Parameters

For this model, most of the circuit parameters can be derived from measured polarization and depolarization currents (i_p and i_d). The capacitance C_0 is determined by conventional capacitance measurement techniques at power frequency. The insulation resistance R_0 is calculated from the difference between polarization and depolarization currents at larger values of time [15]. Various parts of the insulation have their unique relaxation characteristics depending upon the ageing and moisture condition. The paper and pressboard insulation have different time constant of polarization as compared to the time constant of oil. The depolarization currents can thus be modelled as the sum of exponentials of the various relaxation mechanisms. The individual elements R_i-C_i with the corresponding time constants $\tau_i=R_i.C_i$ can then be determined by fitting the depolarization current with the following equation:

$$i_{depol} = \sum_{i=1}^{n} \left(A_i . e^{\left(-t/\tau_i\right)} \right) \quad (8)$$

Where

$$A_i = U_0 \cdot \left(1 - e^{\left(t_p/\tau_i \right)} \right) \Big/ R_i \quad (9)$$

And n = number of R_i – C_i branches, t_p = Polarisation time and U_0 = Applied DC voltage magnitude

The depolarization current comprises of summation of various relaxation mechanisms that appears at different locations within the transformer insulation.

Fig. 3 shows the measured and simulated depolarisation currents along with the constituent exponential components.

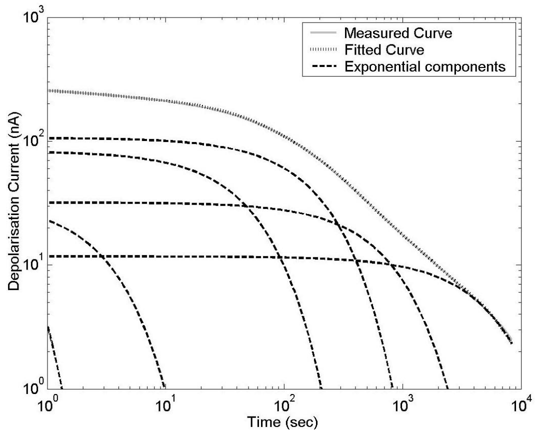

Fig. 3 Measured and simulated depolarisation current for a 45MVA transformer

Table I lists the values of the R-C components of the insulation model of a 45 MVA transformer derived through the curve-fitting programme described in [12].

TABLE I
Equivalent Circuit Parameter Values for 45MVA Transformer

Branch	R_i (GΩ)	C_i (nF)
1	7.0	950
2	6.0	150
3	4.5	30
4	3.5	8.5
5	6.0	0.9
6	2.5	0.3

The difference between the polarisation and depolarisation currents is the time dependent DC current [12]. The value of R_0 is then obtained from the long time constant values of this conduction current. The value of R_0 obtained from the above plot is 2.5GΩ for the same 45MVA transformer. The value of the capacitance C_0 measured at 50 Hz by an AC Bridge is 10.2 nF.

IV. Simulation of Frequency Response Characteristics from R-C Model Parameters

A. Dissipation factor

With the values of R_i, C_i, R_0 and C_0 of the equivalent circuit it is now possible to calculate the dissipation factor tanδ, which is dependent on the frequency. For finding the dissipation factor using (4), we have to determine the real part and the imaginary part of the equivalent circuit Fig 2. After simplifications we get

$$\tan\delta = \frac{\frac{1}{R_0} + \sum_{i=1}^{i=n}\left(\frac{R_i\cdot(\omega C_i)^2}{1+(R_i\omega C_i)^2}\right)}{\omega C_0 + \sum_{i=1}^{i=n}\left(\frac{\omega C_i}{1+(R_i\omega C_i)^2}\right)} \quad (10)$$

In Figure 4, the frequency domain dielectric response tanδ versus frequency is presented.

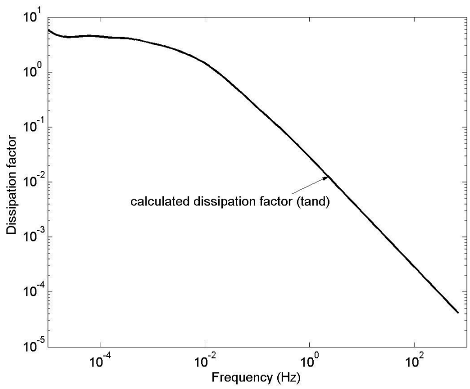

Fig 4 Simulated dissipation factor versus frequency

B. Complex Capacitance

For this calculation we may always define a complex capacitance

$$C^*(\omega) = C'(\omega) - jC''(\omega) \quad (11)$$

The complex capacitance for the equivalent circuit Fig. 2 can be expressed as:

$$C'(\omega) = C_0 + \sum_{i=1}^{n}\frac{C_i}{1+(\omega R_i C_i)^2} \quad (12)$$

$$C''(\omega) = \frac{1}{\omega R_0} + \sum_{i=1}^{n}\frac{\omega R_i C_i^2}{1+(\omega R_i C_i)^2} \quad (13)$$

Fig. 5 shows the simulation result of the calculation of the complex capacitance. The values of the electric components R and C of the equivalent circuit are obtained from Table I.

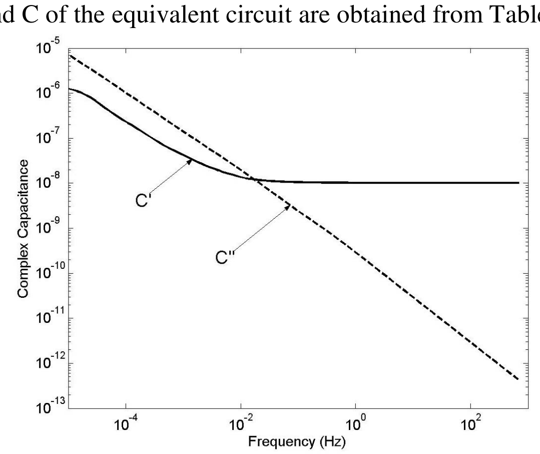

Fig. 5 Simulated complex capacitance curve.

V. Correlation between Time and Frequency Domain for Insulation Condition Assessment

Two different power transformers as described in Table II have been tested for this investigation.

A. Polarization and Depolarization Currents

Fig. 6 shows the plots for the polarization and depolarization currents. PDC measurements on transformer A was conducted at 1000V and transformer B at 500 V. Both transformers have different geometric Capacitances C_0. For comparing the measured curves, the polarization and the depolarization currents are divided with there corresponding voltage U_0 and capacitance C_0 so that they are normalised to the same scale.

TABLE II
Technical Data of the Measured Transformers

Transformer	Power	Voltage	Conditions
A	15 MVA	132/11 kV	Spare transformer (Manufactured in 1963)
B	45 MVA	66/22 kV	In service (Manufactured in 1959)

As can be seen from Fig. 6, the polarisation and depolarisation currents during the initial period are lower for transformer A as compared to those of the transformer B. This indicates the fact that the oil of transformer A is in better condition than that of the transformer B. The long term values of the currents are showing the same nature of variation. The current magnitude of B is much higher than that of A during larger times. This means the paper condition of A is better than that of transformer B.

Table III presents the conductivity of oil and paper calculated from the polarization and depolarization currents. The oil conductivity for transformer A is smaller than that for transformer B. The calculated paper conductivity shows the same relationship. These differences in conductivity values are not significant. Normally the difference in conductivities between a very good and a moist insulation shows a difference in the order of 10's.The value of paper conductivity for transformer A is smaller than for transformer B. The paper condition in transformer A is better.

B. The dissipation factor (tan δ)

Fig. 7 shows the simulation of the dissipation factor (tan δ) with variable frequencies for transformer A and transformer B. It is seen that the curve of transformer A and the curve of transformer B have in the beginning at a common point. After this the magnitude of A is lower than that of B.

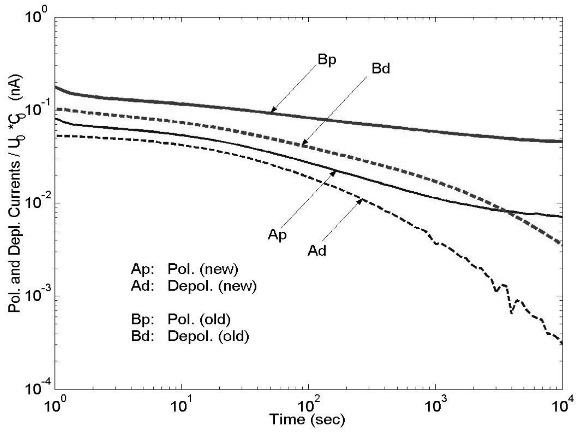

Fig. 6 Polarization and depolarization currents from an old and a new transformer.

TABLE III
OIL AND PAPER CONDUCTIVITIES OF THE TRANSFORMERS

Transformer	Oil conductivity (pS/m)	Paper conductivity (pS/m)
A (15 MVA)	1.1	0.27
B (45 MVA)	2.9	1.7

The difference in the magnitude between A and B in the low frequency range indicates the paper condition of transformer A is better than that of the transformer B. The high frequency dissipation factor shows the oil condition. The magnitude of A is again smaller than that of the transformer B. This indicates the oil condition of transformer A is also better than the oil condition of transformer B.

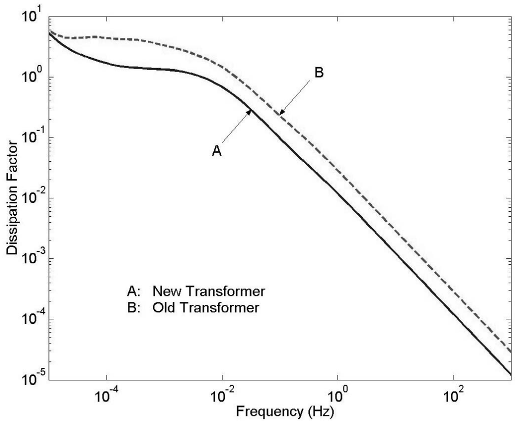

Fig. 7 Simulated dissipation factor from A (new), and B (old) transformer.

These dissipation factor results can be also correlated with moisture content of insulation. However, this paper only attempts a correlation between the time and frequency domain measurements. This investigation is currently on-going and will be reported in a future paper.

C. The complex capacitance

The simulation results of the real and the imaginary part of the complex capacitance (C' and C'') are shown in Fig. 8 and Fig. 9.In Fig. 8 it is seen that both transformers have different capacitance plots over the whole frequency range..

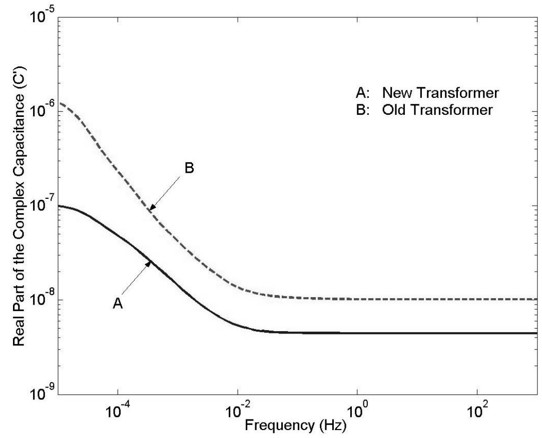

Fig. 8 Simulated real part of the complex capacitance (C') from A, the new and B, the old transformer.

In Fig. 9, the simulation of the imaginary part of the complex capacitance (C'') is displayed. It describes the loss in the test object. As seen in the Fig. 9 the magnitude of C'' of transformer B in the whole frequency range is larger than that of the magnitude of transformer A. This indicates better insulation condition of transformer A than the transformer B.

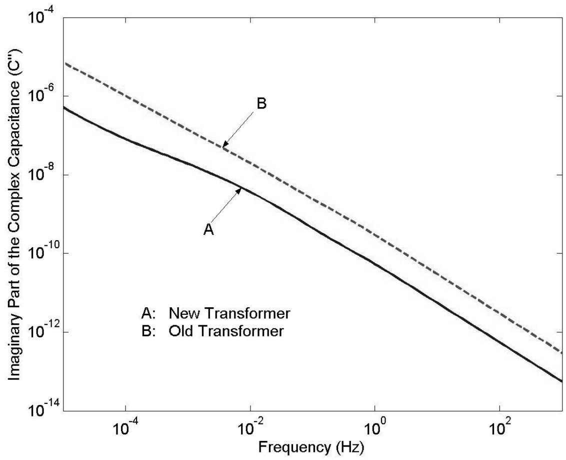

Fig. 9 Simulated imaginary part of the complex capacitance (C'') from A, the new and B, the old transformer.

Thus we can reach the same conclusion from the two approaches of polarisation measurements that insulation of the transformer A was better than that of the transformer B.

VI. CONCLUSIONS

A model of the transformer's main insulation system, which describes its dielectric behaviour, has been presented in this paper with extended Debye model. The values of the parameters of the equivalent circuit have been obtained from time domain (polarisation and depolarisation) current measurements. Once the model has been parameterised, dissipation factor and complex capacitance has been simulated in frequency domain.

The approach adopted in this paper shows a direct relationship between the two measurement schemes. Some qualitative analysis of insulation condition has been investigated by these two schemes and a general correlation has also been established. In the past we have investigated quantitative analysis of insulation ageing/moisture condition with time domain polarisation measurements. This can also be extended to frequency domain measurements and our on-going research is continuing with frequency domain measurements. Further correlation with these methods and their interpretation schemes will be reported in future papers.

VII. References

[1] Vahe Der. Houhanessian and W.S. Zaengl, "Time Domain Measurements of Dielectric Response in Oil-Paper Insulation Systems", IEEE International. Symposium on Electrical Insulation, Canada, pp.47-52, 1996.

[2] 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.

[3] T. K. Saha and P. Purkait, "Investigation of Polarisation and Depolarisation Current Measurement for the Assessment of Oil-Paper Insulation of Aged Transformers", Accepted for publication in the IEEE Trans. Dielectrics and Electrical Insulation, 2003.

[4] U. Gafvert, G. Frimpong, and J. Fuhr, "Modelling of dielectric measurements on power transformers," International Conference on Large High Voltage Electric Systems. CIGRE'98. Session Papers. CIGRE, Paris, France, 1998.

[5] Vahe Der. Houhanessian and W. S. Zaengl, "On-site diagnosis of power transformers by means of relaxation current measurements," Conference Record of the 1998 IEEE International Symposium on Electrical Insulation (Cat. No.98CH36239). IEEE, New York, NY, USA 1998, vol. 2, 1998.

[6] U. Gafvert, L. Adeen, M. Tapper, P.Ghasemi and B. Jonsson, "Dielectric Spectroscopy in Time and Frequency Domain Applied to Diagnostics of Power Transformers", Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials, USA, pp.825-830, 2000.

[7] R. Neimanis, T. K. Saha and R. Eriksson, "Determination of Moisture Content in Mass Impregnated Cable Insulation Using Low Frequency Dielectric Spectroscopy", in Proc. Power Engineering Society Summer Meeting, 2000. IEEE , Volume: 1, pp. 463 -468, 2000.

[8] C. Ekanayake, S. M. Gubanski, K. D. Mularachchi and M. A. R. M. Fernando, "Diagnostic of Power Transformers in Sri Lanka, Application of Dielectric Spectroscopy in Frequency Domain", in Proc. Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, 2001. pp. 593 -596, 2001.

[9] H. Edin, "Comparison Between Time Domain and Frequency Domain Methods for Dielectric Measurements on Oil Impregnated Cellulose", KTH Masters Diploma Work, ABB Corp. Res Report SECR/KH/TR-95/178E, 1995.

[10] F. L. Mopsik, "The Transformation of Time-Domain Relaxation Data into the Frequency – Domain", IEEE Trans. Electrical Insulation, vol. 20, no. 6, 1985, pp. 957-964.

[11] B. Nettleblad, " Effect of Moisture Content on the Dielectric Properties of Cellulose", in Proc. Nordic Insulation Symposium, NORD-IS'92, paper 8.9, 1992.

[12] T. K. Saha, P. Purkait, F. Mueller, "Deriving an Equivalent Circuit of Transformers Insulation for Understanding the Dielectric Response Measurements' – Accepted for publication in the IEEE Trans. Power Delivery, 2003.

[13] T. Leibfried and A. J. Küchler, "Insulation Diagnostics on Power Transformers using the Polarisation and Depolarisation Current (PDC) Analysis", in Proc. IEEE International Symposium on Electrical Insulation, USA, pp. 170-173, 2002.

[14] G. Mohamed and E. Németh, "Computer Simulation of Dielectric Processes", in Proc. 7th. International Symposium on High Voltage Engineering, Dresden, pp. 309-312, 1991.

[15] E. Németh and T. Horváth, "Fundamentals of the Simulation of Dielectric Processes of Insulations", in Proc. 8th. International Symposium on High Voltage Engineering, Japan, pp. 177-180, 1993.

[16] V. der Houhanessian and W. S. Zaengl, "Time Domain Measurements of Dielectric Response in Oil-Paper Insulation Systems", in Proc. IEEE International Symposium on Electrical Insulation, pp. 47-52, 1996.

[17] P. R. S. Jota, S. M. Islam and F. G. Jota, "Modelling the Polarisation in Composite Oil/Paper Insulation Systems", IEEE Trans. Dielectrics and Electrical Insulation, vol. 6, no. 2, pp.145-151, 1999.

[18] A. Küchler and T. Bedel, "Dielectric Diagnosis of Water Content in Transformer Insulation Systems", ETEP Trans., vol. 11, no. 1, pp. 65-68, 2001.

[19] G. Frimpong, U. Gafvert and J. Fuhr, "Measurement and Modelling of Dielectric Response of Composite Oil/Paper Insulation", in Proc. 5th International Conference on Properties and Applications of Dielectric Materials, vol. 1, pp. 86-89, 1997.

[20] U. Gafvert, G. Frimpong and J. Fuhr, "Modelling of Dielectric Measurements on Power Transforms", in Proc. CIGRE, Paris Session, Paris, Paper no. 15/103, 1998.

VIII. Biographies

Tapan K. Saha was born in Bangladesh and came to Australia in 1989. Dr. Saha is an Associate Professor 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 at James Cook University, 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.

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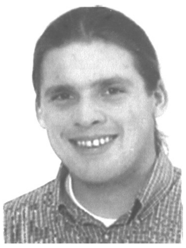

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