Open access • Journal Article • DOI:10.1080/1448837X.2005.11464126

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Tapan Kumar Saha, Richard H. Middleton, Andrew Thomas

Institutions: University of Queensland, University of Newcastle

Published on: 01 Jan 2005 - Australasian Universities Power Engineering Conference

Topics: Current transformer, Distribution transformer, Transformer, Frequency domain and Insulation system

Australasian Universities Power Engineering Conference (AUPEC 2004)

26-29 September 2004, Brisbane, Australia

Correlation between time and frequency domain polarisation measurements for transformer moisture assessment

T.K. Saha*, R. Middleton** and A. Thomas*

*School of Information Technology and Electrical Engineering
University of Queensland

** School of Electrical Engineering & Computer Science
University of Newcastle

Abstract

Preventative diagnosis and maintenance of transformers has become more popular in recent times in order to improve the reliability of electric power systems. A number of transformers have recently been tested using Return Voltage (RV) and Dielectric Dissipation Factor (tanδ) measurements in the time and frequency domain, respectively. This paper outlines a circuit model which describes the dielectric behaviour of the transformer insulation system and has been parameterised from the frequency domain data. This model was then used to simulate RV and Polarisation-Depolarisation current (PDC) results. Some recommendations about the diagnosis of the transformers have been proposed.

1. INTRODUCTION

The condition of oil/paper insulation systems in a transformer is degraded by the electrical, thermal and environmental stresses during its operation. Among these, moisture and ageing strongly influence the dielectric properties of the oil/paper insulation system in a transformer.

Time domain polarisation measurements and frequency domain spectroscopy (FDS) are examples of dielectric response measurements that have been used in recent times for the diagnosis of power transformers insulation condition. In time domain measurements-polarisation/depolarisation current [1, 2, 3, 4] and return voltage [5, 6] measurements have gained significant importance over the last several years. Frequency domain spectroscopy (FDS) is simply the measurement of dissipation factor (tanδ) over a frequency range of 1 mHz to 1 kHz. Though different research groups have been involved in independent development of time and frequency domain diagnostic tools separately, there has always been an urge to establish correlation between the two techniques for obtaining a more accurate 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 diagnostic techniques.

This paper reports development of an extended Debye model of an RC equivalent circuit of the insulation structure of transformers based on the low frequency (1mHz to 1 kHz) dielectric spectroscopy measurement conducted by the IDA200 equipment [7]. The model parameters have been identified using Matlab based software. Then the time domain parameters, such as polarisation/depolarisation currents and return voltage parameters have been estimated from the identified model components by using simple mathematical formulations.

A correlation has been attempted between the frequency-domain and time-domain results regarding diagnosis of the state of insulation. Simulation results have been supported with actual time domain field test results for a few transformers using the Tettex 5461 recovery voltage meter [8] to illustrate the correlation between time and frequency domain diagnostic techniques.

Finally some recommendations about the testing techniques have been proposed in this paper based on findings from these tests and their correlations.

2. THEORY

2.1 Time Domain Polarisation Measurements

If an insulation system with geometrical capacitance C_0 (measured capacitance at or near power frequency 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:

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

Once the step voltage is removed and the insulation system is shorted to ground, the depolarisation current can be written as:

$$i_{depol}(t) = -C_0 \cdot U_0 \cdot \left[f(t) - f(t + t_1) \right] \tag{2}$$

Where t_1 is the duration of the time during which the voltage has been applied to the test object. If the polarisation time is sufficiently long, so that $f(t+t_1)\approx 0$ the response function is assumed to be proportional to the depolarisation current. From (2) we can write (3).

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

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.

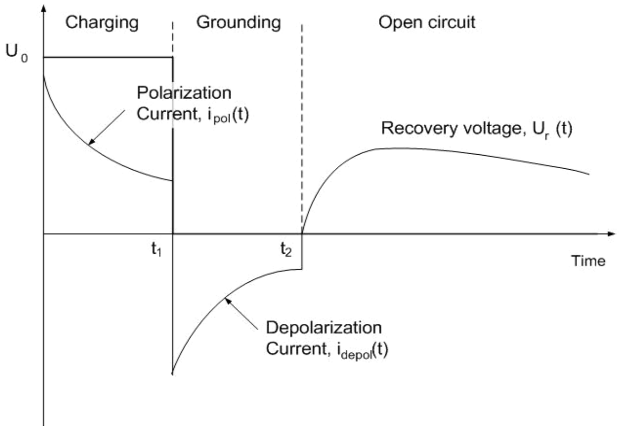

Fig. 1 Principle of polarisation/depolarisation current and RV measurement

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-t1, some of the previously polarised molecules get totally relaxed, but some do not. The polarisation processes, which were not totally relaxed during the grounding period, will relax and give rise to a recovery voltage across the electrodes of the insulation. Fig. 1 shows the nature of the polarization and depolarization currents and the recovery voltage. The test object is charged from $0 \le t \le t_1$, grounded from $t_1 \le t \le t_2$ and for $t > t_2$ the recovery voltage is measured during the open circuit condition.

2.2 Frequency Domain Polarization Measurements

This technique is a generalization of the capacitance and dielectric 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 is 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 (defined below in (7)) in relation to frequency, it is possible to distinguish between the different polarizations mechanisms in the frequency spectra.

When a sinusoidal voltage is applied across 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”.

$$\tan\delta = \frac{\text{Real part of Impedance}}{\text{Imaginary part of Impedance}} \tag{6}$$

The expression for the complex capacitance is given by (7):

$$C = \varepsilon \cdot \frac{A}{w} \tag{7}$$

Where A is the plate area of the capacitance, ε is the complex 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:

(8)

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

C’(ω) corresponds to the geometric capacitance, while the imaginary component C’’(ω) represents the dielectric loss component. The tangent of the loss angle δ is the dielectric dissipation factor and is given by (9).

$$\tan\delta = \frac{C'(\omega)}{C''(\omega)} \qquad (9)$$

2.3 Modelling of Transformer Oil-Paper Insulation using extended Debye Model

Over the last few years, several researchers [1-4, 9-14] 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 linear 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.

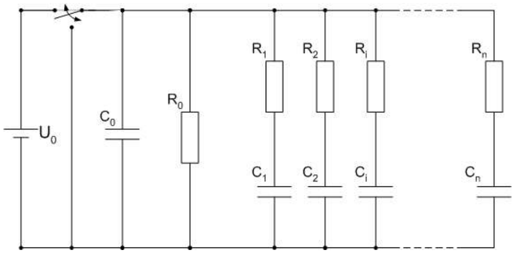

Fig. 2 Equivalent circuit to model a linear dielectric material

2.4 Relations between Time and Frequency Domains:

Information obtained in either frequency or time domain is theoretically equivalent if the dielectric material can be described as a linear system [15]. It then follows that relation as in (10) between the frequency and time domain responses is valid:

$$\chi(\omega) = \chi'(\omega) - j.\chi''(\omega) = \int_0^{\infty} f(t).e^{-j\omega}dt \qquad (10)$$

Where χ(ω) is the frequency dependent complex susceptibility and *f(t)* is the dielectric response function characterising the dielectric response characteristics of the material. If *f(t)* can be estimated from the depolarisation current measurement then equation (10) can be used for frequency domain analysis. The reverse problem can be solved as well if the frequency domain data is available. However, in both cases, analytical solutions are not achievable and different numerical techniques are available to solve such complex problems.

In this case, the conversion from frequency domain to time domain was performed by fitting the $\tan\delta$ versus frequency data to a linear transfer function, which was of a gain, zero, pole form. A least squares fit on this transfer function was then converted to an equivalent circuit model as shown in Fig. 2

Once the linear circuit was derived, the time domain responses could be simulated directly from analysis of the modelled RC circuit. Results of real time domain measurements could then be compared to these simulated results and the validity of the transfer from frequency to time domain could be tested.

3. TEST TRANSFORMERS

A number of transformers have been tested during the period of July-December 2003. In this paper, the results from three laboratory transformers are presented. Our measurements include-

- Frequency domain dielectric spectroscopy measurements
- Recovery voltage measurements

A summary of the details of the laboratory transformers is given below in Table 1.

Transformer Identity	KVA Rating	HV Rating (kV)	LV Rating (V)	Date of Manufacture
50 kV test Tx	5	50	240	Not known
100 kV GE Tx	100 (½ hour)	100	1200	Not known

Petersen Coil	765	66	550	1952

Table 1. Summary of tested transformers

3.1 Measurement Systems

Frequency domain dielectric spectroscopy equipment IDA200 [20] was used to measure complex capacitance and dielectric dissipation factor (tanδ) over a frequency range of 1 mHz to 1 kHz. A sinusoidal voltage is applied to the specimen and the response current is measured, enabling the calculation of a complex impedance and thus the dissipation factor. The red, HI connection was connected to the HV terminals of the test object and the blue; LO connection was connected to the LV terminals of the test object. The box earth was connected to the tank of the test object and the guard terminal was connected to the tank of the test object.

Recovery Voltage was measured using a Tettex 5461 RV meter [8]. For the RV measurements, all HV terminals were shorted and all LV terminals shorted with the LV terminals also grounded. A range of charging times were applied to the test specimens during the test. For each of these charging times the instrument performed a number of operations. A DC voltage was applied to the HV terminals for the predetermined charging time, after which the HV and LV terminals were shorted for half the charging time, then an open circuited was applied across the terminals and the recovery voltage was measured.

3.2 Test Results

Frequency Domain Measurements:

Fig. 3 shows the loss factor measurement in the frequency domain for the Petersen Coil. It also shows the simulated loss factor curve based on the equivalent RC circuit model. Summary results from the frequency domain measurements are shown in Table 2.

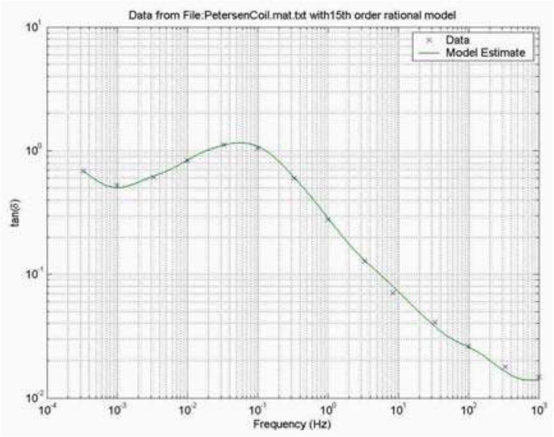

Figure 3: Tanδ versus frequency measurement of the Petersen Coil

As can be seen from the above figure, the match between the simulated and measured data is good. This is also the case for the rest of the tested transformers and gives confidence in the equivalent RC model.

Transformer Identity	Max. Tanδ	Frequency at max Tanδ	Min. Tanδ	Frequency at min Tanδ
50kV Tx	5.42	0.00033	0.0057	1000
100kV GE Tx	1.82	0.001	0.0122	1000
Petersen Coil	1.1174	0.033	0.0148	1000

Table 2. Summary of frequency domain measurements

In our previous study, the findings suggest that the loss tangent has a minimum, which tends to increase with moisture content in similar fashion as the loss part of complex permittivity [16].

The relation between moisture and the minimum of the loss tangent is shown in [16], where the measured minima of the loss tangent are correlated to the respective moisture contents by an exponential function as shown in (11).

$$Y = m_1 + m_2 e^{(m_3 \times M_o)} \qquad (11)$$

Where, m_1=0.0021822, m_2=0.00074104, m_3=0.67344 and M_o is the percentage moisture level.

Using (11) the moisture contents where calculated for the tested transformers. The results can be seen in Table 3.

Transformer Identity	Minimum Tanδ	Moisture % (Approx.)
50 kV test Tx	0.0057	2.3
100 kV GE Tx	0.0122	3.9
Petersen Coil Tx	0.0148	4.2

Table 3. Moisture content estimation for tested transformers

Time Domain Measurements:

Recovery voltage measurements were also performed on the above transformers to compare the simulated time domain response from the equivalent circuit model to the actual time domain response. The measured and simulated results for the Petersen coil are shown in Figure 4.

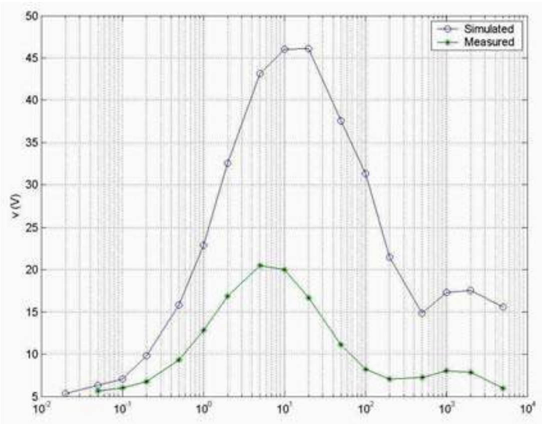

Figure 4: Maximum return voltage versus charging time of the Petersen Coil, measured and simulated

Normally the charging time to peak of the maximum RV voltage varies significantly for transformers with different moisture and ageing conditions. For example, for a very dry transformer, this time could be several hundred to several thousand seconds and this becomes seconds to tens of seconds for a moist and aged transformer.

As can be seen from Fig. 4, the magnitude of the simulated curve is much too large to be classed as an accurate comparison. However, it can be seen that the central time constant (time to reach the maximum RV peak) is practically the same for both the measured and simulated curves. This was also the case for the rest of the tested transformers.

From the simulation, it is clear that a non-linear effect may be involved. To test this, a number of RV measurements were conducted on the Petersen coil at varying voltages. Figures 5-7 show these measurements with the data normalised by the charging voltage.

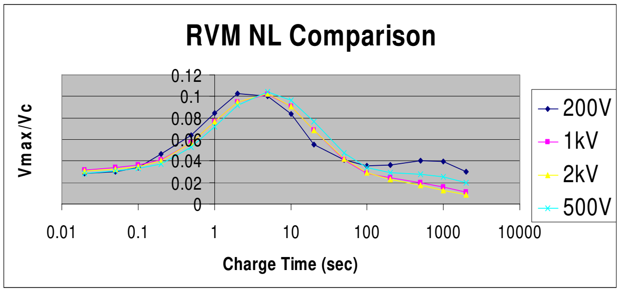

Figure 5: RV maximum value versus charging time for different charging voltage (Data was normalised by dividing the max values by the corresponding charging voltage).

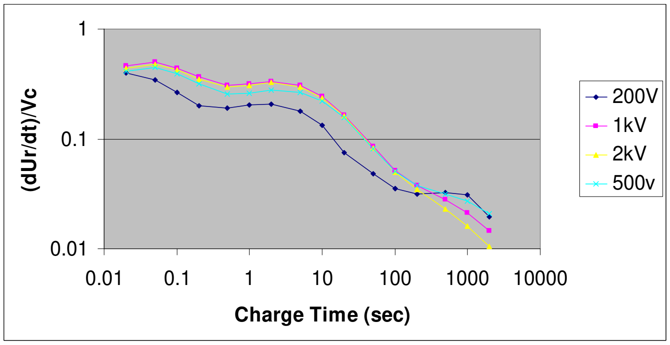

Figure 6: Initial slopes versus charging time for different charging voltage (normalized with charging voltage).

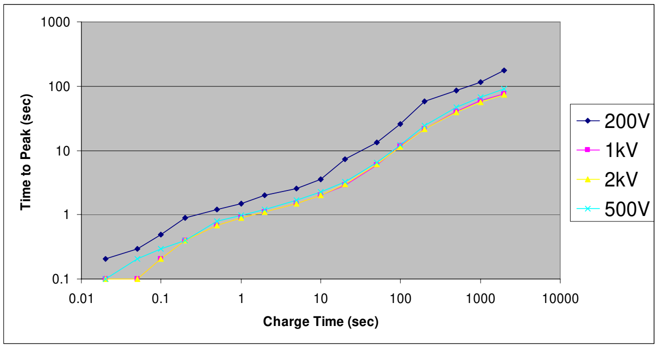

Figure 7: Time to peak versus charging time for different charging voltage

Figures 5-7 suggest that 200 Volt charging produces significantly different results than those produced by 500-2000 volts. In all cases, simulated RV maximum values are significantly higher than the measured value. It is worthwhile to mention that frequency domain dielectric spectroscopy was performed at 200 Volt while the return voltage measurements were performed at 2kV. This suggests that while comparing results from one measurement scheme to another, extra care must be taken to understand the effects of applied voltage, measurement configuration and environmental (temperature humidity etc) conditions.

4. CONCLUSIONS AND DISCUSSIONS

Time and frequency domain measurements were performed on three laboratory based transformers. From the loss factor measurements in the frequency domain, an RC circuit was derived to simulate the insulation properties. The actual loss factors and the simulated loss factors showed good matches, giving confidence in the accuracy of the equivalent RC circuit. However when the time domain measurements were simulated with the same circuit, discrepancies were found between the simulated data and the measured data, particularly in the magnitude of the maximum return voltages.

This lead to the possibility that non-linear factors may be at play. Further tests were conducted on the Petersen coil at different charging voltages to investigate. The resulting measurements showed that the response from a lower charging voltage (200V) differs significantly from larger charging voltages (500-2000V). Further investigation is needed to determine the origins of this effect. Research in this field is continuing and further findings will be reported in future papers.

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6. Acknowledgements

The authors would like to take this opportunity to thank Connell Wagner Advanced Technology Centre at Newcastle for their support with the measurements during July-December 2003.