Abstract—This paper presents both quantitative and qualitative analysis of several polarization based measurements, which include frequency domain spectroscopy (FDS) and polarization depolarization current (PDC) measurements on four different field transformers. The X-Y [1] model and the RC circuit model [2] are mainly used in the analyses. In this study sequential FDS/PDC measurements on the same unit are used to identify the progressive change of the insulation condition. Influence of oil conductivity and geometrical parameters on the estimates from FDS response is shown in detail. Based on this study a simple technique to improve the reliability from FDS measurement is discussed. Influence of the oil refurbishment process on polarization based measurements is also presented and discussed.

Index Terms— Frequency domain spectroscopy, insulation ageing, insulation response modeling, oil conductivity, moisture estimation, polarization depolarization current, transformer insulation

I. INTRODUCTION

In the recent past more attention has been directed to assessment of condition of power transformers as they are the most expensive single unit in a power transmission system. Furthermore, considerable numbers of transformers in operation around the globe are aged beyond their design lives [3]. Consequently, several new techniques for transformer condition monitoring have been developed during recent years. Out of these techniques, polarization based measurements are widely accepted by many utilities due to the advancement in hardware and software interpretation schemes. Also these techniques are useful to estimate moisture in insulation with reasonable accuracy.

Return voltage measurement (RVM) was the first polarization based insulation diagnosis technique introduced in the early ‘90s [4]. RVM determines the polarization spectrum (intensity of the elementary processes as a function of their relaxation time constant or central time constant) in polarization time constant domain of $10^2$ to $10^4$ seconds. Several studies have been presented with the application of RVM to estimate moisture in transformer insulation [5, 6]. Several studies have also been reported to identify the reliability and accuracy of RVM interpretation schemes. It has been identified that established RVM interpretation schemes based on the polarization spectrum often over estimates the moisture content [7]. Moreover, several methodologies have been proposed to improve the reliability of the RVM interpretation schemes [8, 9]. Nevertheless none of these improved interpretation schemes are available with commercially available instruments.

Polarization and depolarization current (PDC) measurement is the other time domain polarization based technique. PDC through the main insulation (insulation between HV and LV) due to a constant voltage is used to assess the insulation condition. Commercially available as well as locally manufactured PDC measuring systems have been used in different studies [10, 11]. Modeling PDC data with circuit parameters is one of the most common techniques utilized in insulation condition assessment [2]. It has been widely accepted that a change in oil conductivity and moisture in the insulation has an immense effect on the elements of the RC circuits. PDC analysis has also been further strengthened by measurements on models and well controlled impregnated paper/pressboard insulation samples [12]. In field applications, eliminating the influence of noise current is one of the key issues associate with PDC measurements.

Frequency domain spectroscopy (FDS) measurement is the frequency domain application of dielectric polarization response measurement. In the FDS technique a known sinusoidal voltage is applied across the transformers’ main insulation and the corresponding current is measured. The measurement is repeated at several pre-defined frequencies. Generally these measurements are carried out from high frequency to low frequency to reduce any memory effects. The usual measurement time for a cycle of FDS measurement could be up to four times the length of the period of the lowest frequency [13]. Numerous studies performed on field application of FDS measurements have revealed that measurement between HV to LV is least affected by different external factors such as bushing conditions, connection configurations and weather conditions [14]. Modeling the FDS response has also been widely discussed. The X-Y model presented in [1] is the most common modeling technique used in most of the real applications, this is mainly due to its simplicity. A combination of X-Y model and FDS measurements on well controlled impregnated
paper/pressboard samples has been widely used to estimate the moisture in transformer insulation [15].

Study presented in this paper is focused on the measurements and analysis of PDC and FDS data from four different transformers. In certain cases polarization measurements on the same unit was performed at various occasions. The X-Y model analysis system developed by the first author [16] and an expert system developed by the second author [6] of this paper are used in the analyses. An effort has been taken to check the reliability of dielectric response data analysis techniques by comparing estimates from different techniques and comparing estimates of moisture/ageing at different occasions of the same unit. The influence of geometry and oil conductivity on estimates from X-Y model is closely studied. This paper also discusses the influence of oil refurbishment on moisture estimates based on FDS measurements.

This paper is structured as follows. Section II covers the theory behind polarization based measurements. It elaborates how PDC and FDS measurements can be used to calculate material properties such as conductivity and permittivity. Different measurement systems used in the presented study for FDS and PDC measurements are explained in section III. The connection configuration adopted during measurements on transformers is also discussed here. Section IV presents details of the transformers studied. Measurement information such as voltage, frequency, time and year of measurement is also shown in this section. Section V presents the results and analysis of the measured data followed by the conclusion in section VI.

II. THEORY ON ANALYSIS OF POLARIZATION BASED MEASUREMENTS

A. Time domain current measurements [2, 6, 10, 16]

Slow polarization processes in a dielectric material can be analyzed using polarization and depolarization current measurements. When a fixed dc voltage ($U_0$) is applied across a completely discharged material the resultant polarization current due to conduction and slow polarization processes can be written as,

$$I_{pol}(t) = \left(\frac{\sigma}{\varepsilon_0} + f(t)\right) C_0 U_0 \text{ for } 0 < t < t_0$$  \hspace{1cm} (1)

$C_0$ is the geometrical capacitance of the insulation. $f(t)$ is a monotonically decreasing function, known as dielectric response function.

Immediately after removing the applied voltage at time $t_0$ if the dielectric is externally short circuited there will be a current flow through the insulation due to re-orientation of the polarized species in the dielectric and it is called depolarization current. This current can be expressed as,

$$I_{depol}(t) = \left[-f(t) - f(t + t_0)\right] C_0 U_0 \text{ for } 0 < t < \infty$$  \hspace{1cm} (2)

If the dielectric is charged for a sufficiently long time effect of $f(t + t_0)$ on (2) can be neglected. As a result $f(t)$ can be calculated as,

$$f(t) = \frac{I_{depol}(t)}{C_0 U_0}$$ \hspace{1cm} (3)

Also conductivity of the insulation can be calculated as,

$$\sigma = \frac{\varepsilon_0}{C_0 U_0} \left[I_{pol}(t) + I_{depol}(t)\right]$$ \hspace{1cm} (4)

Both $f(t)$ and $\sigma$ are useful to identify the condition of the insulation as they are affected by the ageing by products. Equations (3) and (4) elucidate that geometrical capacitance should be known to calculate the $f(t)$ and $\sigma$ using PDC measurements.

In this paper PDC data was analyzed using an equivalent circuit model where dielectric response of the insulation is modeled with R and C circuit elements as shown in Fig. 1. The method of evaluating model parameters can be found in [2]. These model parameters were used in the developed expert system [6] for estimating moisture content and oil/paper conductivity. In this analysis it is assumed that dielectric response is linear.

![Fig. 1. RC equivalent circuit to model the transformer insulation response](image)

B. Frequency domain measurements [1, 13, 16]

Frequency dependent complex permittivity of a dielectric material can be obtained by measuring magnitude and phase of current due to a sinusoidal excitation. The resultant current due to sinusoidal voltage of $U^*(\omega)$ at an angular frequency $\omega$ can be written as,

$$I^*(\omega) = j\omega C_0 \left[\varepsilon'(\omega) - j\varepsilon''(\omega)\right] U^*(\omega)$$

$$= j\omega C 0 \left[\varepsilon'(\omega) - jC'(\omega)\right] U^*(\omega)$$ \hspace{1cm} (5)

Here $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are the real and imaginary components of complex permittivity. $C(\omega)$ and $C'(\omega)$ are the frequency dependent capacitance and loss of the insulation.

Both $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are useful to identify the current state of the insulation. However as seen in (5), to extract these parameters from FDS measurements geometrical capacitance of the insulation should be known.

Furthermore, if FDS measurement is performed on non-polar dielectric material such as mineral oil, losses in the insulation is mainly caused by the conduction. Also permittivity of the material is non-dispersive over a wide frequency interval. As a result (5) can be further simplified as,

$$I^*(\omega) = \frac{j\omega C_0}{\varepsilon_0} \left[\varepsilon'(\omega) - j\frac{\sigma}{\varepsilon_0}\right] U^*(\omega)$$ \hspace{1cm} (6)
This enables us to calculate permittivity and oil conductivity using FDS measurements when $C_0$ is known.

Transformer insulation is a complex combination of oil and paper. To analyze the response of it, a simplified model namely X-Y model can be used [1]. Fig. 2 illustrates the X-Y model. Here, assuming a linear response of insulation system all paper and oil layers are combined together to form the model. In the presented study, X-Y model analysis was done as described in [16]. In the used technique a best fit between a model curve based on measurements of well defined samples and the measured response of transformer estimates moisture content, oil conductivity, geometrical capacitance and oil to paper ratio in the insulation. When a few of the parameters are known those parameters could be fixed in the adopted fitting procedure.

III. MEASUREMENT SYSTEMS AND CONNECTION CONFIGURATIONS

A. PDC measurements [11]

The PDC measurements were carried out by equipment designed and developed by the researchers at the University of Queensland. This system comprises of an Electrometer (Keithley 6571A), four high voltage relays, a power control interface for relay controlling and a laptop computer with GPIB Card. The control software was developed in the Labview environment which enables the operator to record voltage and currents automatically during PDC measurements. RVM can also be performed with the same measuring setup. Fig. 3 shows the schematic diagram of the PDC test setup.

![Fig. 3. Schematic diagram of PDC measurement setup](image)

Relay and protection systems are arranged and controlled in such a way that all transient currents bypass the electrometer. A 2 kΩ resistor is used to avoid high current through the electrometer during a possible low impedance faulty connection. The arrangement of 4 relays and current limiting resistor is illustrated in Fig. 4.

![Fig. 4. Relay arrangement for PDC measurements and electrometer protection](image)

B. FDS measurements [17]

FDS measurements were performed using commercially available equipment-IDA 200. This system allows measuring the frequency response of insulation between 0.1 mHz to 1 kHz at a desired voltage level up to 200 Vpeak. However, during field measurements the lowest frequency measured was 1 mHz, this was due to time constraints.

C. Measurement configuration

Measurement between HV and LV allows collecting FDS/PDC response of a transformer main insulation. Furthermore, in previous studies it has been identified that measuring capacitance between HV and LV (CHL) is least affected by external factors [14]. However in certain circumstances, such as in an auto transformer, winding configuration does not support CHL measurements. As a result, if a tertiary winding exists measurement between the tertiary winding and the short circuited HV and LV (CTH) is the most appropriate measurement for an auto transformer. In the study presented here both CHL and CTH were carried out where it is appropriate. During measurements on three phase units all terminals of each set of windings are separately short circuited.

FDS measurements were performed as the first measurement whenever both FDS and PDC had to be carried out. This minimizes the memory effect due to possible residual charges, which may remain in the insulation system after completing the first measurement.

IV. TRANSFORMERS UNDER STUDY

Analyses of polarization based measurements on two different types of transformers are presented in this paper.

A. Transformer Type A

Three transformers are categorized under Type A. Details of these three phase units are given in Table I.

<table>
<thead>
<tr>
<th>ID</th>
<th>Power (MVA)</th>
<th>Voltage (kV)</th>
<th>Year of manufacture</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>31.5</td>
<td>132/33</td>
<td>1986</td>
<td>X</td>
</tr>
<tr>
<td>A2</td>
<td>31.5</td>
<td>132/33</td>
<td>1986</td>
<td>X</td>
</tr>
<tr>
<td>A3</td>
<td>31.5</td>
<td>132/33</td>
<td>1999</td>
<td>Y</td>
</tr>
</tbody>
</table>

All three transformers were installed at the same substation owned by the Ceylon Electricity Board, Sri Lanka. Historical data revealed that none of these units were overloaded during normal operation. As can be seen in the Table I, A1 and A2 are two identical units. Power and voltage ratings of A3 are equivalent to those of A1 and A2. However its insulation geometry could be different from the other two units as it is from a different manufacturer.

Several FDS measurements with CHL configuration were performed on these three units. Detail of each measurement is shown in Table II. As shown in Table II the lower frequency limit of the measurements were always at 1 mHz. This
allowed completion of each measurement cycle within a 2 hour period.

Table II

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Measurement ID</th>
<th>Year of Measurement</th>
<th>Temperature (°C)</th>
<th>Peak Voltage (V)</th>
<th>Freq. span (Hz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A1.1</td>
<td>2003</td>
<td>50</td>
<td>100</td>
<td>2 m – 1 k</td>
<td>Measured before oil refurbishment</td>
</tr>
<tr>
<td></td>
<td>A1.2</td>
<td>2003</td>
<td>26</td>
<td>100</td>
<td>4 m – 1 k</td>
<td>Measured after about 10 days of oil refurbishment</td>
</tr>
<tr>
<td></td>
<td>A1.3</td>
<td>2007</td>
<td>53</td>
<td>100</td>
<td>1 m – 1 k</td>
<td>-----</td>
</tr>
<tr>
<td></td>
<td>A1.4</td>
<td>2008</td>
<td>30</td>
<td>100</td>
<td>1 m - 100</td>
<td>Measured before oil refurbishment.</td>
</tr>
<tr>
<td></td>
<td>A1.5</td>
<td>2008</td>
<td>51</td>
<td>100</td>
<td>1 m - 100</td>
<td>Measured about 20 days after re-energizing</td>
</tr>
<tr>
<td>B1</td>
<td>B1.1</td>
<td>2005</td>
<td>25</td>
<td>1000</td>
<td>10000</td>
<td>PDC measurements</td>
</tr>
<tr>
<td></td>
<td>B1.2</td>
<td>2009</td>
<td>29</td>
<td>200</td>
<td>1 m – 1 k</td>
<td>FDS measurements</td>
</tr>
<tr>
<td></td>
<td>B1.3</td>
<td>2009</td>
<td>29</td>
<td>500</td>
<td>5000</td>
<td>PDC measurements</td>
</tr>
</tbody>
</table>

Table III

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Power (MVA)</th>
<th>Voltage (kV)</th>
<th>Year of manufacture</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>220</td>
<td>275/110</td>
<td>1972</td>
<td>P</td>
</tr>
<tr>
<td>B1</td>
<td>220</td>
<td>275/110</td>
<td>1972</td>
<td>P</td>
</tr>
</tbody>
</table>

Table IV

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Measurement ID</th>
<th>Year of Measurement</th>
<th>Temperature (°C)</th>
<th>Peak Voltage (V)</th>
<th>Freq span (Hz)/Charging/discharging time(s)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B1.1</td>
<td>2005</td>
<td>25</td>
<td>1000</td>
<td>10000</td>
<td>PDC measurements</td>
</tr>
<tr>
<td></td>
<td>B1.2</td>
<td>2009</td>
<td>29</td>
<td>200</td>
<td>1m – 1 k</td>
<td>FDS measurements</td>
</tr>
<tr>
<td></td>
<td>B1.3</td>
<td>2009</td>
<td>29</td>
<td>500</td>
<td>5000</td>
<td>PDC measurements</td>
</tr>
</tbody>
</table>

Both FDS and PDC measurements were performed on unit B1. Details of each measurement are presented in Table IV.

V. RESULTS AND DISCUSSION

A. FDS response of equivalent transformers

Frequency dependent capacitance and loss obtained from the measurements of A1.1, A2.1 and A3.1 are illustrated in Fig. 5.

As expected, Fig. 5 (a) shows that high frequency capacitances of all three units are similar. This indicates that even though unit A3 is not identical to A1 and A2, its overall geometrical capacitance is similar to A1 and A2. Slight deviation between A1.1 and A2.1 in both capacitance and loss indicates oil conductivity of A2 should be slightly higher than that of A1.

One can clearly see that both loss and low frequency capacitance of A3 are significantly lower than that of A1 and A2. Hence it can be concluded that insulation of both A1 and A2 are significantly aged compared to that of A3. This statement is further supported by the results from X-Y model analysis of A1.1, A2.1 and A3.1. The estimated moisture content in paper and oil conductivities are presented in Table V.

Table V

<table>
<thead>
<tr>
<th>Transformer ID</th>
<th>Moisture content (%)</th>
<th>Oil conductivity (pS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1</td>
<td>1.9</td>
<td>127</td>
</tr>
<tr>
<td>A2.1</td>
<td>1.8</td>
<td>150</td>
</tr>
<tr>
<td>A3.1</td>
<td>0.2</td>
<td>0.81</td>
</tr>
</tbody>
</table>

B. FDS response of non-equivalent units

Absolute capacitance and loss of transformer insulation is dependent on the geometrical capacitance. As a result, the use of capacitance and loss to compare the condition of two units may lead to a wrong conclusion. In such a situation loss factor, which is the ratio between absolute loss and capacitance is more suitable for the comparison. Fig. 6 illustrates the frequency dependent loss (C") and frequency dependent loss factor corresponds to measurements A1.2 and B1.2.
According to Fig 6(a) absolute losses of both transformers are similar. However, loss factor indicates that insulation of B1 is better than that of A1. This was further revealed by the corresponding X-Y model estimates presented in Table VI.

### TABLE VI

**ESTIMATED MOISTURE CONTENT AND OIL CONDUCTIVITY FROM FDS MEASUREMENTS OF A1.2, AND B1.2**

<table>
<thead>
<tr>
<th></th>
<th>A1.2</th>
<th>B1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (%)</td>
<td>2.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Oil conductivity (pS/m)</td>
<td>48</td>
<td>12.7</td>
</tr>
</tbody>
</table>

C. Effect of oil refurbishment on FDS response

During the presented study both A1 and A2 underwent oil refurbishments on two occasions. On both occasions FDS measurements were performed before and after the oil refurbishment process.

Fig. 7 presents the frequency dependent loss factor of unit A2 before and after its 2nd oil refurbishment. It is clearly seen that the spectral shape of the measured response has been significantly altered after oil refurbishment. One possible reason for this could be the non-equilibrium conditions of the transformer insulation. It is expected that during oil refurbishment some of the moisture residing inside the solid insulation was driven to the insulation surface, part of which was taken away by the oil and removed from the transformer insulation. Nevertheless, when the refurbishment process is complete, still considerable amounts of moisture could be trapped on the insulation surface which could affect the interfacial polarization mechanism which appeared during subsequent FDS measurements. Therefore estimated moisture content and oil conductivity from measurements taken after oil refurbishment could be different from the actual values.

A similar variation of response measurements were observed during other measurements carried out before and after oil refurbishment. Results of these FDS measurements were analyzed with X-Y model and corresponding estimates are given in Table VII.

Data shown in Table VII indicates that in some cases oil conductivity is higher after oil refurbishment. One possible reason for this could be a wrong estimation of FDS analysis due to non-equilibrium conditions in the insulation. Results of unit A2 during the 2nd oil refurbishment clearly demonstrate this situation. It shows that estimated oil conductivity from the measurement taken after about 8 days of operation is almost two times higher than the initial oil conductivity, which is not realistic.

These results show that after oil refurbishment, polarization based measurements can only be used effectively after the transformer insulation attains a reasonable equilibrium state.

D. Analysis of sequential FDS measurements

FDS measurements obtained within one month after oil refurbishment is not considered in this section. Measured loss factor of transformer A1 and A2 in three different years are presented in Fig. 8.
Data presented in Fig 8(a) indicates that loss factor of unit A1 is increasing moderately over the considered five year period. However, these measurements were performed at different temperature levels varying from 30 – 50 °C. Consequently further analysis was done using previously developed transformer insulation diagnostic software based on X-Y model [16]. This software estimates moisture content, oil conductivity and geometrical parameters (X, Y and C0) by achieving the best fit between a modeled curve and the measured response.

During this analysis it has been identified that modeled geometrical parameters for the same unit from different measurements are not identical, which is practically impossible. Hence X and Y were kept constant and performed the second analysis, results of which are shown within the parenthesis. Here, X and Y obtained from analysis of A1.1 (X=12% & Y=30%) are taken as the reference for the second analysis, results of which are shown within the parenthesis. Here, X and Y obtained from analysis of A1.1 (X=12% & Y=30%) are taken as the reference values. Results of both analyses are given in Table IX.

**TABLE IX**

<table>
<thead>
<tr>
<th>Moisture content (%)</th>
<th>Conductivity at 30 °C (pS/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1 12% 30%</td>
<td>1.9 49</td>
</tr>
<tr>
<td>A1.3 17% 19%</td>
<td>3 (2.8) 64 (71)</td>
</tr>
<tr>
<td>A1.4 21% 28%</td>
<td>4 (3.5) 72 (77)</td>
</tr>
<tr>
<td>A2.1 8% 39%</td>
<td>1.7 (1.8) 81 (58)</td>
</tr>
<tr>
<td>A2.3 14% 30%</td>
<td>1.8 (1.7) 41 (41)</td>
</tr>
<tr>
<td>A2.4 15% 10%</td>
<td>2.8 (2.9) 62 (74)</td>
</tr>
</tbody>
</table>

* Values estimated when X = 12% and Y = 30% are presented in brackets

Results presented in Table IX elucidates that in five cases estimated moisture content from auto fitting and fixed X,Y are similar, whereas oil conductivity has been significantly affected by the change of X,Y. Based on this study one can conclude that the reliability of moisture estimates by FDS could satisfactorily be improved if oil conductivity is known. X and Y can be estimated if oil conductivity is known for a particular FDS measurement on a transformer. Thereafter those estimated X and Y can be used as the reference for the same unit in future analysis. These criteria will help to reduce the number of unknowns and as a result improve the reliability of estimated quantities.

Estimated moisture contents shown in Table IX shows that moisture content in the solid insulation of both transformers are continuously growing. Two oil purification processes followed were not useful to control the increasing moisture in the solid insulation.

**E. Analysis of sequential PDC measurements**

B1.1 and B1.3 are the two sequential PDC measurements presented in this study. Fig. 9 illustrates the measured polarization and depolarization currents after normalizing for applied voltage.

According to Fig. 9, after 4 years polarization current has increased. Similar conditions are observed with depolarization currents. This implies a higher deterioration of the insulation during the time in between two measurements.

For further studying of this data, PDC analysis software developed by the second author is utilized [6]. This software allowed deriving the Return Voltage (RV) spectrum, using the measured PDC. The RV spectrum and the PDC results were used to estimate the oil and paper conductivities. Apart from PDC data the test voltage and geometrical capacitance details are also required for these calculations. The estimated conductivities of oil and paper are shown in Table X.

One can observe that during the last four years paper conductivity has been increased by about 6 times. Similarly oil conductivity has been increased by more than 3 times. However, this increase is due to both ageing and temperature differences during two measurements. Studies on temperature dependency of oil conductivity have revealed that the increase of conductivity due to temperature change from 25 °C to 29 °C is only about 1.2 times [16]. Therefore these comparisons clearly show that transformer insulation has degraded during the last four years.
The derived RV spectrum is also useful to estimate the moisture content in insulation. The estimated moisture content is also shown in Table X. As shown in Table X moisture content has been increased by about 0.5 % over the last four years. This may be due to further ageing of the solid insulation.

As this unit has been in operation for more than thirty years the conditions observed are not critical for the operation of this unit. However, it needs closer observation if the transformer is used to its full capacity.

F. Comparison of FDS and PDC results

B1.2 is the FDS measurement performed on transformer B1 before carrying out the measurement B1.3 on the same unit.

Measured capacitance and dielectric loss as a function of frequency are shown in Fig. 10. These measured results were used to estimate the moisture content in paper and oil conductivity of oil using the X-Y model software. The estimated modeled parameters are shown in Table XI.

![Image of Fig. 10: Variation of capacitance and loss of the transformer B1 with frequency](image)

Estimates of FDS results reveal that moisture content in this unit is slightly below 2 % while PDC results estimates it as 2.5 %. Oil conductivities estimated by two techniques are different, in the range 6-12 pS/m. The conductivity of an insulation system varies in the order of tens for a significant variation of the condition. Hence these minor variations can be due to different voltage levels used in the techniques utilized if the system behaves non-linearly in the considered voltage range. Another reason for these mismatches could be the deviations in the databases used in two different systems. However, both techniques show that moisture content should be around 2%, which could result further ageing of the insulation during the operation.

<table>
<thead>
<tr>
<th>Table X</th>
<th>ESTIMATED OIL AND PAPER CONDUCTIVITIES AND MOISTURE CONTENT FROM PDC MEASUREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005 (25°C)</td>
<td>2009 (29°C)</td>
</tr>
<tr>
<td>Paper conductivity (pS/m)</td>
<td>0.03</td>
</tr>
<tr>
<td>Oil conductivity (pS/m)</td>
<td>1.84</td>
</tr>
<tr>
<td>Moisture in paper (%)</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table XI</th>
<th>ESTIMATED PARAMETERS FROM FDS MEASUREMENTS ON B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated parameter</td>
<td>Value</td>
</tr>
<tr>
<td>Moisture in paper/pressboard (%)</td>
<td>1.8</td>
</tr>
<tr>
<td>Oil conductivity (pS/m)</td>
<td>12.7</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

In this paper analysis of several FDS and PDC measurements on field installed transformers are presented. It has been shown that comparison of capacitance and absolute loss of equivalent units are useful to identify the relative state of the transformer insulation, whereas comparing the loss factor is meaningful for non-equivalent transformers. The presented quantitative analysis of FDS response through X-Y model shows that geometrical parameters and oil conductivity is always interlocked. As a result known oil conductivity could be used to model the geometrical parameters of the insulation. Moreover, it has been identified that polarization based measurements are strongly affected by non-equilibrium conditions in transformers, especially after performing oil refurbishment.

Comparison of the results from PDC and FDS shows that estimated moisture content from both techniques are not equal but reasonably close.

Finally, the presented study shows the ability of polarization measurement techniques to identify the current status of transformer insulation through appropriate quantitative and qualitative analyses.

VII. ACKNOWLEDGMENT

Authors would like to acknowledge Ceylon Electricity Board (CEB) in Sri Lanka and Chief Engineer Mr. Rohana Ekanayake for providing transformers to carryout FDS measurements. Department of Electrical and Electronic Engineering University of Peradeniya, Sri Lanka are also highly acknowledged for providing required instrumentation in field measurements. Our sincere thanks to the utility in Australia, which allowed us to perform polarization based measurements on their transformers. Finally acknowledgements are due to Australian research Council for supporting this work through an ARC Linkage Grant.

VIII. REFERENCES


IX. BIographies

Chandima Ekanayake (M’00) received his B.Sc.Eng.(Hons) in 1999 from University of Peradeniya. He obtained his Tech. Lic. and PhD from Chalmers University of Technology Sweden in 2003 and 2006 respectively. Currently he is a research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Brisbane, Australia. Before joining UQ he was attached to the department of Electrical and Electronic Engineering, University of Peradeniya Sri Lanka as a Senior lecturer. He was the Chair of IEEE Sri Lanka Section in year 2006 and 2007. His research interests are condition monitoring of power apparatus, Alternatives for insulating oil, transient studies on power systems and energy related studies.

Tapan Kumar Saha (M’93, SM’97) was born in Bangladesh in 1959 and immigrated to Australia in 1989. He received his B. Sc Engineering (electrical and electronic) in 1982 from the Bangladesh University of Engineering & Technology, Dhaka, Bangladesh, M. Tech (electrical engineering) in 1985 from the Indian Institute of Technology, New Delhi, India and PhD in 1994 from the University of Queensland, Brisbane, Australia. Tapan is currently Professor of Electrical Engineering in the School of Information Technology and Electrical Engineering, University of Queensland, Australia. Previously he has had visiting appointments for a semester at both the Royal Institute of Technology (KTH), Stockholm, Sweden and at the University of Newcastle (Australia). He is a Fellow of the Institute of Engineers, Australia.

His research interests include condition monitoring of electrical plants, power systems and power quality.

Hui Ma (M’95) was born in Xi’an, China. He received his B.Eng and M.Eng degrees from Xi’an Jiaotong University, China in 1991 and 1994, M.Eng (research) degree from Nanyang Technological University, Singapore in 1998, and Ph.D. degree from the University of Adelaide, Adelaide, Australia in 2008. Currently he is a research fellow in the School of Information Technology and Electrical Engineering, the University of Queensland, Australia. Prior to joining the University of Queensland, he has many years research and development experience. From 1994 to 1995, he was a researcher in Xi’an Jiaotong University. China. From 1997 to 1999, he worked as a firmware development engineer in CET Technologies Pte. Ltd., Singapore. He was with Singapore Institute of Manufacturing Technology as a research engineer from 1999 to 2003. His research interests include industrial informatics, condition monitoring and diagnosis, wireless sensor networks, sensor signal processing, and power system.

David Allan (SM’00) received his Doctor of Engineering (Higher Doctorate) from the University of Queensland in 1998. Previously he obtained his Master of Engineering (1991), Bachelor of Economics(1968) and Bachelor of Engineering (1963) all from the University of Queensland. He is an adjunct professor at the University of Queensland. Currently he is the manager, Research & Development in Powerlink Queensland (Queensland Transmission Network Service Provider). For the last several years he has been responsible for managing Powerlink’s R&D program. Prior to this role he held a range of professional and management positions in the electricity supply industry over a career spanning 40 years in total. These ranged from grid planning engineer to substation maintenance engineer to manager of HV and light current testing laboratories and a transformer repair workshop. However, the larger part of his career has been associated with the testing, condition monitoring and life assessment of electrical plant and in research into new techniques in these fields.