Investigations of Temperature Effects on the Dielectric Response Measurements of Transformer Oil-Paper Insulation System

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***Abstract*—Dielectric testing techniques, in both time and frequency domains, are currently widely used by power utilities for assessment of the condition of transformer oil-paper insulation systems. However, it has been reported that results of these tests are highly influenced by the operating temperature during measurements. The distribution, migration and equilibrium of moisture between oil and paper in a complicated insulation system is highly temperature dependent. It requires adequate experience and proper understanding to interpret the dielectric response results in the presence of temperature variations and thermal instability. Proper analysis of the dielectric test result is only possible with an understanding of the physical behavior of the insulation system in response to temperature. A circuit model, which describes the dielectric behavior of the transformers main insulation system, has been investigated in this paper. The values of the parameters of the model have been identified from the dielectric tests. A correlation has been observed between the operating temperature and the equivalent model parameters that can be used as additional information for better interpretation of the dielectric test results. This paper thus reports a detailed study on the effects of temperature on dielectric measurements of a transformer under controlled laboratory conditions. Some results of practical on-site testing are also presented to demonstrate the possibility of errors that may be introduced in dielectric test results analysis unless temperature effects are taken into consideration.**

***Index Terms*—Conductivity, depolarization current, dielectric response, dissipation factor, equivalent model, polarization current, recovery voltage, temperature, transformer insulation.**

I. INTRODUCTION

TRANSFORMER life is significantly influenced by degradation of the insulation materials, which is caused largely by thermal stress on the insulating oil and paper. Temperature along with oxygen and moisture are key factors in accelerating the ageing process.

Recovery voltage (RV) [1]–[4] and polarization and depolarization current (PDC) [4]–[7] measurement techniques are now widely used to provide an indication of the general ageing status and moisture content of the oil-paper insulation of a transformer. However, measurement results of these tests are strongly influenced by several environmental factors, predominantly by the temperature [8]–[18]. This temperature effect is more prominent in an open substation environment, where the external environmental conditions are hardly predictable and controllable. Hence it is very important to study the effect of temperature on dielectric behavior of an oil/paper insulation system in a field transformer.

The dielectric behavior of the insulation system is also influenced by moisture content of oil and paper. In a transformer, the total mass of dissolved water is distributed between paper and oil. This distribution or equilibrium of moisture is temperature dependent. When temperature increases, water migrates from paper to oil and vice versa. Hence a small change in temperature modifies the relative water content of the oil and paper. It is therefore essential to study the effect of temperature, and hence impact of moisture distribution on the dielectric behavior of oil and paper separately.

In order to interpret the dielectric diagnosis results more accurately in such cases, it is essential to understand the variations of the RVM and PDC measurement results with temperature. This paper reports laboratory test results of RVM and PDC measurements performed on a transformer with controlled variations of temperature.

Based on PDC measurement results, an equivalent model of the insulation system has been identified [19]–[22]. An attempt has been made to describe the effect of temperature on oil and paper from a detailed study of the derived model. Test results on transformers under outdoor conditions are also reported. These on-site test results demonstrate the effect of temperature on dielectric measurements and their impact on condition assessment.

II. TIME-DOMAIN DIELECTRIC MEASUREMENTS

A. PDC and RVM

For dielectric response (RV and PDC) measurements [6], [7], a dc step voltage $U(t)$ with the following characteristics is applied to an initially relaxed insulation system

$$\begin{aligned} &= 0 \quad 0 \le t \\ U(t) &= U_0 \quad 0 \le t \le t_1 \\ &= 0 \quad t \ge t_1. \end{aligned} \tag{1}$$

During the initial charging period, the step voltage is applied for time $0 \le t \le t_1$. In this time, the charging current (po-

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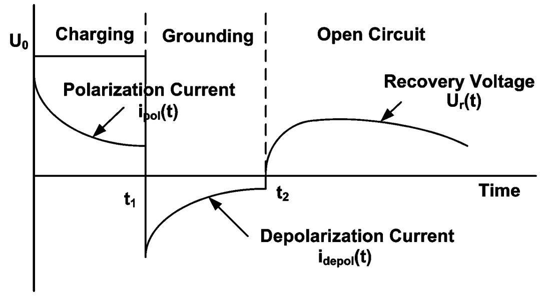

Fig. 1. Polarization, depolarization current, and recovery voltage measurements.

larization current) given by (2) will flow through the insulation system

$$i_{\text{pol}}(t) = C_0 \cdot U_0 \cdot \left[\frac{\sigma_r}{\varepsilon_0} + f(t)\right] \tag{2}$$

where $C_0 = C/\varepsilon_r$ is the geometric capacitance (C is the measured capacitance at or near power frequency and ε_r is the effective permittivity of the composite insulation system at power frequency), ε_0 is the vacuum permittivity, σ_r is the average conductivity of the composite insulation system and $f(t)$ is the dielectric response function of the composite insulation. The response function $f(t)$ describes the fundamental memory properties of the dielectric system and can provide significant information about the insulation material [20].

The insulation is then grounded (short circuited) for a subsequent time period $t_1 \leq t \leq t_2$; the magnitude of the depolarization current is given by (3)

$$i_{\text{depol}}(t) = C_0 \cdot U_0 \cdot [f(t) - f(t + t_1)]. \tag{3}$$

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, but some are not. Polarization 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, depolarization current, and the recovery voltage. The test object is charged from $0 \leq t \leq t_1$, when the polarization current is measured and then grounded from $t_1 \leq t \leq t_2$ when the depolarization current is measured. After that, for $t > t_2$, the grounding is removed, the insulation terminals are open circuited and the voltage appearing across the two electrodes is measured. This voltage is called the recovery voltage or the return voltage.

B. Estimation of Conductivity

From measurements of polarization and depolarization currents, it is possible to estimate average conductivity σ_r, of the test object (oil-paper) [6], [7], and [23]. If the test object is charged and discharged for sufficient time so that $f(t+t_1) \cong 0$, (2) and (3) can be combined to express the average conductivity of the oil-paper system as

$$\sigma_r \approx \frac{\varepsilon_0}{C_0 U_0}\left(i_{p_{ol}}(t) - i_{\text{depol}}(t)\right). \tag{4}$$

Fig. 2. $X - Y$ arrangement structure of oil and paper.

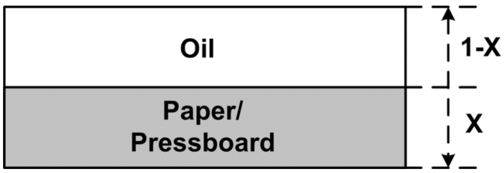

Fig. 3. Series arrangement structure of oil and paper.

The conductivity for a given insulation system thus is found to be dependent upon the difference between polarization and depolarization current values. This conductivity, in practice, is the convolution of the conductivities of oil and paper that make up the insulation structure. For modeling purposes, it is very common to represent the insulation structure by a relative amount of spacers and barriers in the duct, which is commonly, known as the $X - Y$ model, as shown in Fig. 2[24]. In this model, a parameter X is defined as the ratio of the sum of thickness of all the barriers in the duct, lumped together, and divided by the duct width. The spacer coverage Y, is defined as the total width of all the spacers divided by total length of the periphery of the duct [24]. However, when sufficient information about insulation is not available for estimation of the oil and paper conductivities separately, it is very often enough to consider the insulation system to be composed of a simple series arrangement of oil duct and paper insulation [6], [7] as shown in Fig. 3 and this does not significantly lose its accuracy. Each material is characterised by its conductivity and permittivity along with the composite dielectric response function $f(t)$.

The range of X is typically 20% to 50% and Y is typically 10% to 30% [14] for a transformer. Values of X and Y can be calculated more precisely only when the exact structure of the insulation system and all its design parameters are available.

For series arrangement of oil and paper according to [6], [7], the average conductivity may be written in terms of paper and oil conductivities (σ_{paper} and σ_{oil}, respectively) as

$$\sigma_r = \frac{\sigma_{\text{paper}}.\sigma_{\text{oil}}}{\sigma_{\text{paper}} \cdot (1 - X) + \sigma_{\text{oil}}.X}. \tag{5}$$

The effective permittivity ε_r can also be similarly estimated as

$$\varepsilon_r = \frac{\varepsilon_p.\varepsilon_{\text{oil}}}{\varepsilon_p \cdot (1 - X) + \varepsilon_{\text{oil}}.X} \tag{6}$$

where ε_p is the relative permittivity of paper and ε_{oil} is the relative permittivity of the oil duct.

Once the values of effective permittivity ε_r and hence C_0 is estimated, conductivity σ_r can be determined using (4) from the difference between polarization and depolarization currents. The initial polarization current (after the first transient that is normally not recorded) can be written as [6]

$$i_{\text{pol}}(+0) = C_0 U_0 \frac{\sigma_{\text{oil}}}{\varepsilon_0} \cdot \frac{\varepsilon_r}{\varepsilon_{\text{oil}}}. \tag{7}$$

Such that

$$\sigma_{\text{oil}} = \frac{\varepsilon_0 \cdot \varepsilon_{\text{oil}}}{\varepsilon_r \cdot C_0 \cdot U_0} \cdot i_{\text{pol}}(+0). \tag{8}$$

On the other hand, long-time polarization current (steady dc value i_{dc}) can be related to paper conductivity as

$$i_{dc} \approx C_0 \cdot U_0 \frac{\sigma_r}{\varepsilon_0}. \tag{9}$$

If $\sigma_{\text{oil}} \gg \sigma_{\text{paper}}$, then from (5), we get

$$\sigma_r \approx \frac{\sigma_{\text{paper}}}{X}. \tag{10}$$

Combining (9) and (10), we get

$$\sigma_{\text{paper}} \approx \frac{\varepsilon_0 \cdot X}{C_0 \cdot U_0} \cdot i_{dc}. \tag{11}$$

For the $X - Y$ model (as shown in Fig. 2), the composite conductivity may be written in terms of paper and oil conductivities (σ_{paper} and σ_{oil}, respectively) as

$$\sigma_r = \frac{Y}{\frac{1-X}{\sigma_{\text{spacer}}} + \frac{X}{\sigma_{\text{barrier}}}} + \frac{1-Y}{\frac{1-X}{\sigma_{\text{oil}}} + \frac{X}{\sigma_{\text{barrier}}}}. \tag{12}$$

If we take $\sigma_{\text{spacer}} = \sigma_{\text{barrier}} = \sigma_{\text{paper}}$

$$\sigma_r = \frac{Y}{\frac{1}{\sigma_{\text{paper}}}} + \frac{1-Y}{\frac{1-X}{\sigma_{\text{oil}}} + \frac{X}{\sigma_{\text{paper}}}} = \frac{Y}{\frac{1}{\sigma_{\text{paper}}}} + \frac{1-Y}{\frac{\sigma_{\text{paper}}(1-X)+X\sigma_{\text{oil}}}{\sigma_{\text{oil}}\sigma_{\text{paper}}}}. \tag{13}$$

Considering $\sigma_{\text{oil}} \gg \sigma_{\text{paper}}$

$$\sigma_r \approx Y\sigma_{\text{paper}} + \frac{(1-Y)\,\sigma_{\text{paper}}}{X}. \tag{14}$$

After rearrangement of the above equation

$$\frac{\sigma_r}{\sigma_{\text{paper}}} \approx \frac{YX + (1-Y)}{X}. \tag{15}$$

It can be observed that (10) is a special case of (15) with $Y = 0$.

III. INSULATION MODEL FOR DIELECTRIC RESPONSE

Over the last few years, several researchers [1], [19]–[22] 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 of the models proposed so far have been derived from an extended Debye approach based on a simple RC model.

In the presence of an electric field, polarization current is developed due to the tendency of dipoles to align in the direction of the field. When the field is removed, the dipoles relax and return to their original state [11], [12], [15]. In a polymer dielectric, every polar group can have a different configuration of neighbouring molecules. Thus, response time of the groups after application of an electric field may differ from one to another [15]. These processes 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. 4[1], [19]–[22]. These dipoles, represented as $R_i - C_i$, are randomly distributed, and have associated time constants given by $\tau_i = R_i C_i$. Apart from the polarization current, conduction current also flows in the insulation due to the presence of an electric field. The conduction current in the insulation is due to the insulation resistance R_o, as shown in Fig. 4. C_0 represents geometric capacitance of the insulation system. The capacitance C_0 is determined by conventional capacitance measurement techniques at power frequency (50 or 60 Hz) divided by relative permittivity of the oil-paper insulation system [1], [19].

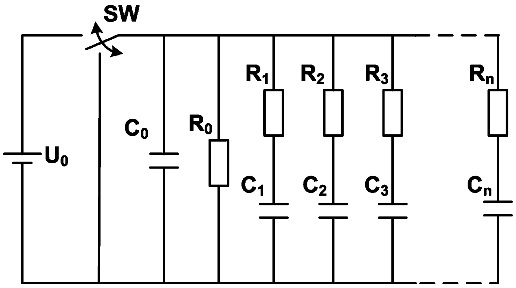

Fig. 4. Equivalent circuit to model a linear dielectric.

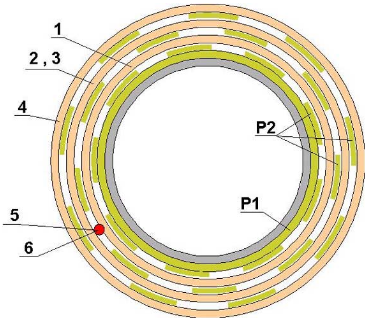

Fig. 5. Internal winding arrangement of test transformer.

For this model, most of the circuit parameters can be derived from measured polarization and depolarization currents (i_{pol} and i_{depol}). The insulation resistance R_o is calculated from the difference between polarization and depolarization currents at larger values of time [19]. Details of the model identification technique have been reported earlier in [19].

IV. EXPERIMENTAL PROCEDURE

The insulation system of the pancake transformer model [24] under study consists of oil and cellulose. The structure of the insulation system, ratio of oil-paper, etc. are similar to a real transformer. The winding arrangement and constructional details of the test transformer is shown in Figs. 5 and 6.

The insulation system of the transformer model consists of three windings insulated with oil and cellulose, as it is in a real power transformer. Geometric details of the winding are given in Table I. Based on the geometric information provided by the manufacturer of the pancake model, values of X and Y for modelling purposes are calculated to be 60% and 40%, respectively.

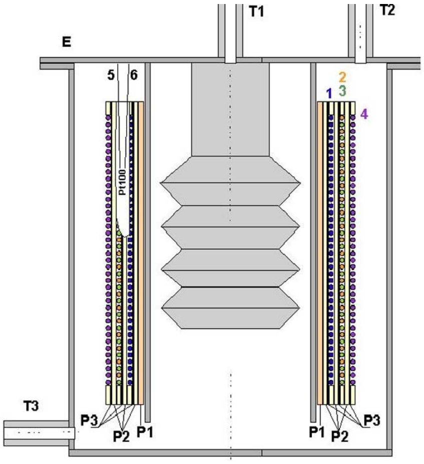

Fig. 6. Internal construction details of test transformer.

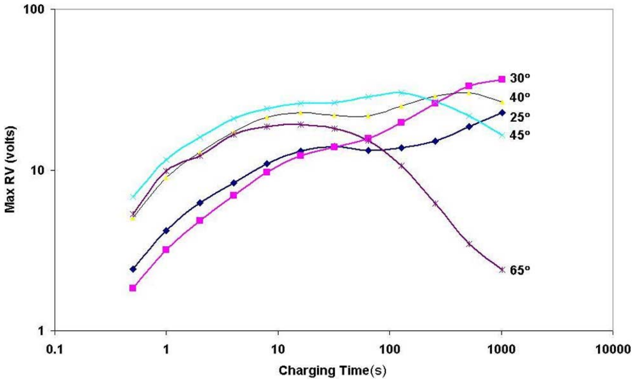

Fig. 7. RV spectra plotted against charging time at different temperatures.

TABLE I
GEOMETRIC DETAILS OF TEST TRANSFORMER MODEL

Label	Description
1	Inner coil, made from copper conductor with diameter of 1.5mm and insulated with 2 layers paper, 146 turns in one layer
2,3	Middle coil bifilar (double) wound, made from copper conductor with diameter of 1.5mm insulated with 2 layers paper, 73 turns in one layer
4	Outer coil, made from copper conductor with diameter of 1.5mm, insulated with 2 layers paper, 146 turns in one layer
5,6	Temperature sensor (RTD) terminals
T1	"Breathing" tap (only for inner equalising)
T2	Oil filling tap
T3	Oil drain tap
P1	Presspan tube of 3 mm thickness, to support the windings (inner/outer diameter 135/141 mm, length 300 mm
P2	18 pieces of presspan "spacer" band of 2 mm thickness / 10 mm width / 300 length on presspan holding band of 1 mm forming oil duct
P3	Presspan band closing end of winding, upper part of 25 mm, lower part 12 mm, 1,7 mm height
E	Grounding point on the tank

A temperature sensor of type 100-Ohm Pt 385 was inserted into the tank to measure the actual temperature inside.

The amount of solid insulation in the model is approximately 1445 g and oil is 8400 g; the ratio of oil/solid insulation is 5.8:1. The ratio of oil/cellulose material is about 10:1 to 6:1 in a real transformer. The whole model was kept inside a temperature controlled cabinet. A temperature controlled cabinet with $+1^\circ\mathrm{C}$ accuracy was used to vary temperature of the transformer at discrete steps over a pre-defined range. Temperature of the control cabinet (and hence the model transformer) was set at discrete values of 25 °C (ambient), 30 °C, 40 °C, 45 °C, and 65 °C. A temperature sensor was placed inside the transformer tank to make sure that the temperature inside the tank was equal to that of the set temperature. After the temperature inside the transformer tank was found to reach the temperature set in the control cabinet, it was allowed to remain like that for ten days. This ensured that the oil and paper could achieve a new state of moisture equilibrium at the elevated temperature. This was further verified by measuring PDC at seven, eight, and nine days as well. The variation of currents was almost unchanged after seven days. The transformer tank was completely sealed from outside ambient conditions, thereby ensuring that test results are solely affected by the variations of temperature. RVM and PDC tests were performed at all of the set temperatures. Relative humidity of the cabinet was also controlled at a value of 65%. This was done to ensure that the experimental results were only influenced by temperature and not by humidity. The PDC and RV measuring equipment [2], [3] developed at the University of Queensland was used for all the measurements.

V. ANALYSIS OF RESULTS

A. *RVM Results*

For obtaining RV spectra at a particular temperature, recovery voltage measurements were performed with the ratio of charging to discharging time being set at 2. Recovery voltages after each of these charging-discharging cycles were measured. Peak of this recovery voltage in each cycle and its corresponding time were recorded. These cycles were repeated for charging times varying from 0.5 s to 1024 s in increasing powers of 2 s. The peak of each RV cycle when plotted against the corresponding charging time produces the RV spectra, as shown in Fig. 7.

It can be seen that the effect of temperature causes significant displacement of the RV spectra peaks. The exact time of occurrence of peak RV value from each RV measurement is defined as the dominant time constant for that particular charging/discharging time. Values of these dominant time constants for each RV measurement were extracted from the recorded data of each RV measurement. However, they are not shown in Fig. 7. Values of these dominant time constants and the corresponding temperature are shown in Table II and graphically plotted in Fig. 8. The peak value of each RV spectrum and its corresponding time (i.e., the dominant time constant) has been reported to be indicative of the condition of insulation [1]–[4].

At normal operating conditions, the bulk of the water remains in the paper; at higher temperature,s however, the moisture migrates from the paper towards the oil. At high temperatures, the spectrum peaks are found to shift to smaller charging times. This peak-shifting has been attributed to increased water availability in oil at high temperatures [12]. Variations of the dominant time constants with corresponding temperature are summarised in Table II.

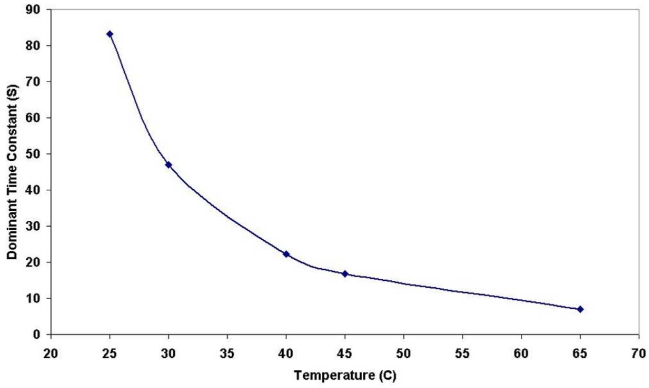

Fig. 8. Dominant time constant versus temperature.

TABLE II
DOMINANT TIME CONSTANT VERSUS TEMPERATURE

Temperature (^{0}C)	Dominant Time Constant (sec)
25	82
30	47
40	22
45	13
65	7

It was reported by Kozlovskis *et al.* [8] that the dominant time constants from the RV spectrum follows an exponential response, which is dependent on temperature and the movement in shape can be described by the following equation:

$$t_{datT_2} = t_{datT_1} \cdot e^{(-b\Delta T)} \qquad (16)$$

where t_{datT1} is the dominant time constant at a reference measurement temperature of T_1, t_{datT2} is the dominant time constant at some different measurement temperature of T_2, ΔT is the temperature difference ($\Delta T = T_2 - T_1$). The constant b is a parameter related to the polarization process inside the insulation material. The exponential nature predicted by (16) is clearly visible in the plot of Fig. 8.

B. PDC Results

Figs. 9 and 10, respectively, show the polarization and depolarization currents obtained at different temperatures. In each case, the transformer was charged (polarized) with 500 volts for 10 000 s and then discharged (depolarized) for 10, 000 s. It can be seen that variation in temperature causes significant displacements of both the polarization and depolarization currents. It can be seen from Figs. 9 and 10 that magnitude of the polarization and depolarization currents tends to shift to higher values with rising temperature.

For calculating paper conductivity, both X and $X-Y$ models were considered. Variation of paper conductivity due to these two models is not significant (Table III). It is worth noting that oil conductivity is not dependent on the X or $X-Y$ model. Figs. 11 and 12 show the nature of variation of oil and paper conductivity with temperature (considering the X model).

Initial currents are considered for oil conductivity calculation and hence initial current will be taken from the measurement conducted at the temperature during the start of measurement and corrected accordingly for the ambient (using Fig. 11). Similarly, since final currents are considered for paper conductivity calculation, the final current will be taken from the corresponding measurement at the last temperature and corrected accordingly using Fig. 12.

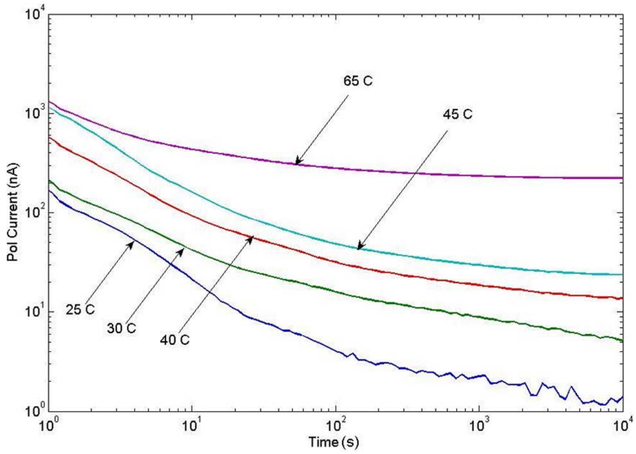

Fig. 9. Variation of polarization current with temperature.

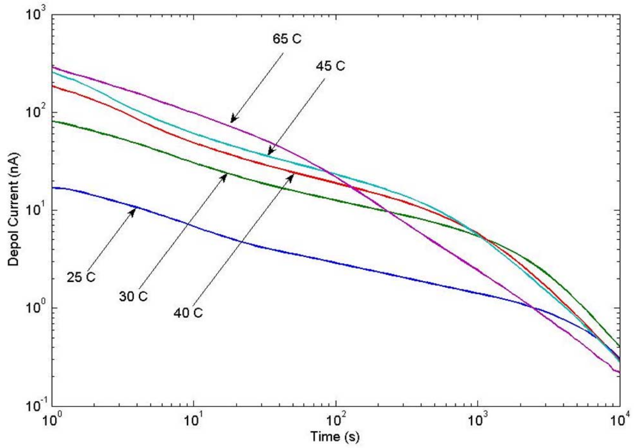

Fig. 10. Variation of depolarization current with temperature.

TABLE III
EFFECT OF $X-Y$ VALUES ON THE CALCULATION OF PAPER CONDUCTIVITY

σ_{paper} x 10^{14}		Temperature (^{0}C)
X-model (X=0.6)	X-Y model (X=0.6, Y=0.4)	
2.46	2.07	25
5.08	4.26	30
13.2	11.1	40
23.9	20.0	45
164.4	141.3	65

Both the oil and paper conductivities are found to increase exponentially with temperature. It was also reported by [10], [13] that conductivity follows an exponential law:

$$\sigma(T) \approx A \cdot e^{(-E_{ac}/kT)} \qquad (17)$$

where T is the absolute temperature in Kelvin, A is a constant related to the mobility of ions in the insulation, k is the Boltzman

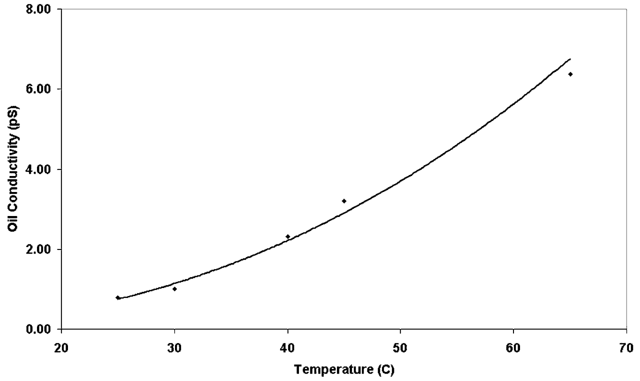

Fig. 11. Variation of oil conductivity with temperature.

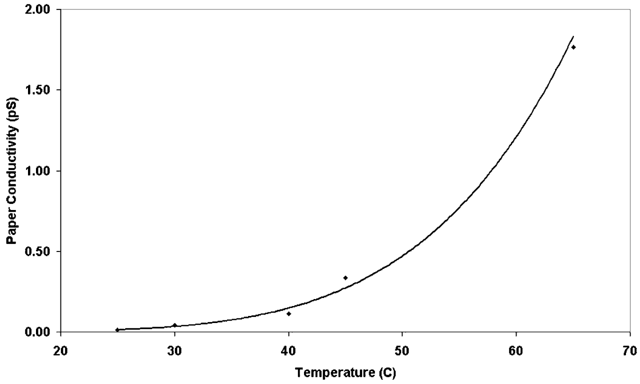

Fig. 12. Variation of paper conductivity with temperature.

TABLE IV
MEASURED RESISTANCE AT DIFFERENT TEMPERATURES

Temp (^{0}C)	Insulation resistance (GΩ)
25	468
30	126
40	33
45	16.8
65	5.63

constant and E_{ac} is the activation energy. Taking natural logarithm on both sides of (17), it can be shown that the conductivity varies linearly with the inverse of the absolute temperature $(1/T)$ [9]. It is interesting to note that both oil and paper conductivities separately demonstrate linear variation with inverse of absolute temperature.

C. Insulation Model Parameters

The equivalent circuit model parameters were obtained using a non-linear optimisation procedure with the help of software codes written in MATLAB [19]. Table IV contains the R_0 values obtained from the polarization and depolarization currents at different temperatures. The reduction in insulation resistance with increasing temperature is due to increased mobility of the charge carriers inside the insulation at higher temperatures.

$R_i - C_i$ branch values of the equivalent insulation model have been calculated at different temperatures and are plotted in Figs. 13 and 14.

Resistance values are in $G\Omega$ and capacitances are in nF.

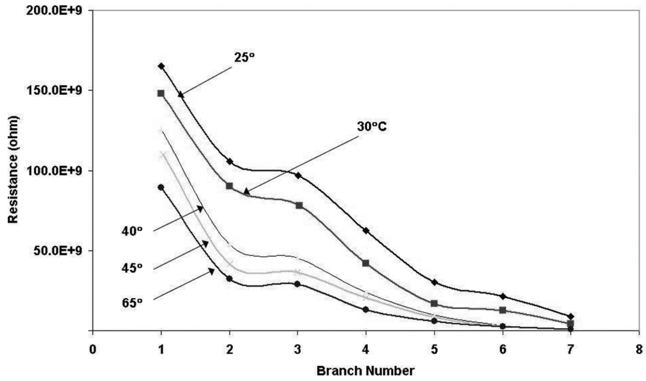

Fig. 13. Variation of model branch resistances with temperature.

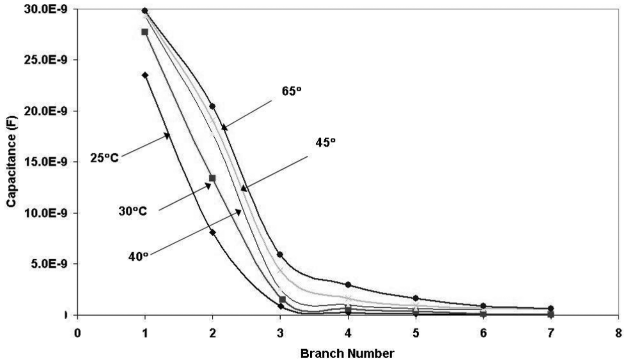

Fig. 14. Variation of model branch capacitances with temperature.

It was found that the number of branches in most practical models varies from six to ten depending upon the nature of the depolarization current [19]. For this work, seven parallel branches were considered and found by best possible curve fittings with least error. It has been reported in [19] that lower indexed branches (corresponding to higher time constants) of R_i and C_i in the model represent paper condition. For example, branches R_1, C_1, R_2, and C_2 are more likely to be dependent on the condition of paper. Whereas, higher indexed branches of R_i and C_i (corresponding to lower time constants) in the model represent the condition of oil. For example, branches R_5, C_5, R_6, C_6 and R_7, C_7 are more likely to be dependent on oil condition.

It is observed from Figs. 13 and 14 that $R_i - C_i$ values of different branches change with a change in temperature. It is observed that resistance of both higher and lower indexed branches have changed due to an increase in temperature. At higher temperatures, the branch resistance values have decreased—indication of a higher mobility of the charge carriers.

At increased temperatures, due to increased mobility of the charge carriers present inside the oil/paper insulation, resistances of all the branches are found to decrease. This indicates that at higher temperatures the insulation condition inside a transformer deteriorates in performance. This change in resistance values, however, does not indicate permanent degradation of the insulation, since the effect is reversed when temperature is lowered. This change in resistance values are only due to change in mobility of charge carriers within the insulation and can not be attributed thus, to a permanent insulation degradation.

TABLE V
STUDY OF OUTDOOR FIELD TRANSFORMER AFFECTED BY TEMPERATURE VARIATION

Capacity Rating	Voltage Rating:	Type and winding connection	Manufacture
35 MVA	HV/LV 66kV/22kV	Three-Phase Distribution Transformer	1936

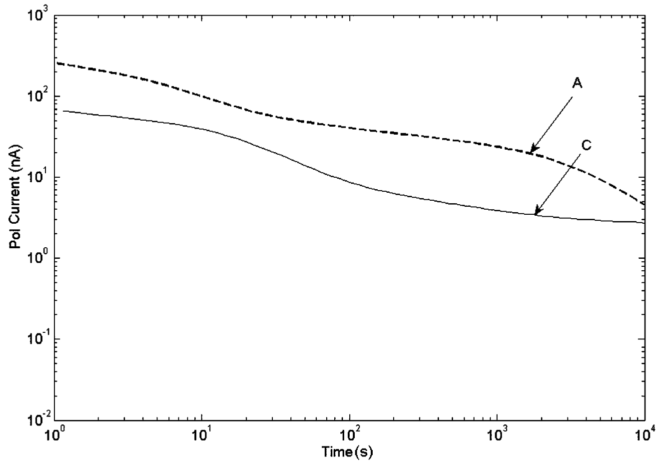

Fig. 15. Polarization current plots for transformer. (A) Under downward temperature transition. (C) At ambient temperature of 28 °C.

VI. IMPACTS OF TEMPERATURE TRANSITION DURING PDC MEASUREMENTS

It is often experienced in actual field testing that the transformer to be tested was previously connected to the electricity grid and was in an operating condition. During normal operating conditions, the temperature inside a transformer is much higher than ambient, depending upon the loading condition. For PDC measurement purposes, if a transformer is taken out of service, it must be given adequate time for the temperature to settle down to ambient condition before commencing the actual PDC testing. A transformer was used for this study. The transformer's information is provided in Table V.

Figs. 15 and 16 are plots for PDC tests on a transformer where PDC measurement has been done while the transformer was in the process of cooling down. Before the start of the test, the transformer was running at a temperature of 60°C. The transformer was then switched off from the supply and allowed to cool down to ambient temperature. The PDC measurement was done during this cooling down process. The temperature was found to cool down from a starting value of 60 °C to 40 °C during the initial polarization period of 3 h. Finally, at the end of 3 h of depolarization current measurement, the temperature had dropped to 28 °C (ambient).

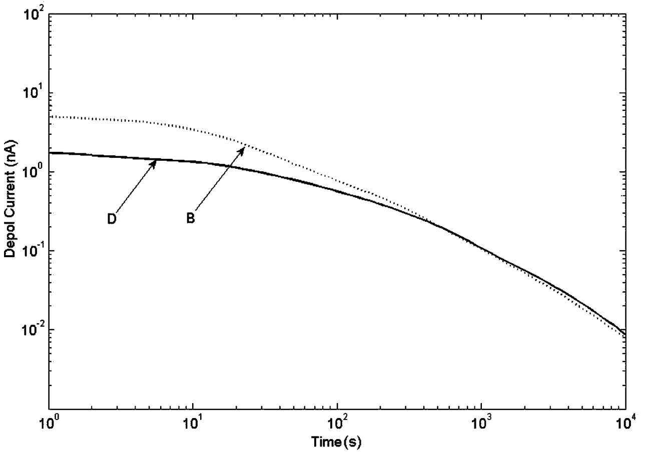

Fig. 16. Depolarization current plots for transformer. (B) Under downward temperature transition. (D) At ambient temperature of 28 °C.

TABLE VI
OIL AND PAPER CONDUCTIVITIES FOR DOWNWARD TRANSITION

	At ambient	Under transition
σ_{oil} (pS/m)	1.32	1.88
σ_{paper} (pS/m)	0.03	0.04

It was pointed out in [25] that if a thermal step is applied to an insulation sample, due to displacement of charges a current appears in the external circuit. This current interferes with polarization and depolarization currents under measurement giving rise to unwanted errors. As seen in Figs. 15 and 16, the polarization and depolarization currents corresponding to the case when transformer temperature was under transition are higher than their ambient temperature counterparts. This may result in erroneous calculation of the response function and conductivities. Conductivity values for oil and paper calculated from polarization and depolarization currents under such conditions are given in Table VI. Errors in conductivity calculations due to transition of temperature are clearly visible in Table VI. Under transition of temperature from a higher to a lower value, the polarization current is higher than the corresponding values at ambient temperature. In particular, this is higher in the initial part of the polarization current, when temperature was much higher than the ambient, while after a couple of hours of transition, the final polarization current becomes closer to the current at ambient temperature. The difference in current between high temperature and ambient can produce erroneous results in conductivity estimation. Midway through the depolarization current measurement (after 3 $\sim$ 4 hours), the transformer had sufficiently cooled down to ambient temperature. Thus, the depolarization currents at transition condition and ambient condition are overlapping after a certain period of time. This higher magnitude of initial polarization current will give higher values of oil and paper conductivities as shown in Table VI.

Thus, it is essential to allow sufficient time for the transformer temperature to settle down to ambient before commencing the actual PDC test. Otherwise, the prediction based on these test results will be erroneous.

A reverse temperature transition effect on PDC measurement can be observed while field testing is performed in open substations, where the ambient temperature varies widely during the day. The ambient temperature during summer may start with 15–20 °C in the morning and may increase to 35-40 °C by midday. In effect, the temperature inside the transformer tank will also go up. This may have a noticeable impact on the PDC measurement. Both the polarization and depolarization currents

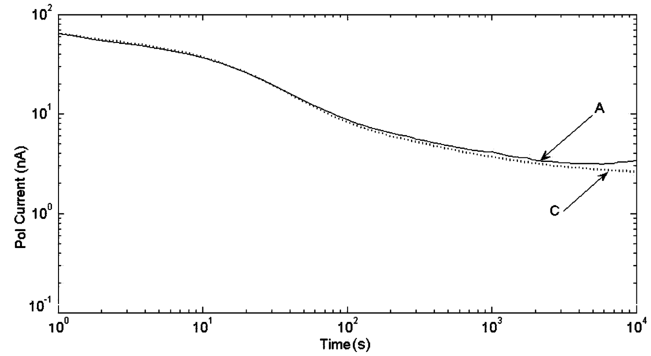

Fig. 17. Polarization current plots for transformer. (A) Under upward transition of temperature. (C) At ambient.

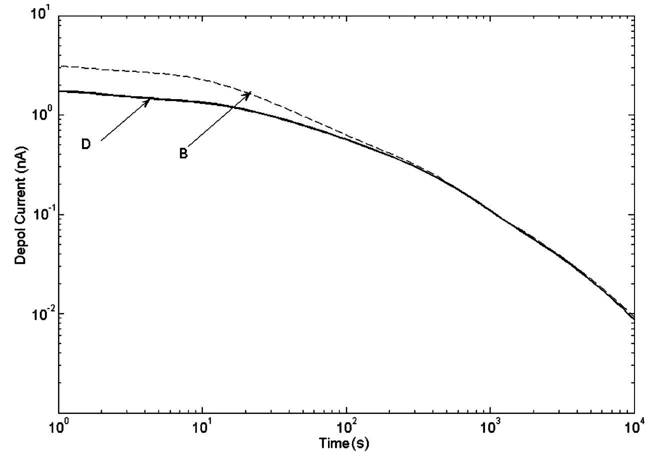

Fig. 18. Depolarization current plots for transformer. (B) Under upward transition of temperature. (D) At ambient.

being very sensitive to temperature variations—this temperature variation during the measurement period may introduce some unwanted variations in the currents.

An experiment was performed in the laboratory with the test transformer being put inside a temperature controlled chamber. The PDC test was started at 20 °C and then the test-chamber temperature was increased at a steady rate of 2 °C per hour up to 30 °C while the test was continuing. Figs. 17 and 18 show polarization and depolarization currents with the temperature around the transformer tank rising steadily from 20 °C to 30 °C during the test. Figs. 17 and 18 also includes polarization and depolarization currents when the same transformer was tested at a constant temperature of 20 °C.

The final value of the polarization current (current at 10^4 sec) at the upward transition temperature (plot A, Fig. 17) slightly varies from the corresponding final polarization current measured at 20 °C (plot C, Fig. 17). It is observed that initial values of the depolarization current under temperature transition (plot B, Fig. 18) vary significantly from the measurement conducted at 20 °C (plot D, Fig. 18). The temperature in the beginning of the polarization measurement is close to 20 °C and then slowly rises to a test chamber value of about 25 °C at the end of this measurement, which is reflected on the last part of the polarization current. While the depolarization measurement now starts at 25 °C, thus the deviation from the 20 °C depolarization curve is more pronounced at the beginning. This has also been reflected in the oil/paper conductivity calculations.

TABLE VII
OIL AND PAPER CONDUCTIVITIES FOR UPWARD TRANSITION

	At ambient	Under transition
σ_{oil} (pS/m)	0.28	0.25
σ_{paper} (pS/m)	0.01	0.03

Oil conductivity calculated from the current measurements under transition is lower than the oil conductivity calculated from the current measurements at 20 °C. On the other hand, the change in paper conductivity is in the opposite direction. It is thus clear from Figs. 17, 18, and Table VII that any dielectric response function and conductivity computed from polarization and depolarization currents obtained under such temperature transition during the PDC measurement will be erroneous.

VII. CONCLUSIONS

The dielectric response measurements are currently being used for the diagnosis of transformer insulation condition. Interpretation of RVM and PDC test results still remains a difficult task as it is influenced by insulation ageing condition, geometry of insulation, moisture content, and also the operating temperature. The condition of oil paper insulation is strongly affected by the presence of moisture and the moisture distribution between oil and paper is highly dependent on the operating temperature.

For correct interpretation of dielectric test results, it is essential that an understanding of temperature effects is available. In this paper, dielectric test results on a model transformer under controlled laboratory conditions and on a substation transformer in field measurement have been reported.

It has been found that with increasing temperature, the oil and the paper insulation inside a transformer appears to exhibit degraded performance compared to lower operating temperatures. The dominant time constant of the RVM tends to shift towards lower values of time as the temperature increases. Polarization and depolarization current magnitudes and oil and paper conductivities estimated from these currents tend to be higher at higher temperatures. An equivalent insulation model has been parameterised in an attempt for quantitative interpretation of the results. The oil and paper conductivity, and insulation resistance have been found to increase with increased temperature. Oil and paper conductivities calculated from the measured currents are found to have a certain mathematical relationship with temperature.

On-site test results presented in the paper indicates the necessity of careful understanding of the effect of temperature on the dielectric response measurement for correct analysis and interpretation.

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