IET Science, Measurement & Technology

Research Article

ISSN 1751-8822
Received on 8th January 2019
Revised 16th June 2019
Accepted on 9th July 2019
E-First on 14th August 2019
doi: 10.1049/iet-smt.2019.0012
www.ietdl.org

Estimation of paper conductivity from short duration polarisation–depolarisation current for diagnosis of power transformer

Deepak Mishra[1] ✉, Nasirul Haque[2], Arijit Baral[1], Sivaji Chakravorti[2]
[1]Electrical Engineering Department, IIT (ISM), Dhanbad, India
[2]Electrical Engineering Department, Jadavpur University, Kolkata, India
✉ *E-mail: deepak2010urs@gmail.com*

Abstract: The value of paper conductivity provides quantitative evaluation of transformer insulation health. However, proper identification of paper conductivity requires complete profile of polarisation–depolarisation current (PDC). PDC measurement being a time-consuming offline process generally takes several hours to complete. Furthermore, magnitude of PDC becomes very low at larger value of time, which makes it sensitive to changes in environmental conditions and field noise. Hence, accuracy of paper conductivity identification can be ensured by conducting multiple measurements. This in-turn prolongs shutdown time of equipment and become less advantageous to utilities. Here, a method is proposed which is capable of estimating paper conductivity using PDC data recorded for only 800 s. The proposed technique is tested on data collected from several real-life in-service transformers. In order to illustrate the accuracy of the proposed technique, paper conductivities (calculated from short duration PDC) were compared with those computed using PDC measured for 10,000 s.

1 Introduction

In a typical polarisation–depolarisation current (PDC) measurement, the concerned transformer has to undergo a very long charging time of the order of 10,000 s followed by an equivalent duration for discharging process. As a result, the typical measurement time for PDC data is 20,000 s (10,000 s for polarisation current and 10,000 s for depolarisation current) [1–5]. This large time is required as measurement (both polarisation and depolarisation current) continues until the response current settles down to a constant value. Such long durations are required because dipole groups present in cellulose have large orientation times [5]. Prior to PDC measurement, the concerned transformer is disconnected from the network and is provided sufficient cooling period (with terminals short-circuited), so that it could attain equilibrium. In addition, the total time taken to complete PDC measurement spans several hours. This is a cause of concern for power utilities from the economical point of view. Another noteworthy point is that during long PDC measurement, environmental conditions (especially temperature) might change and hence affect the insulation response to such an extent that it can lead to erroneous diagnosis [6, 7]. In such cases, several measurements of PDC data may be required to ensure accuracy of the recorded data. This is understandably less practical for the utilities considering the time constraint involved.

A major advantage of PDC measurement is it offers a straightforward approach to estimate the conductivity of the cellulosic component (paper) of the oil–paper composite insulation. This paper conductivity or σ_{paper} is a well-recognised aging sensitive performance parameter capable of providing quantitative evaluation of the overall insulation. Use of σ_{paper} for diagnosis does not involve equivalent circuit modelling of the insulation. Therefore, such technique is free from problems associated with insulation model formulation [8].Unlike, oil conductivity (σ_{oil}) which can be evaluated quickly using initial values of PDC data, computation of σ_{paper} is time-consuming as it requires the steady-state difference between polarisation and depolarisation current [6]. Needless to say, assessment of σ_{paper} needs large measurement time. The urge to minimise transformer shutdown time coupled with the requirement of σ_{paper} measurement suggests that there is a requirement of a methodology that is capable of estimating magnitude ofσ_{paper} using PDC data recorded for a reduced time span. A major difficulty in the fulfilment of this objective is that short duration PDC essentially refers to incomplete polarisation of the test object and paper conductivity can be computed from PDC data only when the polarisation process has been completed.

In present work, a method has been proposed that can satisfactorily predict the value of σ_{paper} using PDC data recorded for a short duration. The developed method is based on charge difference method, details of which are discussed in Section 4.The developed method is successfully tested on PDC data collected from several power transformers (details shown in Tables 1 and 2) for different time durations, ranging from 600 to 10,000 s. The data recorded for 20,000 s (polarisation and depolarisation current both measured for 10,000 s) are later used for validation of the proposed technique.

Table 1 Details of transformers used in this study

Transformer name	Power rating	Approx. age (in years)	PDC measurement temperature
Trafo1	240 MVA, 420 kV	33–36	35°C
Trafo2	240 MVA, 420 kV	30–33	34°C
Trafo3	200 MVA, 420 kV	20–23	35°C
Trafo4	125 MVA, 220 kV	31–34	35°C
Trafo5	250 MVA, 242 kV	31–34	34°C
Trafo6	240 MVA, 420 kV	32–35	35°C
Trafo7	290 MVA, 230 kV	12–15	36°C
Trafo8	200 MVA, 420 kV	18–21	32°C
Trafo9	240 MVA, 420 kV	25–28	28°C

Table 2 Transformer insulation-related information

Transformer name	Geometric capacitance (nF)	tan δ	%pm (IDAX 300)
Trafo1	5.15	0.55	*NA
Trafo2	3.05	0.48	*NA
Trafo3	6.62	0.28	*NA
Trafo4	4.96	0.26	2.20
Trafo5	11.12	0.37	1.80
Trafo6	11.26	0.34	*NA
Trafo7	3.44	0.19	*NA
Trafo8	10.94	0.23	1.00
Trafo9	13.20	0.30	2.20

*Data not available.

Table 3 Influence of X on paper-conductivity

Transformer name	σ_{paper} ($X = 0.3$)	σ_{paper} ($X = 0.28$)	σ_{paper} ($X = 0.25$)
Trafo4	2.03×10^{-13}	1.93×10^{-13}	1.86×10^{-13}
Trafo5	8.79×10^{-14}	8.53×10^{-14}	8.29×10^{-14}
Trafo8	6.51×10^{-15}	6.28×10^{-15}	6.08×10^{-15}
Trafo9	2.95×10^{-13}	2.79×10^{-13}	2.68×10^{-13}e-13

2 PDC data measurement from transformers

Before starting PDC measurement process, terminals of high- and low-voltage windings are kept in short-circuited condition to ensure a charge-free system. On application of DC charging voltage (generally taken as 1000 V), the dipoles present within the insulation begin to orient in the direction of applied field. This process results in flow of polarisation current through the insulation. During depolarisation current measurement, the applied voltage is replaced by short circuit. This causes the dipoles, which previously oriented themselves, return to their initial position which results in flow of depolarisation current through insulation [5]. As the magnitude of PDC data is low, electrometer is generally used for recording purposes [7]. PDC data of different transformer considered in this paper were measured using KEITHLEY 6517B electrometer-based setup developed at high tension laboratory, Jadavpur University [7]. For the present work, PDC data were measured for 600, 700, 800, 900, and 10,000 s from the transformers. These measurements were carried out over a span of several weeks. It is assumed that during this tenure, the insulation of the concerned transformer did not undergo significant aging. Furthermore, before each measurement, the concerned transformer was provided sufficient cooling time with shorted terminals to ensure the thermal equilibrium state- and charge-free system. In the present work, PDC data recorded for 10,000 s is used during development stage and is used only for validation of the proposed method. The developed method (as explained later) does not require PDC data for $0 < t < 10{,}000$ s for proper functioning.

3 Brief theory about PDC

According to linear dielectric theory, polarisation current is considered to be composed of dipole contribution and conduction current while the depolarisation current is assumed to exist only due to dipole relaxation process. Hence, the polarisation and depolarisation current are generally represented by (1) and (2) [5]

$$i_{\text{polar}} = i_{d(\text{polar})} + i_{\text{condn}} \tag{1}$$

$$i_{\text{depolar}} = i_{d(\text{depolar})} \tag{2}$$

where $i_{d(\text{polar})}$ and $i_{d(\text{depolar})}$ represent the dipole contribution in polarisation and depolarisation current, respectively. On the other hand, i_{condn} represents the DC conduction current which can be calculated using (3)

$$i_{\text{condn}} = i_{\text{polar}}(t_f) + i_{\text{depolar}}(t_f);\ t_f \to \infty \tag{3}$$

In (3), if t_f is considered to be large, then i_{condn} can be considered practically equal to i_{polar} (t_f). Once the value of DC conduction current is identified, aging sensitive performance parameter like paper conductivityσ_{paper} can be evaluated. This can be done as follows: first, average conductivity σ_r is computed from the i_{condn} using (4) [9]

$$i_{\text{condn}} \simeq C_0 \times U_0 \times \frac{\sigma_r}{\varepsilon_0} \tag{4}$$

where C_0 is geometric capacitance and U_0 is charging voltage applied during polarisation current measurement. The relation of oil and paper conductivity with DC conductivity σ_r is given by (5) [9]

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

Here, X is defined as the ratio of the sum of thickness of all the barriers in the duct to the duct width [9]. The oil conductivity is related to initial part of polarisation current and is given by (6) [9–11]

$$\sigma_{\text{oil}} = \frac{\varepsilon_0 \varepsilon_{\text{oil}}}{\varepsilon_r C_0 V} i_{\text{pol} \times (0+)} \tag{6}$$

After estimation of σ_r and σ_{oil}, the value of σpaper can be calculated using (5). It can be observed from (4) and (5) that estimation of σ_{paper} is not possible without the knowledge of X and complete profile of PDC data. The typical range of X for real-life transformers lies between 20 and 50% [9]. IDAX 300 test results corresponding to four transformers (*Trafo4, Trafo5, Trafo8,* and *Trafo9*) were made available to the authors of the present work. The values of X corresponding to these transformers (identified by IDAX 300) were observed to be 25, 30, 28, and 30%, respectively. In order to test the influence of X on paper conductivity calculation, σ_{paper} is evaluated for *Trafo4, Trafo5, Trafo8,* and *Trafo9* for $X = 25$, 28, and 30%. Table 3 shows the result of such investigation.

It can be observed from data presented in Table 3 that minor variations in X do not significantly affect the value of paper conductivity. Hence, in present work, the value of X is taken as 30%.

4 Developed method

In PDC measurement conducted on real-life transformers, it is often encountered the profile polarisation current does not completely match with the profile of depolarisation current, even when adjusted for conduction current. This is because of two reasons, the non-linearity present in oil–paper insulation and the extraction of interfacial charge during depolarisation process [12, 13]. The proposed method is based on analysis of difference in charge quantity that is introduced/removed during PDC measurement [11]. The amounts of charge introduced $Q_{\text{pol}}(t)$during polarisation phase and removed $Q_{\text{depol}}(t)$ from insulation during depolarisation phase are related to $i_{\text{pol}}(t)$ and $i_{\text{depolar}}(t)$ using (7) and (8)

$$Q_{\text{pol}}(t) = \int i_{\text{polar}}(t)\mathrm{d}t \tag{7}$$

$$Q_{\text{depol}}(t) = \int i_{\text{depolar}}(t)\mathrm{d}t \tag{8}$$

From (7) and (8), charge difference is calculated represented by (9)

$$
\begin{aligned}
Q_{\text{diff}}(t) &= \int \Delta i_{\text{pdc}}(t)\mathrm{d}t \\
&= Q_{\text{pol}}(t) - Q_{\text{depol}}(t)
\end{aligned} \tag{9}
$$

It is worth mentioning here that (9) is valid only when measurement time and sampling frequency of both polarisation and depolarisation are same. Fig. 1*a* through Fig. 1*c* shows the $Q_{\text{diff}}(t)$ and PDC profiles of transformers considered in the present work. PDC data of various transformers (as shown in Fig. 1*a* through Fig. 1*c*) are plotted in logarithmic scale while corresponding charge profiles are plotted in linear scale. It is reported in [11] that $Q_{\text{diff}}(t)$ follows a linear relationship with time. Compared to the units reported in [11], the transformers considered in the present work are of much larger power rating. Analysis of PDC data, recorded from the tested transformers, indicate that the entire $Q_{\text{diff}}(t)$ profile cannot be approximated with the help of a single linear or non-linear equation. At larger value of time, $Q_{\text{diff}}(t)$ is found to maintain a quadratic relationship with time which can be modelled by (10)

$$
Q_{\text{diff}}(t) = \left(a \times t^2\right) + (b \times t) + c \tag{10}
$$

It is worth mentioning here that for first few hundred seconds, (10) fails to approximate $Q_{\text{diff}}(t)$ profile as illustrated in Fig. 2.

Table 4 presents the value of (10) coefficients obtained for the tested transformers.

Data presented in Table 4 show that the sign of (10) coefficients remain unchanged for all tested transformers. Furthermore, it can be observed that the difference between magnitude of coefficients *a* and *b* and also between *a* and *c* remain relatively same for all the tested transformers. This implies that influence of coefficient *a* is felt by the derivative of $Q_{\text{diff}}(t)$ only at larger value of time. Therefore, at larger value of time, derivative of $Q_{\text{diff}}(t)$ is given by (11)

$$
\begin{gathered}
\frac{\mathrm{d}}{\mathrm{d}t}(Q_{\text{diff}}(t)) = (b - 2\lambda \mathrm{t}) \\
\lambda = |a|;\ t \gg 0
\end{gathered} \tag{11}
$$

It can be understood that the current difference profile $\Delta i_{\text{relax}}(t) = i_{\text{pol}}(t) - i_{\text{depolar}}(t)$ is related to $Q_{\text{diff}}(t)$ by (12):

$$
\Delta i_{\text{relax}}(t) = i_{\text{pol}}(t) - i_{\text{depolar}}(t) = \frac{\mathrm{d}}{\mathrm{d}t}(Q_{\text{diff}}(t)) \tag{12}
$$

As $t \to t_{\text{fnl}}\left(= 10^4 s\right)$, the difference in current difference profile is due to conduction only. Therefore, DC conduction current i_{condn} is related to $\Delta i_{\text{relax}}(t)$ by (13)

$$
i_{\text{condn}} = \Delta i_{\text{relax}}(t \to t_{\text{fnl}}) = b - 2\lambda \mathrm{t}_{\text{fnl}} \tag{13}
$$

From (4),

$$
\sigma_r = \varepsilon_0 \times \frac{\Delta i_{\text{relax}}(t_{\text{fnl}})}{C_0 U_0} \tag{14}
$$

It can be understood from above discussion that if the coefficients of (10) are identified properly, σ_r can be evaluated using (12)–(14). From σ_r, paper conductivity can be calculated using (5) and (6). It is observed that linear relationship is incapable of modelling $Q_{\text{diff}}(t)$ profile for the tested transformers. This is illustrated in Fig. 3 which shows the performance of linear and quadratic relationship in modelling $Q_{\text{diff}}(t)$ obtained for *Trafo1*. It should be mentioned here that in Fig. 3, the entire span of $Q_{\text{diff}}(t)$ is used for fitting purposes.

As mentioned earlier, deviation of $Q_{\text{diff}}(t)$ profile from straight line is attributed to the non-linear nature of oil–paper insulation and effect of interfacial charge. Fig. 3 shows that at larger value of time $Q_{\text{diff}}(t)$ can be approximated by predicting the coefficients of (10). As $Q_{\text{diff}}(t)$ starts to follow (10) after few hundred seconds, it might be possible to use Q_{diff} corresponding to first few hundred seconds to predict Q_{diff} at larger value of time. Hence, in the present work, $Q_{\text{diff}}(t)\,;\ t_1 \le t \le t_2$ is used to estimate the coefficients of (10) and thereafter $Q_{\text{diff}}(t)\,;\ t_2 \le t \le 10000\,\text{s}$ is predicted using (10).

In the present work, charge difference profile obtained using PDC recorded only up to t_2 is represented by $Q_{\text{diff}}^{m2}(t)$ while that

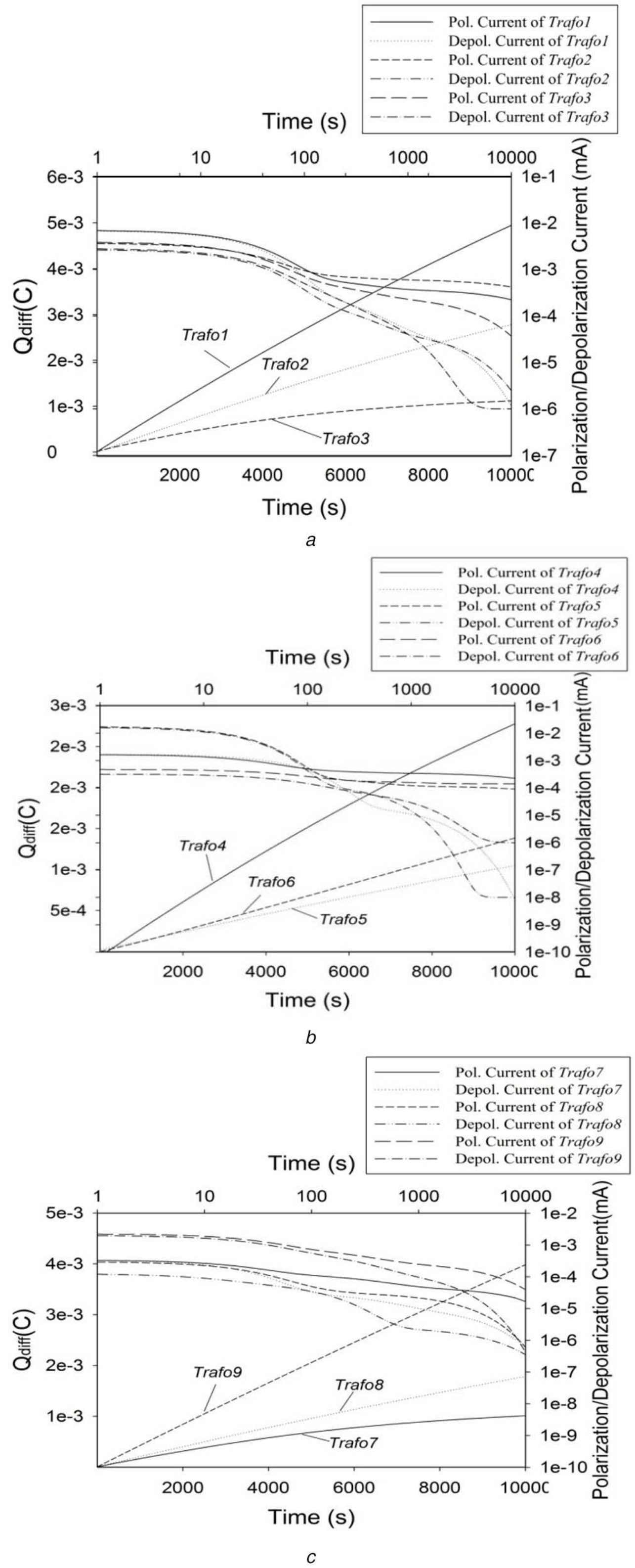

Fig. 1 *Charge Difference and PDC profile*

(a) Charge difference profile of tested transformers1, 2, and 3, ***(b)*** For transformer 4, 5, and 6, ***(c)*** For Transformers 7, 8, and 9

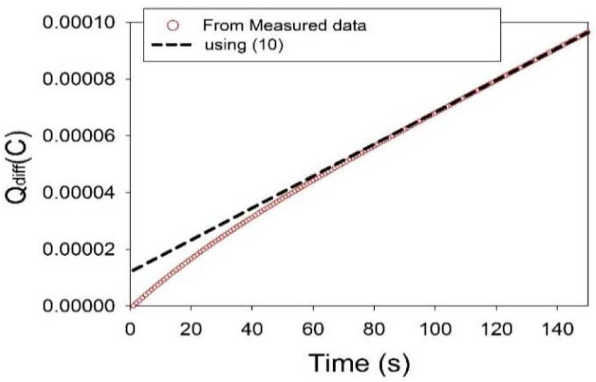

Fig. 2 *Charge difference profile of Trafo1 showing initial non-linearity*

Table 4 Coefficients of (10) obtained for different transformers

Transformer name	a	b	c	R2
Trafo1	-6.598×10^{-13}	5.637×10^{-7}	1.201×10^{-5}	0.99
Trafo2	-6.013×10^{-12}	3.340×10^{-7}	7.092×10^{-6}	0.98
Trafo3	-1.409×10^{-11}	2.261×10^{-7}	1.907×10^{-5}	0.98
Trafo4	-1.382×10^{-11}	4.045×10^{-7}	7.031×10^{-6}	0.99
Trafo5	-3.082×10^{-12}	1.295×10^{-7}	1.976×10^{-5}	0.98
Trafo6	-2.329×10^{-12}	1.380×10^{-7}	4.963×10^{-6}	0.99
Trafo7	-8.524×10^{-12}	1.784×10^{-7}	1.985×10^{-6}	0.96
Trafo8	$--5.841 \times 10^{-11}$	2.047×10^{-7}	4.013×10^{-6}	0.98
Trafo9	-3.628×10^{-12}	6.431×10^{-7}	4.414×10^{-5}	0.96

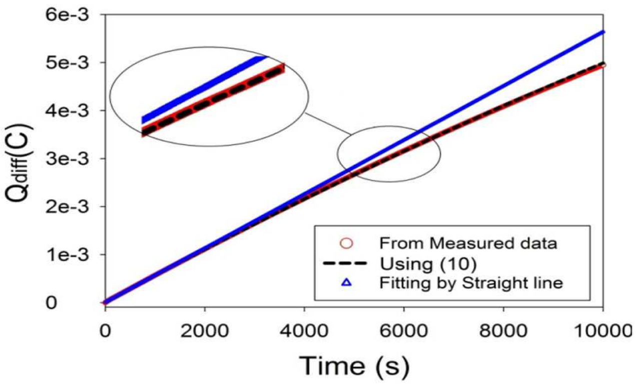

Fig. 3 *Charge difference profile of Trafo1 fitted with straight line [11] and proposed relation (10) (It is difficult to identify each plot)*

obtained using PDC data recorded for 10,000 s is represented by $Q^{m1}_{\mathrm{diff}}(t)$. The value of t_1 needs to be suitably selected so that initial non-linearity in $Q_{\mathrm{diff}}(t)$ (which does not maintain (10)) can be avoided. In order to identify the optimum value of t_1, its value is varied from 50 to 120 s. Fig. 4*a* through Fig. 4*d* illustrates the capability of (10) in approximating $Q^{m1}_{\mathrm{diff}}(t)$ when t_1 is varied for *Trafo1*, *Trafo3,* and *Trafo4*. It can be observed from Fig. 4*a* through Fig. 4*d* that the profile of $Q_{\mathrm{diff}}(t)$ estimated by (10) almost overlaps with that of $Q^{m1}_{\mathrm{diff}}(t)$ for $t_1 \geq 100$ s. This in turn ensures proper identification of (10) coefficients. Such observation is also found to be true for all the other tested transformers. Hence, in the present work, t_1 is assumed to be 100 s.

Equation (9) through (10) show that difference between polarisation and depolarisation current can be obtained from $Q_{\mathrm{diff}}(t)$. Furthermore, (11) shows that i_{condn} is equal to (b-2|a|t_{fnl}). Discussion presented above suggests that i_{condn} can be easily identified using (12), (13) and $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq 10000)$. Therefore, minimisation of time required for i_{condn} estimation can be addressed by minimising span of PDC data $0 \leq t \leq t_2$ which is used for identification of $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq 10000)$. In the present work, $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq 10000)$ is obtained from PDC data $0 \leq t \leq t_2$ in two steps. First, PDC data measured for $0 \leq t \leq t_2$ is used to identify $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq t_2)$. Next, coefficients of (10) are evaluated using above-mentioned $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq t_2)$. Finally, $Q^{m1}_{\mathrm{diff}}(t_2 \leq t \leq 10000)$ is predicted using (10). Hence, the span $0 \leq t \leq t_2$ must be selected in such a way so that the following conditions are satisfied:

- PDC data recorded for $0 \leq t \leq t_2$ must be capable of identifying $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq t_2)$ successfully.
- Span of $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq t_2)$ so obtained, must be sufficient for identifying (10) coefficients.

Identification of $Q^{m1}_{\mathrm{diff}}(0 \leq t \leq t_2)$ profile from PDC data measured for $0 \leq t \leq t_2$ is not straight forward. This is due to the inherent nature of the dipolar relaxation processes responsible for the generation of depolarisation current. During the polarisation process, the dipoles slowly get oriented in the direction of applied field. The energy gained by the dipoles during this process is spent in the subsequent depolarisation period when the previously aligned dipoles relax to their original position. Therefore, depolarisation current profile invariably gets affected if the polarisation current measurement phase is conducted only for a short duration. The energy (E_{ps}) gained by the insulation during short duration polarisation (<10,000 s) is sufficient for generation of a depolarisation current with magnitude that is lesser than that which would have been obtained after charging the insulation for 10,000 s. It is understood that this depolarisation current also remains distinctly different from the current that would have been obtained if polarisation phase was allowed to continue for 10,000 s. As the polarisation period is shortened, less energy is stored in the dielectric and consequently the depolarisation current (with respect to magnitude and profile) get affected. In order to improve readability, this short duration depolarisation current is henceforth represented as $i^{\mathrm{red}}_{\mathrm{depolar}}(0 < t \leq t_2)$. It is understood that the magnitude of polarisation current remains unaffected even if it is measured for a short duration as long as the charging voltage (U_0)

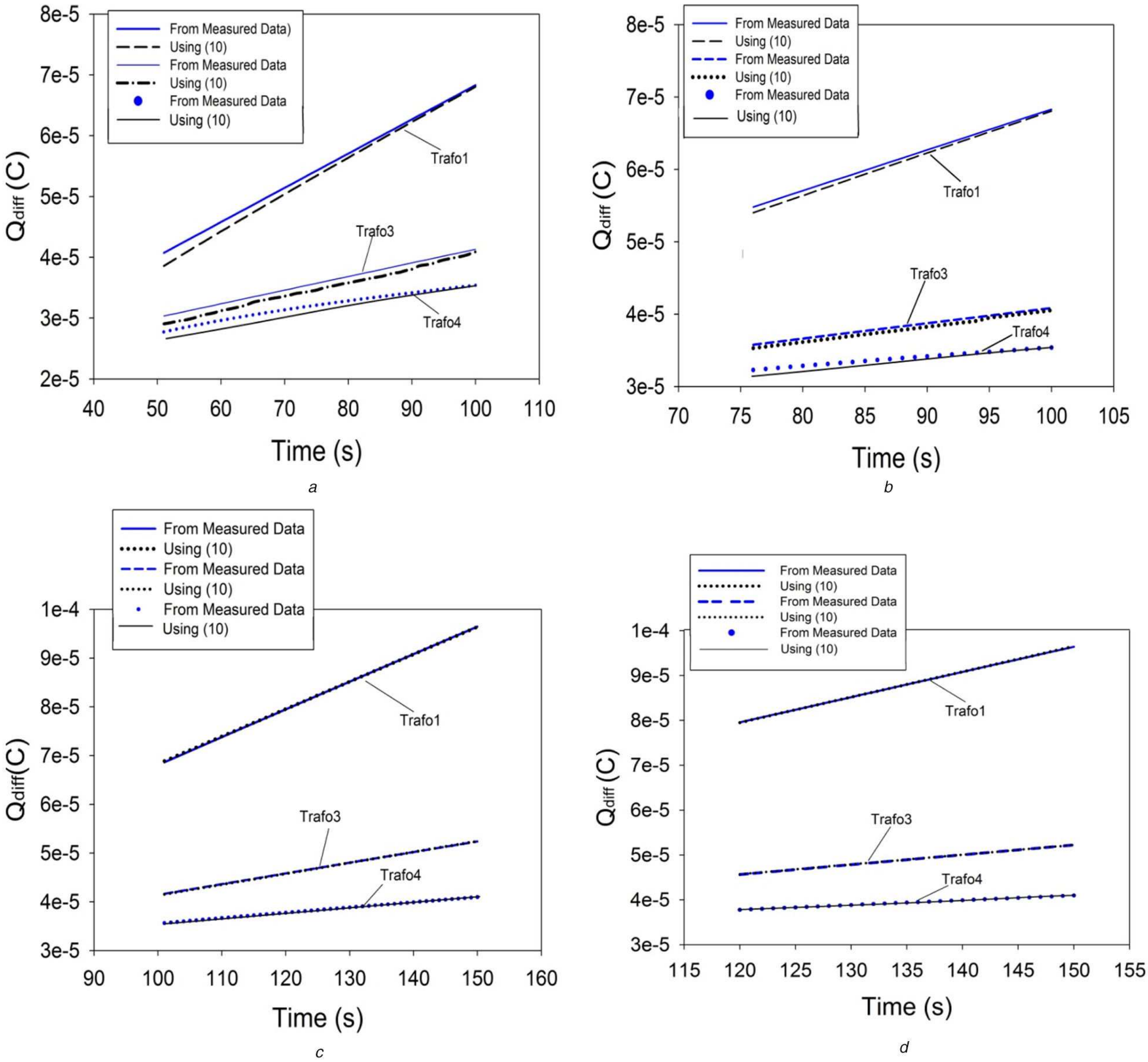

Fig. 4 *Estimated and measured Q_{diff} profile*

(a) Estimated and measured $Q_{\text{diff}}(t)$ for $t_1 = 50$ s, ***(b)*** Estimated and measured $Q_{\text{diff}}(t)$ for $t_1 = 75$ s, ***(c)*** Estimated and measured $Q_{\text{diff}}(t)$ for $t_1 = 100$ s, ***(d)*** Estimated and measured $Q_{\text{diff}}(t)$ for $t_1 = 120$ s

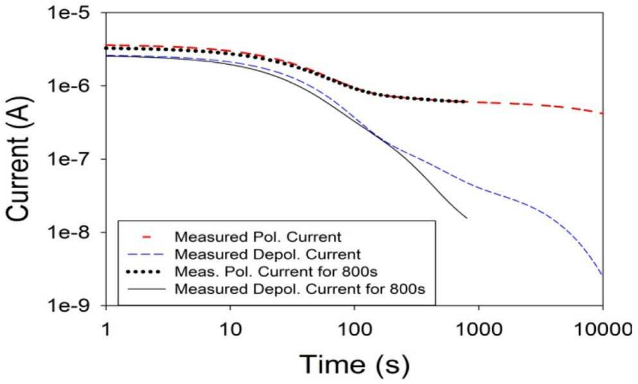

Fig. 5 *PDC data recorded from Trafo1 for different time duration*

remains same. Therefore, the charge difference profile $Q^{m2}_{\text{diff}}(t)$ (obtained using $i_{\text{polar}}(0 \le t \le t_2)$ and $i^{\text{red}}_{\text{depolar}}(0 \le t \le t_2)$) will have higher magnitude compared to $Q^{m1}_{\text{diff}}(t)$ for $0 < t < t_2$.Authors of the present paper have reported a neural network-based forecasting technique [14] for reducing polarisation current measurement time. Although applicable of polarisation current, this technique [14] is incapable of identifying profile of $i_{\text{depolar}}(t)$; $0 < t < 10{,}000$ using only $i^{\text{red}}_{\text{depolar}}(0 < t \le t_2)$. Consequently, technique mentioned in [14] finds limited application in determination of $Q^{m1}_{\text{diff}}(t)$ in the present work. Fig. 5 shows the profile of PDC data of different durations obtained for *Trafo1*. In Fig. 5, the polarisation current measured for 800 and 10,000 s almost overlaps with each other. This is expected as the charging voltage is kept same for both the measurements. It is worth mentioning here that in Fig. 5 PDC corresponding to 800 and 10,000 s were measured on two separate occasions with sufficient *cooling time* between the two measurements. During the *cooling time,* the terminals of the transformer were kept short-circuited to neutralise any residual charge present in the system. This is done to ensure that two measurements are not influenced by each other. The above discussion suggests that identification of $Q^{m1}_{\text{diff}}(t)$ from $i_{\text{polar}}(0 \le t \le t_2)$ and $i^{\text{red}}_{\text{depolar}}(0 \le t \le t_2)$ is possible by suitably reducing the magnitude of $i_{\text{polar}}(0 \le t \le t_2)$. This in turn implies application of charging voltage <1000 V during polarisation current measurement phase.

Available literature [4, 15] shows that application of reduced charging voltage only affects the magnitude of polarisation current without significantly affecting its profile. In the present work, an iterative approach is taken to identify $Q^{m1}_{\text{diff}}(t)$ from $i_{\text{polar}}(0 \le t \le t_2)$

Table 5 Correlation coefficient (R) and NRMSE obtained between measured and estimated profile of Q^{m1}_{diff} for Trafo1

t_2	Straight line fitting [16]		Quadratic relation given by (12)	
	R	NRMSE	R	NRMSE
600s	0.74	9.32	0.91	4.67
700s	0.81	7.71	0.94	2.92
800s	0.86	6.16	0.99	1.89
900s	0.89	5.27	0.99	1.87

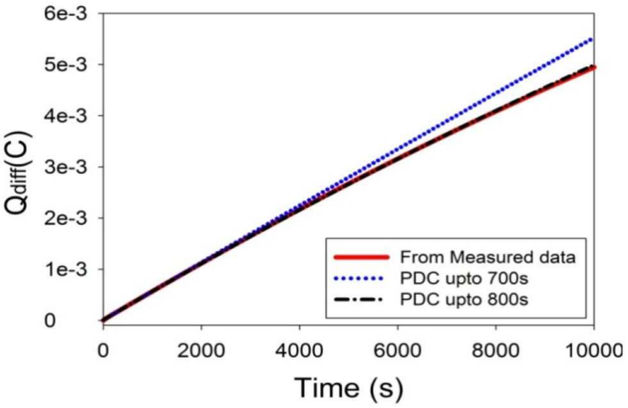

Fig. 6 *Measured and predicted charge difference profile of Trafo1 using (12) for $t_2 = 700$ s and 800s*

and $i^{\text{red}}_{\text{depolar}}(0 \le t \le t_2)$ for $0 < t < t_2$.This approach introduces the concept of a modified polarisation current $i^{\text{short}}_{\text{polar}}(t)$(with magnitude lesser than $i_{\text{polar}}(t)$) which coupled with $i^{\text{red}}_{\text{depolar}}(t)$ provides $Q^{m1}_{\text{diff}}(t)$ for $0 < t < t_2$ as per (15)

$$Q^{m1}_{\text{diff}}(t) = \int_{t=0}^{t} \left(i^{\text{short}}_{\text{polar}}(t) - i^{\text{red}}_{\text{depolar}}(t)\right)\mathrm{d}t;\ 0 \le t \le t_2 \qquad (15)$$

The relationship between $i^{\text{short}}_{\text{polar}}(t)$ and $i_{\text{polar}}(t)$ is given by (16)

$$i^{\text{short}}_{\text{polar}}(t) = k \times i_{\text{polar}}(t);\ 0 < k < 1\,;\ 0 \le t \le t_2 \qquad (16)$$

It should be mentioned here that $i^{\text{short}}_{\text{polar}}(t)$ is not actually measured from the insulation but is only used as an intermediate variable to reach $Q^{m1}_{\text{diff}}(0 \le t \le t_2)$ using $i_{\text{polar}}(0 < t < t_2)$ and $i^{\text{red}}_{\text{depolar}}(0 < t \le t_2)$. In the case of tested transformers, k is observed to have value of 0.863, 0.885, 0.906, and 0.920 as t_2 varies from 600 to 900 s in steps of 100 s. For a given t_2, the value of k is observed to remain relatively same for all the tested transformers. Hence, it can be opined that the value of k is not influenced by insulation geometry and can be safely used in the case of an in-service transformer which is not considered in the present work. The methodology of identifying k for the tested transformers (with different values of t_2) is given below.

Step 1: Assume $k = 1$.

Step 2: Find $i^{\text{short}}_{\text{polar}}(t)$ using (16).

Step 3: Evaluate charge difference profile $Q_{\text{diff}}(t)$ using $i^{\text{short}}_{\text{polar}}(t)$, $i^{\text{red}}_{\text{depolar}}(0 < t \le t_2)$ and (9).

Step 4: If $Q_{\text{diff}}(t)$ and $Q^{m1}_{\text{diff}}(t)$ have identical profile, display k and stop.

Step 5: If $Q_{\text{diff}}(t)$ and $Q^{m1}_{\text{diff}}(t)$ have dissimilar profiles reduce k by 0.001 and go to Step 2.

It was observed, for $t_2 \ge 800$ s, that the charge difference profile (estimated using proposed method) matches well with actually observed charge difference profile for *Trafo1*. Table 5 shows the result obtained for *Trafo1* when t_2 is varied from 600 to 900 s. It is reported in [11] that $Q_{\text{diff}}(t)$ follows a linear relationship with time. In order to present the merit of the discussed method over that reported in [11], $Q_{\text{diff}}(t)$ is modelled using both linear relationship [11] and proposed quadratic relationship given by (10). Table 5 shows the performance of the above-mentioned methods.

Table 5 shows that application of straight-line-based modelling for $Q_{\text{diff}}(t)$ prediction does not provide satisfactory result even for $t_2 = 900$ s. Paper conductivity or σ_{paper} is a well-recognised aging sensitive performance parameter among utilities. Unlike, oil conductivity (σ_{oil}) which can be evaluated quickly using initial values of PDC data, computation of σ_{paper} is difficult as it requires PDC data measured for larger value of time [6]. Needless to say, assessment of σ_{paper} needs large measurement time. This time can be significantly reduced using the proposed method. Using (14) along with (5) can essentially reduce σ_{paper} computation time from 20,000 s (10,000 s each for polarisation and depolarisation current measurement) to only (2×800) s. Fig. 6 shows the profile of $Q_{\text{diff}}(t)$ obtained in the case of *Trafo1* when t_2 is varied from 700 to 800 s. The red colour line in Fig. 6 represents $Q^{m1}_{\text{diff}}(t)$ (evaluated from PDC measured for 10,000 s) while the blue and black colour lines represent $Q^{m1}_{\text{diff}}(t)$ profile estimated by the proposed method for $t_2 = 700$ and 800 s. Fig. 6 coupled with Table 5 show that beyond $t_2 = 800$ s correlation coefficient (R) and NRMSE does not vary appreciably when (10) is used for modelling $Q^{m1}_{\text{diff}}(t)$. On the other hand, variation of R and NRMSE given in columns 2 and 3 of Table 5 suggest that even PDC data recorded up to 900 s is insufficient for predicting $Q_{\text{diff}}(t > 900\text{ s})$ when a linear relationship is used to model $Q_{\text{diff}}(t)$. Similar results were observed when data obtained from other tested transformers were analysed. Hence, it can be opined that PDC data recorded up to 800 s coupled with (10) can be successfully used for predicting successfully $Q^{m1}_{\text{diff}}(t)$ for $800 < t < 10^4$s. In order to illustrate that $t_2 = 800$ s is indeed sufficient for satisfactory operation of proposed method, value of σ_{paper} (evaluated using (5) and (14)) is evaluated for the tested transformers. Table 6 shows the values of σ_{paper} obtained for different transformers when t_2 is varied from 600 to 900 s in steps of 100 s. The percentage deviation between value of σ_{paper} (obtained using measured PDC data recorded upto 10,000 s) and that evaluated using the proposed method (for different value of t_2) is shown in column 5 of Table 6.

The error values are observed to be significantly high for $t_2 \le 700$ s which becomes acceptable for $t_2 \ge 800$ s. This signifies that PDC data measurement time up to 800 s is sufficient to identify σ_{paper} using PDC data recorded up to 800 s. Available literature shows that paper-moisture can be obtained using paper-conductivity. In [16], an expert system was developed to calculate paper moisture (%pm) from paper conductivity. In [17], a mathematical relationship between paper conductivity and paper moisture was proposed at room temperature, given by the following equation.

$$\%p.m. = 0.3642\ln(\sigma_{\text{paper}}) + 2.7984 \qquad (17)$$

The relationship between %pm andσ_{paper} (in pS/m) given in (17) is found to be capable of modelling the data provided in other notable published results i.e. Fig. 11 of [16] and Fig. 5.40 of [3]. Therefore, it can be opined both %pm and σ_{paper} can be obtained using PDC data recorded up to 800 s. Table 7 shows the value of %pm obtained using (17) andσ_{paper} (corresponding to $t_2 = 800s$) given in Table 6. It can be observed that the value of %pm is increasing as the operational age increases. This is in accordance with CIGRE WG A2.30 report [18] which states that %pm increases as the operational age of the transformer increases.

Flow chart shown in Fig. 7 illustrates the major steps involved in identifying paper conductivity from short duration PDC data.

Table 6 Comparison σ_{paper} obtained using the proposed method with that obtained using PDC data for various real life power transformers

Transformer name	$t2$ (s)	Paper conductivity σ_{paper} (S/m)		
		Using PDC data measured for 10,000s	Using predicted data	%Error
Trafo1	600	6.56×10^{-13}	8.13×10^{-13}	19.31
	700		7.54×10^{-13}	12.99
	800		6.70×10^{-13}	2.08
	900		6.64×10^{-13}	1.20
Trafo2	600	3.52×10^{-14}	5.02×10^{-14}	29.88
	700		4.38×10^{-14}	19.63
	800		3.62×10^{-14}	2.75
	900		3.58×10^{-14}	1.67
Trafo3	600	2.56×10^{-13}	4.32×10^{-14}	40.74
	700		3.76×10^{-14}	31.91
	800		2.65×10^{-14}	3.39
	900		2.61×10^{-14}	1.91
Trafo4	600	2.03×10^{-13}	3.49×10^{-13}	41.83
	700		2.89×10^{-13}	29.75
	800		2.13×10^{-13}	4.69
	900		2.07×10^{-13}	1.93
Trafo5	600	8.79×10^{-14}	1.12×10^{-13}	21.51
	700		9.87×10^{-14}	10.94
	800		9.02×10^{-14}	2.54
	900		8.96×10^{-14}	1.89
Trafo6	600	1.03×10^{-12}	2.14×10^{-12}	51.86
	700		1.67×10^{-12}	38.92
	800		1.09×10^{-12}	5.50
	900		1.08×10^{-12}	4.62
Trafo7	600	3.991×10^{-15}	8.091×10^{-16}	79.72
	700		1.262×10^{-15}	68.37
	800		3.832×10^{-15}	3.98
	900		3.876×10^{-15}	2.88
Trafo8	600	6.51×10^{-15}	1.271×10^{-14}	48.81
	700		8.795×10^{-15}	25.98
	800		6.726×10^{-15}	3.21
	900		6.663×10^{-15}	2.29
Trafo9	600	2.95×10^{-13}	9.189×10^{-13}	67.89
	700		4.647×10^{-13}	36.51
	800		3.121×10^{-13}	5.47
	900		3.077×10^{-13}	4.12

5 Conclusion

In the present work, a methodology is proposed which can estimate paper conductivity using PDC measurement that is carried out for short durations. Based on the findings reported in the paper, the following conclusions can be made:

- • The proposed method is capable of identifying σ_{paper} using PDC data spanning only few hundred seconds.
- • The estimated value of σ_{paper} can be further used for predicting paper-moisture using (17).
- • Estimation of both σ_{paper} and %pm from PDC data measured for few hundred seconds (instead of conventional 10,000 s) significantly reduces the equipment shut-down time. Hence, the proposed method is beneficial for utilities.

Table 7 Paper moisture content (%pm) of different tested transformers using (17) and σ_{paper} obtained from PDC data (measured upto800 s)

Transformer name	%pm (Using IDAX)	%pm	Operational age (in years)
Trafo1	NA	2.65	33–36
Trafo2	NA	1.59	30–33
Trafo3	NA	1.47	20–23
Trafo4	2.20	2.23	31–34
Trafo5	1.80	1.92	31–34
Trafo6	NA	2.83	32–35
Trafo7	NA	0.77	12–15
Trafo8	1.00	0.96	11–14
Trafo9	2.20	2.35	27–30

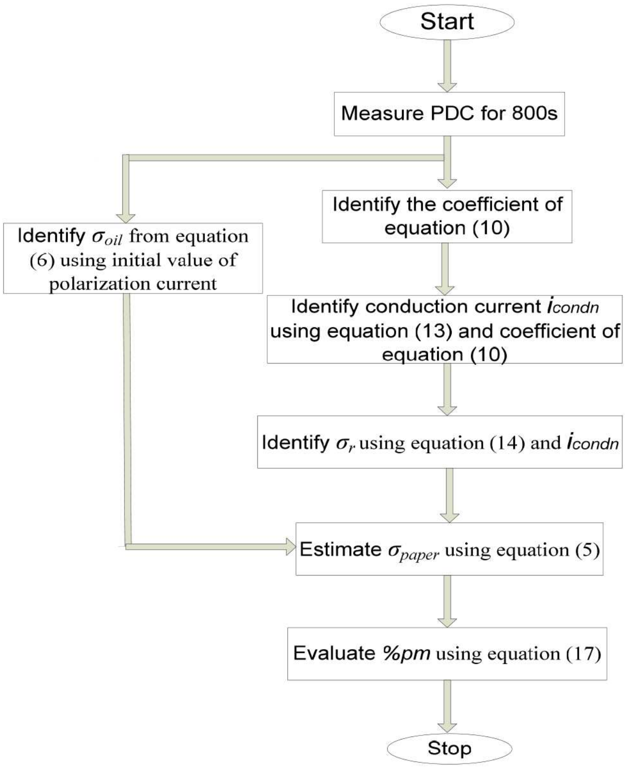

Fig. 7 *Flow chart of proposed method*

- • The proposed method is tested on data collected from several in-situ powers transformers. Hence, the accuracy of the proposed method is ensured for real-life units.
- • The final steady value of PDC data is crucial for evaluating σ_{paper} (using existing technique). Due to its low magnitude, the steady value becomes prone to noise during field measurement. The proposed method eliminates the requirement of measuring PDC at larger value of time and hence is more immune to field noise.
- • Reduction of PDC measurement time for insulation diagnosis makes the subsequent analysis less susceptible to changes in environmental conditions which rarely stay constant for a long duration.

6 References

[1] Zaengl, W.S.: ‘Dielectric spectroscopy in time and frequency domain for HV power equipment, part i: theoretical considerations’, *IEEE Electr. Insul. Mag.*, 2003, **19**, (5), pp. 5–19

[2] Houhanessian, V.D., Zaengl, W.S.: ‘Application of relaxation current measurements to on-site diagnosis of power transformers’. in Proc. of IEEE Conf. on Electrical Insulation and Dielectric Phenomena, Minneapolis, USA, 1997, pp. 45–51

[3] Chakravorti, S., Dey, D., Chatterjee, B.: ‘*Recent trends in the condition monitoring of transformers*’ (Springer, London, 2013)

[4] Saha, T.K., Purkait, P.: 'Some precautions for the field users of PDC measurement for transformer insulation condition assessment'. Proc. of Power Engineering Society General Meeting, Toronto, Canada, 2003, pp. 2371–2376

[5] Saha, T.K., Purkait, P., Müller, F.: 'Deriving an equivalent circuit of transformers insulation for understanding the dielectric response measurements', *IEEE Trans. Power Deliv.*, 2005, **20**, (1), pp. 149–157

[6] Bisht, N., Mishra, D., Baral, A., *et al.*: 'Denoising of polarization current for effective diagnosis of power transformer insulation'. Proc. of CIGRE-CBIP 6th Int. Conf. on Large Power Transformers - Modern Trend in Application, Installation, operation and maintenance, New Delhi, India, 2017, pp. 237–248

[7] Baral, A., Chakravorti, S.: 'Compensating the effect of temperature variation on dielectric response of oil–paper insulation used in power', *IEEE Trans. Dielectr. Electr. Insul.*, 2016, **23**, (4), pp. 2462–2474

[8] Baral, A., Chakravorti, S.: 'A modified Maxwell model for characterization of relaxation processes within insulation system having non-uniform aging due to temperature gradient', *IEEE Trans. Dielectr. Electr. Insul.*, 2013, **20**, (2), pp. 524–534

[9] Saha, T.K., Purkait, P.: 'Investigations of temperature effects on the dielectric response measurements of transformer oil–paper insulation system', *IEEE Trans. Power Deliv.*, 2008, **23**, (1), pp. 252–260

[10] Saha, T.K., Purkait, P.: 'Investigation of polarization and depolarization current measurements for the assessment of oil–paper insulation of aged transformers', *IEEE Trans. Dielectr. Electr. Insul.*, 2004, **11**, (1), pp. 144–153

[11] Saha, T.K., Pradhan, M.K., Yew, J.H.: 'Optimal time selection for the polarisation and depolarisation current measurement for power transformer insulation diagnosis'. Proc. of Power Engineering Society General Meeting, Tampa, USA, 2007, pp. 1–7

[12] Mishra, D., Haque, N., Baral, A., *et al.*: 'Assessment of interfacial charge accumulation in oil-paper interface in transformer insulation from polarization-depolarization current measurements', *IEEE Trans. Dielectr. Electr. Insul.*, 2017, **24**, (3), pp. 1665–1673

[13] Mishra, D., Haque, N., Baral, A., *et al.*: 'Effect of charge accumulated at oil-paper interface on parameters considered for power transformer insulation diagnosis', *IET Sci. Meas. Technol.*, 2018, **12**, (3), pp. 411–417

[14] Mishra, D., Pradhan, A.K., Baral, A., *et al.*: 'Reduction of time domain insulation response measurement duration for fast and effective diagnosis of power transformer', *IEEE Trans. Dielectr. Electr. Insul.*, 2018, **25**, (5), pp. 1932–1940

[15] Der Houhanessian, V., Zaengl, W.S.: 'Time domain measurements of dielectric response in oil–paper insulation systems'. IEEE Int. Symp., Montreal, QC, Canada, 1996, pp. 47–52

[16] Saha, T.K., Purkait, P.: 'Investigation of an expert system for the condition assessment of transformer insulation based on dielectric response measurements', *IEEE Trans. Power Deliv.*, 2004, **19**, (3), pp. 1127–1134

[17] Ojha, S.K., Purkait, P., Chakravorti, S.: 'A comparative study of conductivity and moisture for condition assessment of oil–paper insulation of a transformer'. Proc. of IEEE Int. Conf. on Condition Assessment Techniques in Electrical Systems (CATCON), Bangalore, India, 2015, pp. 99–104

[18] Sokolov, V., Aubin, J., Davydov, V., *et al.*: 'Moisture equilibrium and moisture migration within transformer insulation systems', Report of CIGRE WG A2.30 Technical Brochure 359, 2008