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Compensating the effect of residual dipole energy on dielectric response for effective diagnosis of power transformer insulation

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Abstract: Analysis of relaxation current is a widely accepted method for diagnosis of power transformer insulation. The accuracy of such diagnostic tool is dependent on insulation model parameters which are formulated using relaxation current. This implies that the accuracy and hence the reliability of existing insulation diagnosis methods indirectly depends on the accuracy of the recorded polarisation depolarisation current. Sometimes during field measurement relaxation current measurement equipment fails to record proper current, even after application of dc charging voltage. As per utilities, this primarily happens due to improper/loose connections (this cannot be avoided entirely due to the involvement of human factors) and such situation is usually followed by checking and rectifying improper connection. The analysis presented in this study shows that the polarisation current recorded immediately after rectifying the correction is inaccurate and leads to the erroneous diagnosis. Furthermore, it is observed that in these cases, the measured and calculated (using insulation model) values of performance parameters like dissipation factor, polarisation index, and paper-moisture differ by a large extent. This work is aimed at removing the effect of this residual dipole energy introduced during the improper connection phase.

1 Introduction

During the operational life of a transformer, its insulation experiences different stresses [1–7] which reduce its desirable properties and change the relaxation characteristics of dipole groups present therein. This affects the profile of the measured dielectric response in time and frequency domain. Consequently, in recent times two techniques have gained popularity in the field of insulation diagnosis namely time-domain spectroscopy (TDS) and frequency-domain spectroscopy (FDS). As far as the information related to the condition of insulation is concerned, both TDS and FDS are reported to provide the same results [8–10].

The TDS data analysis contains two techniques, namely ‘return voltage measurement’ (RVM) and ‘polarisation depolarisation current’ (PDC). According to the report of Cigre Task Force D1.01.09 [11], the available interpretation schemes of RVM result are too simple to ensure reliable insulation diagnosis. Consequently, many researchers [2–4] reported techniques based on analysis of PDC data for providing information relevant to the insulation condition [1–4, 8–13]. Researchers have reported [2, 4] many *R*–*C* networks for modelling the time-domain dielectric response function of insulation [1, 8]. Perhaps, one of the most widely used circuits by researches is the conventional Debye model (CDM) [2]. CDM consists of the parallel combination of series *R*, *C* branches where each *RC* branch represents the different dipole groups present in dielectric insulation. In all these papers it is inherently assumed that the PDC data being analysed have been recorded correctly. It is shown in this paper that during field measurement this assumption is not always true due to the involvement of human factors. Results reported in this paper suggest that inaccuracy in PDC data caused by such incorrect measurement is due residual dipole energy (E_r). Under such a situation, the accuracy of the results obtained using available techniques [1–4] cannot be ensured. This inadvertently leads to an incorrect diagnosis of the insulation system concerned. The present work is aimed at removing the effect of E_r from the recorded polarisation current for obtaining correct insulation model parameters and ensures satisfactory diagnosis.

2 Effect of residual dipole energy on insulation model parameters

As per the utilities, using Electrometer-based PDC equipment [8, 14] it is observed that sometimes even after application of dc charging voltage, the instrument does not record proper relaxation current. In some of these cases, the Data Acquisition (DAQ) system is observed to be unable to record any current whatsoever. While in few other cases, the recorded current data does not match the well-known monotonic decreasing profile thus rendering it useless. Upon investigation, it is found that the reason behind this inability of the DAQ system of the instrument to record proper data is an improper or a loose connection. It is understood that such problem during field measurement cannot be avoided entirely due to the involvement of human factors. It is also not possible to detect the presence of loose connection immediately after application of dc charging voltage as the DAQ system is specifically designed not to record relaxation current for the first few seconds [3] in order to avoid transients. The KEITHLEY 6517B Electrometer-based equipment (schematically shown in Fig. 1) referred above is developed at High Tension Laboratory, Jadavpur University. The equipment, successfully used on several sites [14, 15], is less susceptible to field noise as it employs appropriate filtering [16, 17].

It can be observed from Fig. 1 that the DAQ will not be able to record any data if the BLACK wire is not connected securely to the insulation. As the tank remains grounded, the dc charging voltage applied to the insulation using RED wire will introduce dipole energy (E_r) during this phase. On the other hand, loose connection between the tank and GND terminal of 6517B might lead to the introduction of noise rendering the recorded data useless. As per the utility, when the above mentioned problems occur, it is usually followed by checking and rectifying improper connection. The reading obtained post-correction will no longer be accurate, as E_r injected into the system during improper connection phase is not accounted for. It can be observed that the initial charge present in the insulation will alter the profile of the polarisation current which affects the accuracy of relaxation current based diagnosis techniques. Further, insulation model parameters (and also parameters like tanδ, paper-moisture) calculated from affected PDC

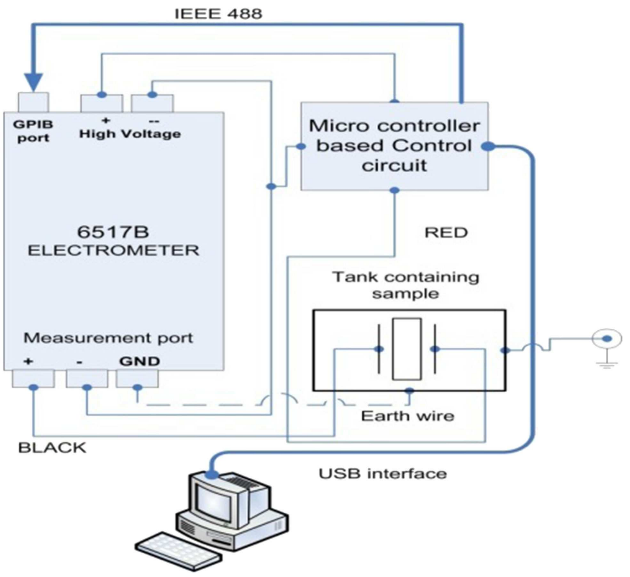

Fig. 1 *Schematic of PDC equipment*

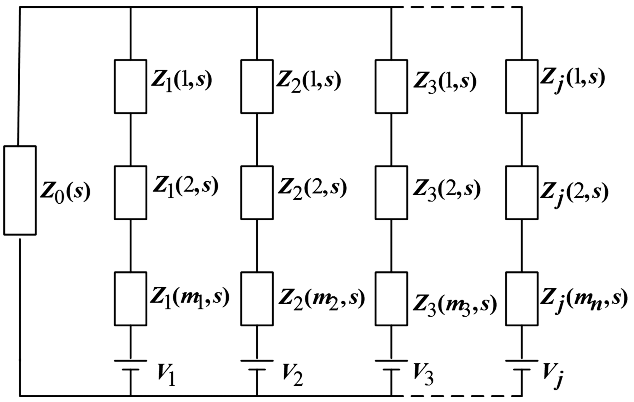

Fig. 2 *Structure of MDM affected by E_r*

data, will differ significantly from actual values thus influencing insulation diagnosis.

Unless the DAQ module of the measurement system checks for a residual charge within the insulation (before the commencement of PDC measurement), the presence of E_r cannot be detected. It is a known fact that post-shutdown and prior PDC measurement, terminals of a power transformer are kept short-circuited for a considerable amount of time to attain thermal equilibrium and neutralise any residual charge. This is the reason why at the design stage of the KEITHLEY Electrometer-based PDC measurement setup [12–14], it is assumed that the insulation under test is in the charge-free state. It can be understood from the above discussion that the short-circuited phase prior to PDC measurement is unable to influence the effect of E_r on the recorded relaxation characteristic. As per the information provided to the authors, the tenure of this improper connection (t_{conn}) does not extend beyond several seconds to few minutes. The authors are further informed that the utility considers the effect of E_r on polarisation current data insignificant as dipole groups present in cellulose have a much larger time constant [1, 2]. As a result, neutralising the effect of E_r by short-circuiting transformer terminals is not considered necessary by utilities after the improper connections are identified and rectified. The related analysis presented in this paper shows that ignoring the influence of E_r renders the predicted value of critical parameters like %pm unreliable leading to inaccurate insulation diagnosis. Data presented in this paper suggests that severity of inaccuracy in estimating %pm [13] increases with increase in the value of t_{conn}, irrespective of the operational age of the unit concerned. In order to address this problem, an iterative method (discussed in the next section) is proposed which takes as input $i_{pol}^{afct}(t)$ (affected by E_r) and predicts the profile of $i_{pol}^{pred}(t)$ (not influenced by E_r) using commonly measured performance parameters that are likely to be available with the utilities.

3 Developed method

The influence of E_r can be modelled in the form of non-zero initial condition for branch capacitors in CDM. Recent developments in the field of insulation modelling suggest that modified Debye model (MDM) (formulated using polarisation current) is a better option for representing insulation. Therefore, the proposed method first identifies the MDM parameters using the affected polarisation current. Thereafter, it tries to estimate the value of the non-zero initial condition in each branch of the identified MDM using parameters that are likely to be available with utilities. These parameters include polarisation index or *PI* (ratio of insulation resistance (*IR*) measured at 10 and 1 min), dielectric absorption ratio or *DAR* (ratio of *IR* measured at 1 min and 30 s) and tanδ. In order to reduce computational complexity, non-zero initial conditions of all sub-elements in a branch are clubbed together and are represented by a single voltage source as shown in Fig. 2.

In Fig. 2, $Z_0(s)$ represent the influence of insulation dc IR (R_0) and geometrical capacitance (C_0). On the other hand, the series elements $Z_j(n,s) = R_j(n) + 1/sC_j(n)$; $n = 1, 2, \ldots, m_j$ of any branch j represents the relaxation process of a specific dipole group present in different regions of the insulation [4, 12, 13]. The dc voltage source V_j represents the effect of non-zero initial condition in the jth branch of MDM. The expression of V_j shown in Fig. 2 is modelled as

$$\left.\begin{aligned} V_j &= V_{dc} \times \left(1 - \exp\left(-\frac{t_{conn}}{\Lambda_R^j/\Lambda_C^j}\right)\right) \\ \Lambda_R^j &= \sum_{k=1}^{m_j} R_i(k), \quad \Lambda_C^i = \sum_{k=1}^{m_j} \frac{1}{C_i(k)} \end{aligned}\right\} \tag{1}$$

In (1), V_{dc} and t_{conn} represent the dc charging voltage and the time for which the DAQ system did not record proper relaxation current (after the initial transients are over), respectively. Given the nature of the problem and the polarity of the dc charging voltage, it is evident that the polarity of the voltage V_j will be such that it will always oppose the dc step voltage. Therefore, in the presence of E_r, the value of Λ_R^j obtained from the insulation model will always be less than the actual value. It is understood that the effect of such E_r will be less pronounced for the branches having higher time constants. However, it should be remembered that Λ_R^j alone finds limited use in determining cellulose condition as its value is affected by insulation geometry [1, 2]. On the other hand, computation of performance parameters like transfer function zero (Z_1) [12, 13] (reported to be less sensitive to insulation geometry) is affected by all branch parameters. The discussion presented above suggests that identification and hence proper diagnosis can be ensured once the value of t_{conn} in (1) is identified. The developed method does so by an iterative method which identifies t_{conn} by comparing the estimated and measured values of conventional parameters of insulation diagnosis. Validation of the results generated by the developed method is done by comparing the predicted and measured values PI, DAR, tanδ, IR and %pm. At the kth iteration of the proposed technique to calculate the deviations between the calculated and measured values of the following parameters:

- DAR,
- PI,
- IR measured at 60 s,
- tanδ.

Next, the deviations calculated for tanδ, *PI*, *DAR* and *IR* values are normalised by their respective measured values. These normalised

Fig. 3 *Constructed test sample immersed in mineral oil*

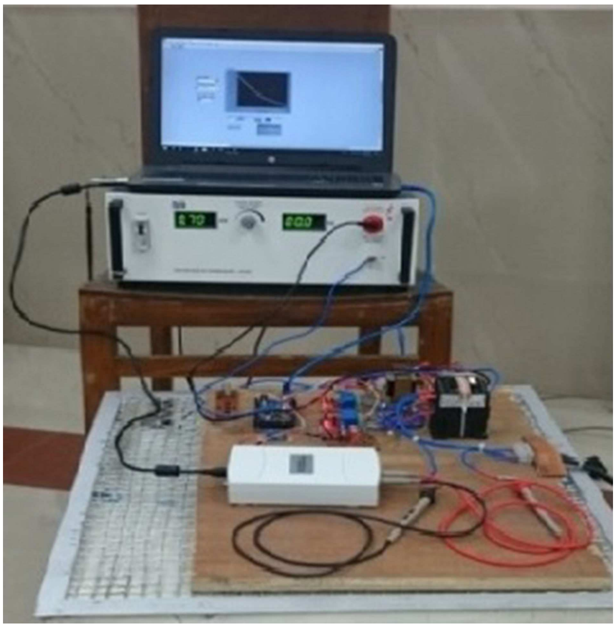

Fig. 4 *NI USB DMM 4065 based PDC measurement setup*

errors are then added to obtain total error *Err*. Thereafter, the values of $\Lambda_R^j(k)$, $\Lambda_C^j(k)$ and $t_{\text{conn}}(k)$ are obtained using (2)–(4)

$$\left.\begin{aligned} \Lambda_R^j(k) &= \Lambda_R^j(k-1) \times \left(1 + \frac{V_j(k-1)}{V_{\text{dc}}}\right) \\ \frac{1}{\Lambda_C^j(k)} &= \frac{\tau_j(k-1)}{\Lambda_R^j(k)} \\ \tau_j(k) &= \Lambda_R^j(k)/\Lambda_C^j(k) \end{aligned}\right\} \quad (2)$$

In (2), the factor $V_j(k-1)$ is dependent on $(k-1)$th iteration values and is given as

$$V_j(k-1) = V_{\text{dc}} \times \left(1 - \exp\left(-\frac{t_{\text{conn}}(k-1)}{\tau_j(k-1)}\right)\right) \quad (3)$$

At the start of the iteration procedure, values of $\Lambda_R^j(1)$ and $\Lambda_C^j(1)$ are obtained from MDM, parameterised using affected polarisation current. The value of t_{conn} in (1) on the other hand, is set to a small predetermined value. At the end of the *k*th iteration, the value of t_{conn} is updated using as

$$t_{\text{conn}}(k) = t_{\text{conn}}(k-1)/Err \quad (4)$$

IR (measured at 60 s) used in the proposed method is selected based on the fact that is likely to be available with the utilities. However, any number of points from IR profile [18] can be used for the proposed method. This iterative process of branch parameter adjustment is stopped when any more adjustment does not affect the total error *Err* appreciably. In order to improve clarity, the major steps involved in the proposed method are given below:

Step 1: Obtain MDM branch parameters using affected polarisation current data.
Step 2: Assume the initial value of t_{conn}.
Step 3: Evaluate V_j using (3) and update MDM parameters using (2).
Step 4: Calculate tanδ, *IR*, *PI*, *DAR* using MDM parameters obtained in Step 3.
Step 5: Obtain total error (*Err*) using deviation between measured and calculated values of tanδ, *IR*, *PI*, *DAR*.
Step 6: If *Err* is greater than predetermined small value, update t_{conn} value as per (4) and go to Step3.
Step 7: Evaluate Z_1 using latest MDM parameters followed by tanδ, *IR*, *PI*, *DAR*.
Step 8: Predict the nature of compensated polarisation current using MDM parameters.

4 Application to laboratory sample

In order to test the effectiveness of the proposed method, it is imperative that the method is first tested on laboratory samples. The proposed method is designed for compensating the effect of E_r, which might have been introduced due to reasons mentioned earlier. PDC measurement being an off line measurement technique, it is implied that the method is applicable to temperature equilibrium. However, the influence of paper moisture, aging, and temperature on the accuracy of the method needs to be investigated as these factors directly influence the dielectric response of the insulation. Other external environmental factors like humidity are less likely to affect the dielectric response. Laboratory samples (containing different amount of paper moisture) are constructed according to the steps outlined in [4, 12, 13]. Fig. 3 shows one of many laboratory samples constructed for testing the proposed method. An experimental setup based on NI USB DMM 4065 is constructed for recording the polarisation current of the test samples. Fig. 4 shows the polarisation current measurement setup.

The values of measurement temperature (T_{MEAS}) and t_{conn} are varied. PDC data is recorded from laboratory samples for different values of T_{MEAS} and t_{conn}. Tables 1–4 demonstrate the effect of T_{MEAS} and t_{conn} on the performance of the proposed method when applied to data collected from different test samples. The %*err*1 and %*err*2 given in the last two columns of Tables 1–4 represent the percentage deviation between quantities provided in (columns 1and 4) and (columns 1 and 5) of these tables, respectively.

Fig. 5 pictorially represents the capability of the proposed technique to compensate for E_r when applied to data recorded from a sample containing 4.0% paper-moisture with $t_{\text{conn}} = 120$ s and $T_{\text{MEAS}} = 50$°C. It can be observed from Tables 1–4 that the accuracy of the proposed method is not significantly affected by values of T_{MEAS}, t_{conn} or %pm. Once the proposed method is successfully tested on data recorded from laboratory sample, the discussed technique is applied to data collected from real-life in-situ power transformers.

5 Application to real-life power transformer

Power transformer being a crucial equipment, utilities always try to minimise its shutdown time. PDC measurement is an offline technique that is carried out on equipment that is at thermal equilibrium. This implies sufficient cooling time, post shutdown must be provided prior PDC measurement. Given this scenario, it

Table 1 Calculated values of *DAR* for samples with different paper-moisture

DAR (measured)	T_{MEAS}, °C	t_{conn}, s	DAR (using $i_{\mathrm{pol}}^{\mathrm{afct}}$)	DAR (using $i_{\mathrm{pol}}^{\mathrm{pred}}$)	%err1	%err2
Sample 4.0%						
1.18	50	90	1.02	1.19	13.55	0.84
	50	120	1.08	1.16	8.47	1.69
	50	150	1.05	1.184	11.01	0.33
1.2	70	90	1.12	1.19	6.66	0.83
	70	120	1.07	1.21	10.83	0.83
	70	150	1.04	1.192	13.33	0.66
Sample 3.0%						
1.19	50	90	1.12	1.183	5.88	0.58
	50	120	1.101	1.186	7.47	0.33
	50	150	1.089	1.185	8.48	0.42
1.21	70	90	1.116	1.206	7.76	0.33
	70	120	1.084	1.199	10.41	0.90
	70	150	1.058	1.204	12.56	0.49
Sample 2.5%						
1.15	50	90	1.09	1.142	5.21	0.69
	50	120	1.07	1.141	6.95	0.78
	50	150	1.04	1.145	9.56	0.43
1.18	70	90	1.121	1.179	5.24	0.33
	70	120	1.103	1.181	6.76	0.16
	70	150	1.077	1.180	8.96	0.25
Sample 2.0%						
1.21	50	90	1.12	1.206	7.43	0.33
	50	120	1.09	1.201	9.91	0.74
	50	150	1.071	1.208	11.48	0.16
1.23	70	90	1.15	1.221	6.50	0.73
	70	120	1.11	1.211	9.75	1.54
	70	150	1.08	1.227	12.19	0.24

Table 2 Calculated values of *PI* for samples with different paper-moisture

PI (measured)	T_{MEAS}, °C	t_{conn}, s	PI (using $i_{\mathrm{pol}}^{\mathrm{afct}}$)	PI (using $i_{\mathrm{pol}}^{\mathrm{pred}}$)	%err1	%err2
Sample 4.0%						
2.14	50	90	1.65	2.11	22.89	1.40
	50	120	1.44	2.08	32.71	2.80
	50	150	1.34	2.12	37.38	0.934
2.42	70	90	2.10	2.40	13.22	0.82
	70	120	1.73	2.41	28.51	0.41
	70	150	1.57	2.413	35.12	0.33
Sample 3.0%						
2.26	50	90	1.83	2.27	19.02	0.44
	50	120	1.69	2.28	25.22	0.88
	50	150	1.62	2.30	28.31	1.76
2.63	70	90	2.29	2.60	12.92	1.14
	70	120	2.18	2.60	17.11	1.14
	70	150	2.07	2.61	21.29	0.76
Sample 2.5%						
2.31	50	90	1.893	2.30	18.05	0.43
	50	120	1.74	2.29	24.67	0.86
	50	150	1.63	2.306	29.43	0.17
2.67	70	90	2.34	2.661	12.35	0.33
	70	120	2.17	2.652	18.72	0.67
	70	150	2.08	2.666	22.08	0.14
Sample 2.0%						
2.36	50	90	1.93	2.348	18.22	0.50
	50	120	1.78	2.351	24.57	0.38
	50	150	1.69	2.355	28.38	0.21
2.82	70	90	2.41	2.793	14.53	0.95
	70	120	2.27	2.784	19.50	1.27
	70	150	2.13	2.812	24.46	0.28

Table 3 Calculated values of tan*d* for samples with different paper-moisture

tanδ (measured)	T_{MEAS}, °C	t_{conn}, s	tanδ (using i_{pol}^{afct})	tanδ (using i_{pol}^{pred})	%err1	%err2
Sample 4.0%						
0.76	50	90	0.46	0.75	39.47	1.31
	50	120	0.32	0.759	57.89	0.13
	50	150	0.24	0.754	68.42	0.78
0.81	70	90	0.68	0.809	16.04	0.12
	70	120	0.46	0.81	43.20	0.00
	70	150	0.37	0.807	54.32	0.37
Sample 3.0%						
0.61	50	90	0.46	0.602	24.59	1.31
	50	120	0.37	0.609	39.34	1.63
	50	150	0.33	0.61	45.90	0.00
0.69	70	90	0.56	0.677	18.84	1.88
	70	120	0.47	0.683	31.88	1.01
	70	150	0.41	0.686	40.57	0.57
Sample 2.5%						
0.57	50	90	0.49	0.57	14.03	0.00
	50	120	0.42	0.568	26.31	0.35
	50	150	0.38	0.569	33.33	0.17
0.63	70	90	0.52	0.62	17.46	1.58
	70	120	0.46	0.623	26.98	1.11
	70	150	0.41	0.627	34.92	0.47
Sample 2.0%						
0.54	50	90	0.48	0.535	11.11	0.92
	50	120	0.43	0.54	20.37	0.00
	50	150	0.40	0.539	25.92	0.18
0.58	70	90	0.47	0.58	18.96	0.00
	70	120	0.39	0.572	32.75	1.37
	70	150	0.32	0.576	44.82	0.68

Table 4 Calculated values of *IR* for samples with different paper-moisture

IR (measured at 60 s) MΩ	T_{MEAS}, °C	t_{conn}, s	IR (using i_{pol}^{afct}) MΩ	IR (using i_{pol}^{pred}) MΩ	%err1	%err2
Sample 4.0%						
71.6	50	90	91.0	71.8	27.09	0.27
	50	120	107.0	72.1	49.58	0.69
	50	150	121.0	71.8	35.86	0.27
34.7	70	90	39.2	34.3	12.96	1.1
	70	120	50.2	34.4	44.66	0.86
	70	150	51.1	34.5	32.09	0.57
Sample 3.0%						
91.0	50	90	111.0	88.9	21.97	2.30
	50	120	120.0	89.6	31.86	1.53
	50	150	128.0	89.5	40.65	1.64
48.7	70	90	56.7	48.4	16.42	0.61
	70	120	59.8	48.2	22.79	1.02
	70	150	62.6	48.46	28.54	0.49
Sample 2.5%						
128	50	90	178	130.4	39.06	1.84
	50	120	204	130.2	59.37	1.68
	50	150	212	131.0	65.62	2.29
64.9	70	90	78.1	64.21	20.33	1.06
	70	120	80.3	64.42	23.72	0.73
	70	150	82.7	64.58	27.42	0.71
Sample 2.0%						
160	50	90	176	158.0	10.00	1.12
	50	120	189	157.8	8.12	1.37
	50	150	205	158.7	28.12	0.81
72.1	70	90	79.2	71.7	9.84	0.55
	70	120	81.8	71.5	13.45	0.83
	70	150	83.2	71.92	15.39	0.24

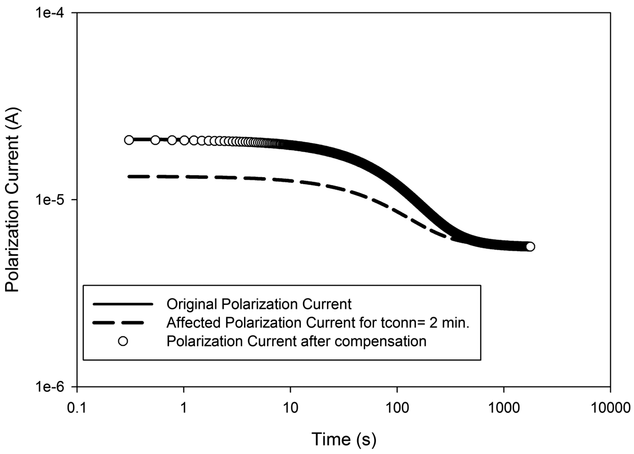

Fig. 5 *Performance of the proposed method on data collected from laboratory samples*

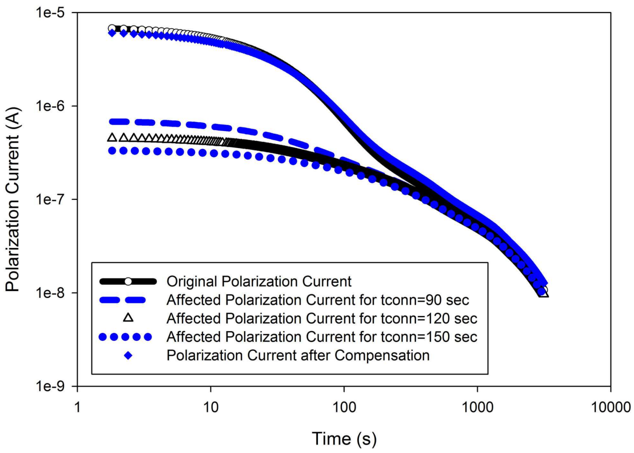

Fig. 6 *Performance of the proposed method on data collected from Trafo1*

is not practically beneficial to prolong the shut-down time by carrying out the second round of measurement after ensuring proper connections. Furthermore, the influence of V_j in (1) does not affect the monotonically decreasing profile of polarisation current (as shown in Fig. 5). This fact coupled with lack of information related to V_j, τ_j makes it difficult for the person carrying out the measurement to determine how much further time should be provided to the equipment (with terminals shorted) to neutralise the effect of V_j. Allowing sufficiently long time (to ensure complete neutralisation of V_j) again prolongs the shut-down time. Considering the fact that PDC measurement time of in-service transformer can continue for 1–2 h depending on insulation condition, it is practically advantageous for utilities to correct the affected current rather than restoring to multiple measurements.

To illustrate the effectiveness of the proposed method for in-service equipment, PDC data $i_{\text{pol}}^{\text{org}}(t)$ (not affected by E_{r}) of a 230 MVA, 420 kV power transformer (*Trafo1*), is used. The affected polarisation current $i_{\text{pol}}^{\text{afct}}(t)$ is obtained by introducing non-zero initial condition in the insulation model. This is done in the two steps. First, the MDM model for *Trafo1* is identified using the steps detailed in [4]. Thereafter, the influence of E_{r} is introduced in the form of the voltage source V_j in each branch of the insulation model. At this stage, the value of t_{conn} (in (1)) is varied from 90 to 150 s. Finally, $i_{\text{pol}}^{\text{afct}}(t)$ is obtained using the insulation model containing the effect of V_j. Polarisation current $i_{\text{pol}}^{\text{afct}}(t)$ thus obtained is used by the proposed method to identify the nature of the original current $i_{\text{pol}}^{\text{org}}(t)$. Fig. 6 shows the effect of varying the value of t_{conn} on the overall profile of polarisation current $i_{\text{pol}}^{\text{afct}}(t)$ for t_{conn} = 90, 120, 150 s for *Trafo1*. In order to improve readability, Fig. 6

Table 5 Calculated and measured values of *PI*, *DAR* for *Trafo1*

t_{conn}, s	PI		DAR	
	Calculated	Actual	Calculated	Actual
90	1.89	4.1	1.29	2.1
120	1.71		1.22	
150	1.56		1.16	

Table 6 Calculated and measured values *of* tan*δ*, *IR* for *Trafo1*

t_{conn}, s	tan*δ*		IR Ω	
	Calculated	Actual	Calculated	Actual
90	0.29	0.45	1.91×10^9	6.6×10^8
120	0.24		2.21×10^9	
150	0.20		2.68×10^9	

also contains the profile of $i_{\text{pol}}^{\text{org}}(t)$ and the profile of the polarisation current $i_{\text{pol}}^{\text{pred}}(t)$ predicted by the proposed method.

It can be observed from Fig. 6 that the proposed method is indeed capable of identifying the effect of t_{conn}. In order to understand the influence of E_{r} on variables that are often measured by utilities like *PI*, *DAR*, tan*δ*, *IR* values are computed using MDM (parameterised using $i_{\text{pol}}^{\text{afct}}(t)$ and compared with the measured values. It can be observed from Tables 5 and 6 that the non-zero initial condition affects the values of these commonly measured insulation diagnosis parameters. This discrepancy, if allowed to persist, may create doubt regarding measurement accuracy of PDC data and/or standard parameters (like *PI*, *DAR*). This ambiguity, in turn, may render the data useless for the purpose of reliable diagnosis. As per utility, the problem with DAQ system due to improper connection is generally detected within few minutes after initiating PDC measurements. Hence, in this work, t_{conn} value for the transformer is spanned from 90 to 150 s.

At the time of writing this paper %pm value for *Trafo1* was not available with the utility. However, the relationship between Z_1 and %pm reported in [12, 13] is formulated entirely using real life transformer data and hence is applicable in the present case for prediction of %pm using $i_{\text{pol}}^{\text{org}}(t)$ as well as $i_{\text{pol}}^{\text{afct}}(t)$. The value of %pm for *Trafo1* predicted using this reported relationship [13] and $i_{\text{pol}}^{\text{org}}(t)$ is observed to be 1.91%.

The values of %pm, *DAR*, *PI*, tan*δ* are computed using $i_{\text{pol}}^{\text{afct}}(t)$ and $i_{\text{pol}}^{\text{pred}}(t)$ for different values of t_{conn}. It is worth mentioning here that at this stage %pm for *Trafo1* is computed in three steps: first, the MDM parameters are evaluated. Next, the Z_1 is evaluated. Finally, %pm is evaluated using relationship reported in [13]. Tables 7 and 8 present the result of such comparison. The %err1 and %err2 given in the last two columns of Tables 7 and 8 represent the percentage deviation between quantities provided in (columns 1 and 3) and (columns 1 and 4) of each table, respectively. It can be observed from the data presented in Tables 7 and 8 that the effect of E_{r}, if not compensated, indeed affect the value of paper-moisture value and hence the accuracy of insulation diagnosis. However, the applicability of the method lies in its capacity to handle data for which the value of E_{r} is not known beforehand. In order to address this issue, two case studies are made.

5.1 Case I: 167 MVA, 220 kV power transformer Trafo2

In the case of *Trafo2*, the data recorded by the DAQ system (initially) is affected by noise due to improper connection of earth wire and/or BLACK wire (Fig. 1). As per the utility, the DAQ system successfully recorded PDC data (having the well-known monotonic decreasing nature) from *Trafo2* on the third attempt. The success of data measurement, mentioned in the previous

Table 7 Calculated values of *PI* and *DAR* for *Trafo1*

PI (measured)	t_{conn}, s	PI (using i_{pol}^{afct})	PI (using i_{pol}^{pred})	%err1	%err2
4.1	90	1.93	3.78	52.92	7.8
	120	1.71	3.66	58.29	10.73
	150	1.56	3.79	61.95	7.56

DAR (using i_{pol}^{org})	t_{conn}, s	DAR (using i_{pol}^{afct})	DAR (using i_{pol}^{pred})	%err1	%err2
2.1	90	1.29	1.97	38.57	6.19
	120	1.22	1.89	41.90	10.00
	150	1.16	1.91	44.76	9.04

Table 8 Calculated values of tan*δ*, *IR*, %pm for *Trafo1*

tan*d* (using i_{pol}^{org})	t_{conn}, s	tan*δ* (using i_{pol}^{afct})	tan*d* (using i_{pol}^{pred})	%err1	%err2
0.45	90	0.29	0.448	35.55	0.44
	120	0.24	0.45	45.66	0.22
	150	0.20	0.49	55.55	0.44

IR (60 s) (using i_{pol}^{org}) Ω	t_{conn}, s	IR (60 s) (using i_{pol}^{afct}), Ω	IR (60 s) (using i_{pol}^{pred}), Ω	%err1	%err2
6.66×10^8	90	1.91×10^9	7.17×10^8	186.78	7.65
	120	2.21×10^9	7.01×10^8	231.83	5.25
	150	2.68×10^9	7.19×10^8	302.40	7.95

%pm (using i_{pol}^{org})	t_{conn}, s	%pm (using i_{pol}^{afct})	%pm (using i_{pol}^{pred})	%err1	%err2
1.91	90	1.18	1.82	38.21	4.71
	120	1.11	1.81	41.88	5.23
	150	1.06	1.79	44.50	6.28

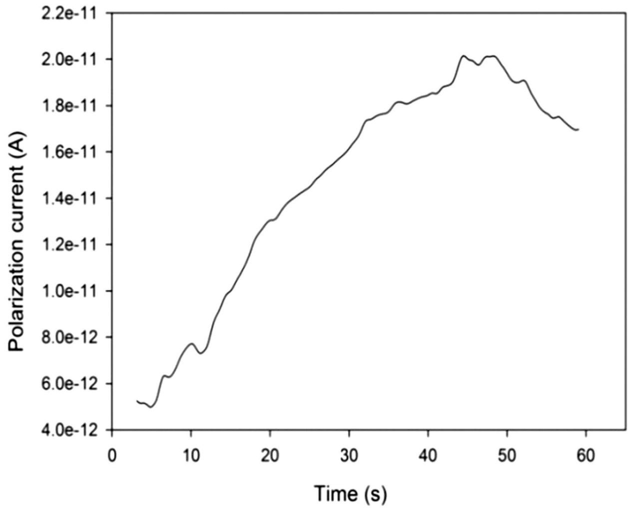

Fig. 7 *Polarisation current measured during improper connection from Trafo2*

sentence, is used to designate a situation where the DAQ system detected and recorded monotonically decreasing polarisation current. This situation is not to be confused with measurement of proper PDC data. In fact, the explanation provided above suggests that data recorded on the third attempt (though has a monotonically decreasing profile) is affected by E_r. This invariably affects the value of performance parameters as explained later in this paper.

In the first two attempts, the polarisation current was reported to be of not proper shape. Fig. 7 shows the recorded polarisation current that is recorded during the second attempt. Though the DAQ system was interrupted at 58 s (Fig. 7), unfortunately, the tenure for which the two improper phases actually persisted were not recorded by the utility. As a result t_{conn} in (1), (3) is assumed to be 58 s for *Trafo2*.

The values of performance parameters both measured and calculated (using either $i_{pol}^{afct}(t)$ or the MDM parameters formulated from $i_{pol}^{afct}(t)$) for *Trafo2* are presented in Table 9. Column 4 of Table 9 shows the value of performance parameters that are calculated using either predicted profile of polarisation current

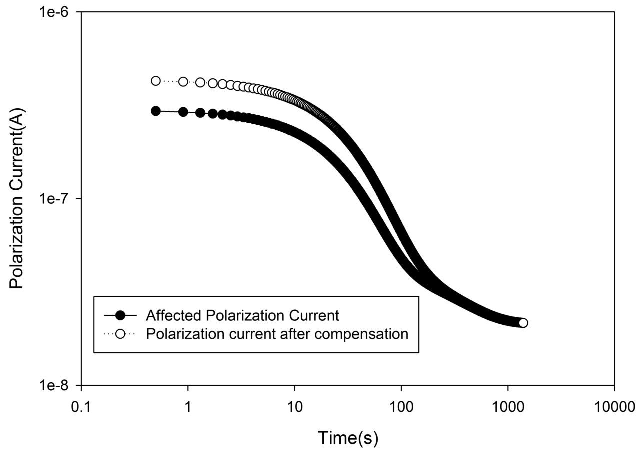

Fig. 8 *Polarisation current of Trafo2 before and after compensation*

Table 9 Measured and computed values of parameters for *Trafo2*

Parameters	Measured	Computed (using i_{pol}^{afct})	Computed (using i_{pol}^{pred})	%err1	%err2
tanδ	0.318	0.22	0.317	30.8	0.31
PI	4.6	2.95	4.43	35.86	3.69
DAR	1.67	1.56	1.71	7.0	2.3
IR (60 s), Ω	1.13×10^{10}	1.85×10^{10}	1.04×10^{10}	63.71	7.96
%pm[a]	0.6	0.41	0.55	33.33	8.33

[a]Measured using IDAX 300.

Table 10 Measured and computed values of performance parameters for *Trafo3*

Parameters	Measured	Computed (using i_{pol}^{afct})	Computed (using i_{pol}^{pred})	%err1	%err2
tanδ	0.35	0.29	0.34	19.44	0.27
PI	2.6	1.66	2.52	36.15	3.07
DAR	1.74	1.52	1.71	12.64	1.72
IR (60 s), Ω	1.7×10^{10}	1.97×10^{10}	1.67×10^{10}	15.88	1.76

$i_{pol}^{pred}(t)$ or using MDM parameters (parameterised using $i_{pol}^{pred}(t)$). It is known that a non-steady measurement temperature can also affect the profile of the polarisation current [3, 4]. The authors were informed by the utility that the unit under consideration was allowed sufficient cooling time before the PDC measurement was carried out and there were no observable temperature variations during PDC measurement. Hence, the temperature is less likely to the cause of variation presented in Table 9. In order to improve readability, the measured values of performance parameters are also included in Table 9. It is worth mentioning here that the measured value of %pm is obtained using IDAX 300 instrument. It can be observed from the data presented in Table 9 that the differences in performance parameters (second and fourth columns) are significantly reduced. Furthermore, it is observed from Table 9 that the value of %pm obtained using IDAX 300 is close to that predicted using MDM parameters (identified using $i_{pol}^{pred}(t)$). This suggests that the MDM parameters are identified correctly. This in turns confirms the capability of the proposed method to identify the correct profile of polarisation current. Fig. 8 shows the measured and predicted profiles of polarisation current for *Trafo2*.

5.2 Case II: 200 MVA, 420 kV power transformer (Trafo3)

In the case of *Trafo3*, the DAQ failed to record any data initially. As per the information provided to the authors, this situation existed for several seconds before the dc voltage source is finally switched off and all the connections are remade by the equipment operator. Thereafter, the DAQ system is reported to record monotonically decreasing nature of the PDC current.

As the abnormal situation did not continue for tenure >1000 s, the operator did not think it was necessary to record the duration. The values of performance parameters measured from *Trafo3* (prior PDC measurement) and that calculated using PDC data referred above are presented in Table 10.

Unfortunately, the measured value of paper moisture was not available for *Trafo3* with the utility at the time of testing. It can be observed from Table 10 that the measured and calculated values of performance parameters (second and third columns) vary by a significant extent. Similar to *Trafo2*, a sufficient cooling time prior to PDC measurement was provided. Hence, these variations in performance parameters cannot be attributed to temperature variation. Thereafter, the proposed method is applied to the recorded dielectric response of *Trafo3*. Fig. 9 shows the measured and predicted polarisation current profiles as obtained for *Trafo3*. Once, the predicted current profile is obtained, the values of performance parameters are once again calculated and compared with the measured values. Table 10 presents the result of this comparison. It can be observed from Tables 9 and 10 that the proposed method is effective in identifying the original polarisation current even if the tenure of the improper connection phase is not known with satisfactory accuracy. Furthermore, it is observed by the author that on the application of the proposed method to data not affected by E_r, results in a predicted current profile which is identical to the measured relaxation current. In order to compare the performance of the proposed algorithm, %err2 (maximum value %err2) obtained for different transformers (samples) are presented in Table 11.

Data presented in this paper shows that application of proposed method results in significant reduction in deviation between measured and estimated values of performance parameters (%err1). Though substantially reduced, the resulting error (%err2) is observed to be high for *IR Trafo2*. This is due to the fact *IR* is not only affected by E_r but also by other factors like environmental

Table 11 Performance comparison of proposed method for laboratory sample and transformers

Parameters	Value of %err2			
	tan*δ*	*PI*	*DAR*	*IR* (60 s)
Sample (2.0%)	1.37	1.27	1.54	1.37
Sample (2.5%)	1.58	0.86	0.78	2.29
Sample (3.0%)	1.88	1.76	1.16	2.30
Sample (4.0%)	1.31	2.80	1.69	1.10
Trafo2 (0.6%)	0.31	3.69	2.30	7.96
Ttrafo3 (NA[a])	0.27	3.07	1.72	1.76

[a]NA: not available.

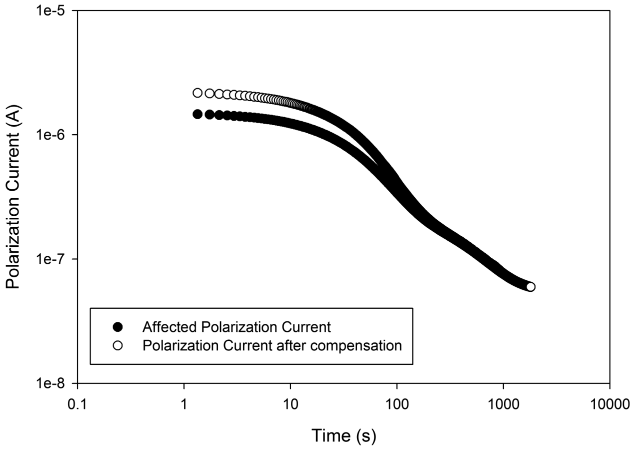

Fig. 9 *Polarisation current of Trafo3 before and after compensation*

condition and temperature. These influences are reduced for parameters like *PI* and *DAR* as their values are dependent on ratios of IR at different time instants. This is reflected by the lesser value of %err2 (compared to that obtained for *IR*) in Table 11.

6 Conclusions

During field measurement, sometimes (DAQ) system of PDC measurement instrument fails to record proper polarisation current data even after application of dc charging voltage. As per the utility, this situation primarily happens due to the improper or loose connection. It is difficult to avoid such problem entirely during field measurement due to the involvement of human factors. The utility considers the effect of energy E_r introduced during this phase insignificant as dipole groups present in cellulose have a much larger time constant. The related analysis presented in this paper shows that the value of calculated parameters (for instance %pm) cannot be considered as reliable unless the effect of E_r is compensated. In fact, data presented in this paper show that the error between measured and calculated parameters will increase with an increase in the value of E_r.

A method is proposed in this paper that successfully compensates the effect of E_r on the recorded polarisation current. Results presented in this paper shows that parameter values calculated using the polarisation current, predicted by the proposed methodology, are in good correlation with those measured using commercially available instruments. The related analysis presented in this paper shows that the proposed method is capable of delivering results with satisfactory accuracy for data recorded from real life in-situ units.

7 References

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

[2] 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

[3] 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

[4] 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

[5] Saha, T.K., Darveniza, M., Hill, D.J.T., *et al.*: 'Electrical and chemical diagnosis of transformer insulation, part A: Aged transformer samples', *IEEE Trans. Power Deliv.*, 1997, **12**, (4), pp. 1547–1554

[6] Tang, C., Chen, G., Fu, M., *et al.*: 'Space charge behavior in multi-layer oil-paper insulation under different DC voltages and temperatures', *IEEE Trans. Dielectr. Electr. Insul.*, 2010, **17, (3)**, pp. 775–784

[7] Moreau, E., Paillat, T., Touchard, G.: 'Evolution of the streaming current generated by an oil flow through a pressboard – application to flow electrification in power transformers'. Conf. Electrical Insulation and Dielectric Phenomena, Minneapolis, 1997, pp. 19–22

[8] 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

[9] Zaengl, W.S.: 'Applications of dielectric spectroscopy in time and frequency domain for HV power equipment', *IEEE Electr. Insul. Mag.*, 2003, **19**, (6), pp. 9–22

[10] Jadav, R.B., Ekanayake, C., Saha, T.K.: 'Dielectric response of transformer insulation - comparison of time domain and frequency domain measurements'. 2010 Conf. Proc. IPEC, 2010, pp. 199–204

[11] Gubanski, S.M., Boss, P., Csépes, G., *et al.*: 'Dielectric response methods for diagnostics of power transformers', Report of the TF D1.01.09

[12] Baral, A., Chakravorti, S.: 'Condition assessment of cellulosic part in power transformer insulation using transfer function zero of modified Debye model', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (5), pp. 2028–2036

[13] Baral, A., Chakravorti, S.: 'Prediction of moisture present in cellulosic part of power transformer insulation using transfer function of modified Debye model', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (3), pp. 1368–1375

[14] Chatterjee, B., Dey, D., Chakravorti, S.: 'Implementation of integrated, portable transformer condition monitoring instrument in the classroom and on site', *IEEE Trans. Educ.*, 2010, **53**, (3), pp. 484–489

[15] Sarkar, S., Sharma, T., Baral, A., *et al.*: 'An expert system approach for transformer insulation diagnosis combining conventional diagnostic tests and PDC, RVM data', *IEEE Trans. Dielectr. Electr. Insul.*, 2014, **21**, (2), pp. 882–891

[16] Dey, D., Chatterjee, B., Chakravorti, S., *et al.*: 'A hybrid filtering scheme for proper denoising of real-time data in dielectric spectroscopy', *IEEE Trans. Dielectr. Electr. Insul.*, 2007, **14**, (5), pp. 1323–1331

[17] Biswas, S., Dey, D., Chatterjee, B., *et al.*: 'Importance of denoising in dielectric response measurements of transformer insulation: an uncertainty analysis based approach', *Measurement*, 2010, **43**, pp. 54–66

[18] McKinnon, D.L.: 'Insulation resistance profile (IRP) and its use for assessing insulation systems'. IEEE Int. Symp. Electrical Insulation (ISEI), San Diego, USA, 2010, pp. 1–4