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RESEARCH ARTICLE

Importance of Depolarization Current in the Diagnosis of Oil-Paper Insulation of Power Transformer

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ABSTRACT Recently, Polarization Depolarization current (PDC) measurement is widely accepted time domain spectroscopy-based method for assessing the insulation condition. Various performance parameters like Dissipation factor (%tanδ), Paper Moisture (%pm), Dielectric Adsorption Ratio (DAR), Polarization index (PI) etc. can be estimated by analyzing the PDC data. During field measurement various factors influences the recorded PDC data. As per existing literature, presence of low frequency noise, effect of temperature variation and influence of residual charge are common during field measurement. These factors significantly affect recorded polarization current and hence estimated performance parameters. Hence, analysis using recorded polarization current data may provide misleading information regarding insulation condition. Under such practical situation where polarization current is affected by above mentioned factors that generally observed during field measurement, depolarization current should be used for analysis of insulation condition. The depolarization current does not influence by such external factors. The present work shows the importance of depolarization current where polarization current is influenced by external low frequency noise and residual charge. The analysis firstly applied on sample prepared in the laboratory and then on data collected from real life in-situ transformers. The results obtained from the analysis shows that the data obtained from depolarization current is more reliable.

INDEX TERMS Power transformer, oil-paper insulation, residual charge, dissipation factor, paper moisture.

I. INTRODUCTION

The performance of any transformer mainly depends on their insulation condition. During the operational life of transformer, various stresses like mechanical, electrical and environmental reflect the adverse effect on insulation and sometimes causing the permanent failure of transformer [1]. Therefore, regular monitoring of insulation is needed for continuous operation of power transformer [2], [3]. Available literature shows various methods for assessing the insulation condition. Some of them are based on chemical diagnosis like Dissolved Gas Analysis (DGA), Degree of Polymerization (DP) etc. [2]. Due to various limitations of above said methods, these methods are not widely used on transformer operating in field [4]. Researchers show that Polarization Depolarization Current (PDC) analysis technique is continuously gaining popularity in the field of insulation diagnosis [5]. Available literature assumes that Classical Debye Model (CDM) is a good choice for analyzing the PDC data that provides the reliable information regarding insulation condition [6]. Conventional Debye Model (CDM) is preferable because it does not consider the effect of temperature gradient that exists across the length of insulation. The parameter identification of Cole - Cole model requires an intensive iterative method, which is a time taking process. There is no direct relation between Cole - Cole model parameter with moisture content. Such model parameters are related to paper conductivity. Existing literature reported that paper

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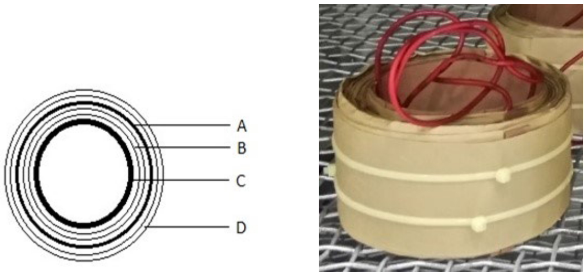
conductivity is related to moisture. Hence, indirect prediction of moisture is possible using Cole - Cole model, due to which more errors can be introduce in the system. On the other hand, CDM parameters are directly related to moisture prediction is also less than 5 percent. Hence in the present work, CDM is used to predict moisture and $tan\delta$. Various performance parameters like %$tan\delta$, %pm, Polarization index (PI), Dielectric adsorption ratio (DAR) have also been estimated from the CDM model [7]. These parameters indicate the insulation condition. The formulation of CDM is represented by the parallel combination of series R-C branches. The accuracy of this method depends on CDM parameters resulted from relaxation current. Thus, it can be said that the reliability of information from the CDM is mainly depends on the measured PDC data [8]. Sometimes during field measurement, it is noticed that equipment unable to record the proper polarization current even under the application of dc voltage [9]. Researchers also reported [6] that this situation arises due to lose or improper connections. This situation cannot be avoided due to involvement of human factor. It is reported in [7] and [10] that when the polarization current measured just after rectifying the loose connection, the effect of residual dipole energy also affects the measured data. These residual dipoles energy in the system appears during the improper phase measurement under the application of charging voltage. Another problem that arises during field measurement is effect of low frequency noise [11]. The other energized equipment near the unit being tested may create such issue. In addition to this, other sources like slow variation in environmental condition (especially ambient temperature) at the time of measurement [12]. Due to such factors, the recorded polarization current may lose its monotonically decreasing trend. Therefore, it is difficult to formulate insulation model using such noisy data and hence prediction of insulation sensitive performance parameters. On the other hand, these issues do not have significant effects on depolarization current. A given dielectric can only store a fixed amount of energy. In the presence of residual dipole energy, less amount of energy will enter into the dielectric during polarization phase [13]. Irrespective of presence or absence of residual energy, the amount of energy content present within the insulation after the polarization phase is over will always be constant. Hence, the presence of residual energy influences only the profile of polarization current data without significantly affecting the depolarization current. In the literature [11], [14], in the presence of residual energy, if the performance parameters are calculated using polarization current then proper compensation (for Er) is required. On the other hand, if parameters are estimated using depolarization current then no compensation is required for estimation of various performance parameters.

The analysis in this paper shows that CDM formulation through depolarization current is more accurate as this current is not much more affected by residual charge and other problems that encountered during field measurement. Thus, in situation where polarization current is affected by practical field issues like residual charge, low or high frequency noise, changing of ambient temperature etc., the performance parameters evaluation from depolarization current provides reliable information regarding insulation instead of polarization current. Firstly, the analysis is performed on laboratory sample showing residual charge effect and then on real life transformer whose polarization current is affected by low frequency noise. A number of in-situ transformers have been tested. During testing, it is observed that the depolarization current does not get affected low frequency noise and temperature variation.



(a) (b)

FIGURE 1. (a) Schematic top view of laboratory sample (A) strips pressboard to isolate HV and LV winding (B) Copper sheets folded on Kraft paper (C) Pressboard cylinder (D) folded copper foil; (b) laboratory prepared sample.

II. SAMPLE CONSTRUCTION

For analysis purpose and the measurement in the laboratory samples have been constructed. Initially the sample structure begin with a pressboard cylinder (having height 10 cm and diameter 50 cm). The pressboard is made up of a 2 mm thick pressboard and provides internal support to the sample. Two copper foils that have been wrapped in Kraft paper are used to imitate low and high voltage windings. Fig. 1a shows the schematic diagram of the sample constructed in the laboratory. In Fig. 1a, B, D represents the copper sheets overlap with Kraft paper C represents the inner pressboard cylinder while D is the pressboard strips used to isolate HV and LV windings. Fig. 1b shows the finally constructed structure of laboratory sample for pre-measurement processing.

In order to dry the prepared samples, these samples are put in oven with a temperature control. The heater used to dry the samples at $80^\circ C$ for more than 96 hours is shown in Fig. 2. After this drying procedure, the sample is left in open for absorbing the requisite amount of moisture content from the environment. Once these samples have soak up the predetermined moisture (by weight). The samples are put inside the 1.5 litres of mineral oil-filled steel container. It is believed that after the samples have been dipped into the steel container, all of the moisture has been absorbed. For Polarization and Depolarization current (PDC) measurement the setup has been prepared in the laboratory as shown in Fig. 3. Fig. 3 shows the PDC measurement setup prepared in High Tension Laboratory, Jadavpur University.

TABLE 1. Technical Specification of Oven.

Manufactured By	Electrolyte Enterprises, Kolkata, India
Model No.	HAV-CT-120
SL.No.	1067/2016
Temperature Range	0-120 $°C$
Voltage	230 Volt
Current	12Ampere
Power Rating	2.5KilloWatt

The polarization current discussed above can be modeled by (1).

$$i_{pol}(t) = C_0V(\frac{\sigma_r}{\varepsilon_0} + \varepsilon_\infty\delta(t) + f(t)) \quad (1)$$

where ε_0 is permittivity of vacuum, $\delta(t)$ is the delta function arises due to sudden application of dc excitation voltage at $t = t_0, f(t)$ is a monotonically decreasing dielectric response function, and V is the applied voltage.

In Fig. 4, $0 \leqslant t \leqslant t_c$, is the is the time duration for which the voltage is applied across the test sample. Dielectric response function describes the basic memory properties of any dielectric material and has the capability to provide reliable information about the dielectric material [6]. Therefore, at present, modeling of $f(t)$ is a major concern for researchers. Available literature shows that modeling of $f(t)$ and hence the behavior of insulation is possible using simple Resistive-capacitive network [2]. Numerous similar resistive-capacitive networks for simulating the response function of insulation have been described by researchers [6]. The Conventional Debye Model (CDM), among these, is arguably the most well-known [2]. The parallel combination of series resistive-capacitive elements makes up the CDM. Concerned insulation has a number of dipole groups with varying relaxation periods. The $R_i - C_i$ branches of CDM (shown in Fig. 5) are used to represent these randomly oriented groups, and they have an associated time constant denoted by $\tau_i = R_i - C_i$.

This model analyzes the characteristics of insulation by considering the entire insulation as black box. Hence, without knowing the actual geometry of insulation structure, it can be used to analyze the data [2], [9]. In Fig. 5, the geometric capacitance and dc insulation resistance are denoted by R_0 and C_0, respectively.

III. ASSESSMENT OF INSULATION CONDITION USING PDC ANAYSIS

During polarization current measurement, dc voltage is impressed across the insulating material under test [15]. On application of dc step field, the insulating material's internal dipoles began to rotate in the direction of the applied field, and the polarization process starts. This leads to generation of polarization current through material. During depolarization current measurement, the supply terminal is shorted [16].

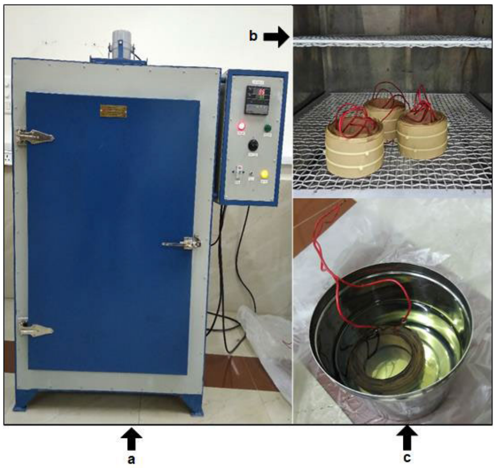


FIGURE 2. (a) Temperature Controlled Oven, (b) Drying process of samples in the oven, (c) Impregnation process of samples with transformer oil.

FIGURE 3. Laboratory setup for PDC measurement.

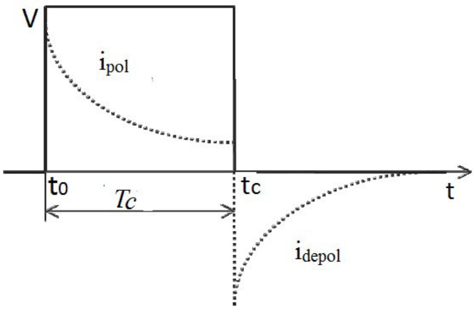


FIGURE 4. Typical profile of PDC data.

Therefore, Depolarization current flows through insulation as the dipoles once more align with their initial orientation. Fig. 4 shows the typical profile of polarization and depolarization current (PDC) [8], [13]. Keithley 6517B Electrometer is used for field test to get data from real-life transformer.

It is worth mentioning here from [14], that samples kept at any fixed temperature for about 24 hours is enough for the samples to reach thermal equilibrium. Here, 1000 V dc is used as excitation voltage during polarization current

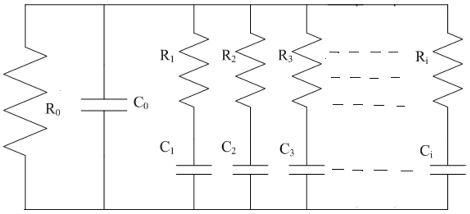


FIGURE 5. Conventional Debye Model Structure.

measurement phase. Various aging-sensitive Parameters may be investigated to forecast the insulation status of transformers, according to the literature currently available (transfer function zero, pole) estimated from Debye Model derived based on PDC data [13], [17]. It is reported in [10] that performance parameters of transformer insulation like *tanδ*, %pm hold favorable relationship with the transfer function zeros as (2) and (3).

$$\% \tan\delta = 0.4423 + 0.0457 \times \ln(|Z_1|) \tag{2}$$

$$\%pm = 1.718 + 0.418 \times \ln(|Z_1|) \tag{3}$$

where, Z_1 is the system's zero that is furthest from the origin in the LHS of the s-plane. Therefore, %*tanδ* and %pm of transformer insulation can be estimated once the Z_1 is derived from PDC data. Other Parameters, such as the Dielectric Absorption Ratio (DAR), which measures the insulation resistance at 60 seconds to 30 seconds, and the Polarization Index (PI), which measures the insulation resistance at 600 seconds to 60 seconds, are also used to determine the state of the insulation. These parameters can be obtained directly from the measured PDC data [8]. Therefore, if the polarization current is affected by the residual dipole energy or any other field issues, the above described performance parameters wrong information regarding the insulation condition. As during depolarization measurement phase there is no such problem thus it is better to use depolarization current for the formulation of Debye model and estimation of insulation sensitive parameters [18], [19]. To simulate a situation where a known amount of residual charge is present in the insulation, polarization current from a sample (which is not affected by residual energy) is considered. The performance parameters for the sample insulation are identified using equation (2) and (3) [20]. After this a controlled amount of dipole energy, the insulation model includes a non-zero beginning condition for the branch capacitances of CDM. Thereafter, polarization current of the sample (affected by residual energy) is simulated using the insulation model having nonzero initial condition. Fig. 6 represent the Debye model affected by residual dipole energy [11], [14]. To reduce the complexity in calculation the nonzero initial condition in sub-branches is represented by voltage source.

A. APPLICATION TO THE LABORATORY SAMPLE

The suggested method is tested on sample prepared in the laboratory. After simulating the dipole energy for different time instant various performance parameters are calculated from affected polarization current of sample. Fig. 7 pictorially represent the polarization current measured from sample is affected by dipole energy for various time instants. Different polarization current shown in Fig. 7 are measured from 10s to 60s. Different performance parameters like *tanδ*, %pm and DAR are calculated from polarization current contains different residual dipole energy [21].

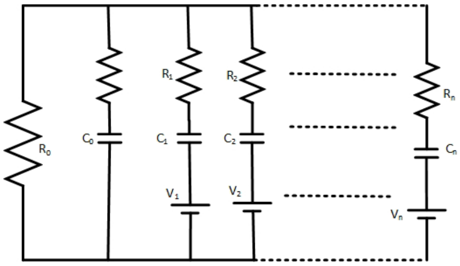


FIGURE 6. Conventional Debye Model affected by dipole energy.

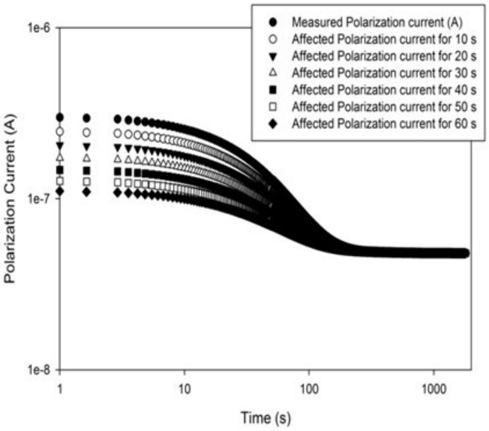


FIGURE 7. Polarization current affected by residual charge for different time instant.

TABLE 2. Calculated values of DAR for sample with 3.2% paper-moisture.

DAR (using i_{pol}^{unaffc})	T_{MEAS}	DAR (using i_{pol}^{affc})	DAR (using i_{depol})	% err1	% err2
1.546	10s	1.537	1.5434	3.84	0.168
	20s	1.5262		7.05	
	30s	1.4489		9.61	
	40s	1.4079		12.17	
	50s	1.3819		16.66	
	60s	1.3603		18.87	

The calculated values of DAR for sample with paper-moisture content of 3.2% and 1%, are presented in Table 2 and Table 3, respectively. The values of performance parameters calculated from polarization current of samples (measured at different instant of time without discharging the samples) and depolarization current have been tested.

Table 4 displays the performance parameter values derived from the sample polarization current (measured at different instant of time without discharging the samples) and

TABLE 3. Calculated values of DAR for sample with 1% paper-moisture.

DAR (using i_{pol}^{unaffc})	T_{MEAS}	DAR (using i_{pol}^{affc})	DAR (using i_{depol})	% err1	% err2
1.799	10s	1.243	1.7213	0.82	4.319
	20s	1.2162		32.39	
	30s	1.1942		33.61	
	40s	1.1763		34.61	
	50s	1.162		35.4	
	60s	1.1506		43.19	

TABLE 4. Calculated values of DAR for sample with 2.1% paper-moisture.

DAR (using i_{pol}^{unaffc})	T_{MEAS}	DAR (using i_{pol}^{affc})	DAR (using i_{depol})	% err1	% err2
1.56	10s	1.5	1.54	3.84	1.28
	20s	1.45		7.05	
	30s	1.41		9.61	
	40s	1.37		12.17	
	50s	1.3		16.66	
	60s	1.25		18.87	

TABLE 5. Calculated values of $tan\delta$ for sample with 2.1% paper-moisture.

$tan\delta$ (using i_{pol}^{unaffc})	T_{MEAS}	$tan\delta$ (using i_{pol}^{affc})	$tan\delta$ (using i_{depol})	% err1	% err2
0.36	10s	0.33	0.357	8.33	0.83
	20s	0.31		13.88	
	30s	0.28		22.22	
	40s	0.26		27.77	
	50s	0.25		30.55	
	60s	0.22		38.88	

TABLE 6. Calculated values of $tan\delta$ for sample with 2.1% paper-moisture.

%pm (using i_{pol}^{unaffc})	T_{MEAS}	%pm (using i_{pol}^{affc})	%pm (using i_{depol})	% err1	% err2
1.98	10s	1.88	1.95	5.05	1.51
	20s	1.81		8.58	
	30s	1.73		12.62	
	40s	1.65		16.66	
	50s	1.55		21.71	
	60s	1.46		26.26	

depolarization current. Column 1 of Table 4, Table 5 and Table 6 shows the calculated value of parameters from unaffected measured polarization current. Column 2 of these Table 4 to Table 6 represent the data calculated from the polarization current measured for different charging instant. The %err1 and %err2 given in the last two columns of Table 4 to Table 6 represent the percentage deviation between quantities provided in (column 1, column 3) and (column 1, column 4) of these tables.

It is observed from Table 4 to Table 6 that various performance parameters calculated from polarization current of insulation having residual dipole energy provides misleading results regarding insulation condition. From Table 4 to Table 6, it is clear that the calculated values of parameters from unaffected polarization current and depolarization are very much closer to each other. Thus, the suggested method is applicable where polarization currents are affected by residual charge or low frequency noise.

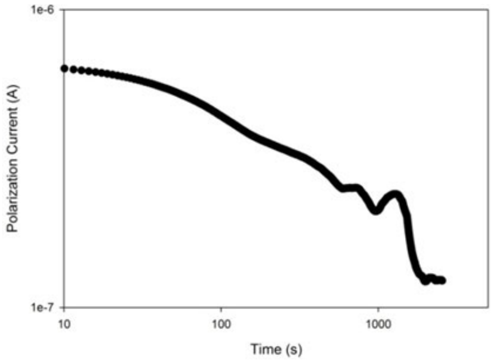


FIGURE 8. Polarization current affected by low frequency noise.

B. APPLICATION TO REAL LIFE POWER TRANSFORMER (200 MVA, 420 kV)

1) EFFECT OF LOW FREQUENCY NOISE ON RECORDED POLARIZATION PROFILE

Once the suggested method is tested on laboratory sample, the method is also applied on the data collected from the real-life transformer for validation purpose. It is understood that due to very low magnitude of the polarization current, it is very susceptible to noise during field measurements [22]. Other energized equipment and additional circuitry present in the vicinity of the unit being tested tend to contribute to the PDC noise [23]. As relaxation current data has a monotonically decreasing profile, it is practically difficult to design a filter to detect and reject very low frequency noise. This low frequency noise affects the measured polarization current [20], [24]. In this case, polarization current is not following the exponential decaying profile. In order to estimate the insulation sensitive parameters polarization current must have monotonically decreasing exponential profile [6]. Fig. 8 shows the polarization current affected by low frequency noise (generally due to environmental factors) [25]. With such a noisy profile of polarization current it is not possible to estimate the reliable information regarding the insulation condition. Fig. 9 shows the depolarization of same transformer. It can be seen from Fig. 9 that depolarization current is not affected by any noise. Thus, in such cases it is good to estimate the performance parameters from the depolarization current rather than polarization current [26].

Table 2 shows that comparison between the measured parameters and the parameters calculated by depolarization current. Column 2 of Table 3 shows the measured parameters of concerned insulation while column 3 shows the parameters estimated using the depolarization current. It is clear from the results that there is very less deviation between the measured and calculated values of performance parameters. Column

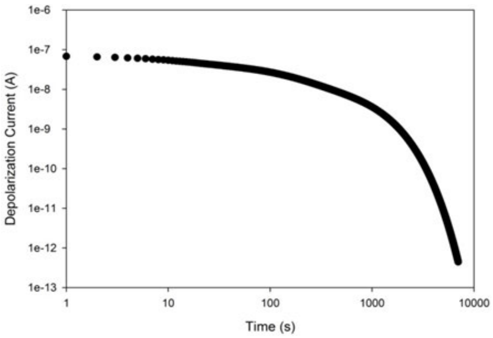


FIGURE 9. Depolarization current of tested Transformer.

TABLE 7. Measured and computed values of parameters.

Parameters	Measured	Computed (using i_{depol})	% err1
$tan\delta$	0.318	0.309	2.83
PI	2.92	2.53	1.33
DAR	1.67	1.61	3.59
IR	1.13E+10	1.04E+10	7.96
%pm	0.6 (IDAX 300)	0.55	8.33

TABLE 8. Measured and computed values of parameters.

Parameters	Measured	Computed (using i_{depol})	% err1
$tan\delta$	0.55	0.51	7.27
PI	2.12	2.04	3.77
DAR	1.37	1.31	4.37
IR	2.54E+10	2.38E+10	6.29
%pm	2.0 (IDAX 300)	2.12	6

4 depicts the error between the measured and calculates values of parameters. Overall from Table 3, it is clear that if polarization current of any transformer is either affected by residual charge or noise (high or low frequency) then is such case the analysis can be done with the help of depolarization current [13].

2) EFFECT OF TEMPERATURE VARIATION ON RECORDED POLARIZATION PROFILE (167 MVA, 220 kV)

Other issue which is commonly encountered during field recording of polarization current from real transformer is the effect of change in ambient temperature. This variation is mainly due to environmental factors [27]. This change in atmospheric temperature may create unbalancing with thermal equilibrium condition of testing equipment. It can be observed from Fig. 10 that the recorded polarization current data does not following monotonically decreasing profile and approaching increasing trend after a certain time. With such temperature affected data formulation of insulation model is not possible hence estimation of reliable performance parameters is not possible [28]. In such situation, performance parameters estimation is only possible with recorded depolarization current profile. However, few iterative techniques are available to compensate this practical issue. Using depolarization current data, it is possible to avoid such complex iterative process to compensate the temperature effect on polarization current [29], [30]. Table 4 shows the values of different performance parameters which are predicted using depolarization current data. It is clear from Table 4 that the predicted values of such parameters are close to that of their measured value.

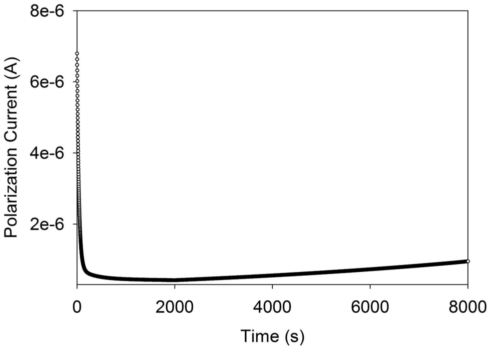


FIGURE 10. Polarization current affected by temperature variation.

IV. CONCLUSION

In the field measurement of PDC data, numerous practical problems arise. Sometime even after application of dc voltage the DAQ system is unable to record any data. After rectifying the issues, when the dc voltage again applied across insulation to measure data then there may be a possibility that polarization current is affected by residual charge if sufficient discharging time is not provided. Another main issue that arises during field measurement is low frequency noise and variation of ambient temperature affects the measured polarization current due to which polarization does not follow monotonically decreasing profile. In these situations, information regarding insulation from polarization current does not provide the reliable information. Thus, in such cases the depolarization current should be used for estimating the insulation sensitive parameters. The suggested method is verified on sample prepared in laboratory and then applied on real life in-situ transformer. It is found that the suggested method is successfully worked on sample as well as on real life transformer.

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