Effective assessment of power transformer insulation using time-varying model without temperature constraints

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ABSTRACT

This paper proposes a method for insulation diagnosis using the time-varying model. The parameters of the stated model are unique and can be recognized by the polarization current. Several methodologies have been reported for insulation diagnosis using various insulation models. However, moisture information without considering the effect of measurement temperature is bound to provide inaccurate result. Temperature significantly affects the dielectric response of materials. As the temperature rises, various important changes take place. Increased temperatures can boost molecular mobility, resulting in higher polarization, which in turn affects the material's dielectric constant and loss. Additionally, higher temperatures typically raise conductivity due to improved charge carrier mobility, further influencing the dielectric response. Hence, the effect of measurement temperature on insulation diagnosis is discussed in this paper so that responses recorded at different temperatures can be effectively compared. The proposed methodology for determining insulation state is tested using data from real-life power transformers.

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1. INTRODUCTION

Insulation models have been crucial in advancing various non-invasive diagnostic techniques [1]-[3]. Recent developments show that RC-based insulation models are essential for analyzing temperature effect [4]-[6], non-uniform aging [7], and the influence of copper-sulphide [8]. Simple models like the conventional Debye model (CDM) need modifications before they can represent in-situ transformer insulation affected by practical conditions [9], [10]. Hence, a few modifications were proposed which resulted in the formulation of the modified Debye model (MDM) and the modified Maxwell model (MMM) [9], [10]. However, these models are essentially modifications of the base structure CDM. CDM assumes that the insulation comprises a finite number of dipole groups [9], whose distinct properties can be approximated by series RC branches for a practical transformer the insulation response at a given time instant is influenced by several dipole groups, whose number and properties vary with the unit's operating age. As the number of dipole groups to be considered during CDM formulations is not fixed, the overall count of branches in a CDM for a specific unit is not fixed [3]. Non-unique branch parameters in CDM (and other modified versions of CDM) affect the accuracy and reliability of all available insulation model-based diagnosis methods. Thus, it is only logical to have an insulation model that analyses insulation response by considering the collective behavior of all dipole groups rather than concentrating on a few distinct dipole groups. Such a model, by definition, will be unique for a given transformer and hence will be better suited for developing reliable diagnosis techniques. Consequently, the time-varying model (TVM) (shown in Figure 1), was reported in [11]. Using this model, you can estimate different condition-sensitive parameters of oil-paper insulation [11].

Oil moisture is measured in ppm. It is relatively easy to assess oil moisture through invasive testing as there is an arrangement in every power transformer to collect oil sample. The aim of this current work is to estimate the percentage of paper moisture (%pm) present in paper insulation. Getting information about paper insulation is a challenging task for the researchers. Recently, numerous studies have reported different methodologies for condition monitoring [12]-[16]. Banerjee *et al*. [11] have reported that such a time-varying model can be used for the diagnosis of insulating materials. The method described in [11] can evaluate the state of oil-paper insulation when polarization current data is obtained at 30 °C. However, it should be noted that the applicability of a particular method does not have to be limited by such temperature constraints. Any insulation condition monitoring methodology that does not include temperature data is meaningless.

As a result, the current paper also proposes a TVM-based methodology for evaluating aging-sensitive parameters such as moisture while taking into account the effect of measurement temperature. The proposed method comprises both time domain as well as frequency domain insulation sensitive parameters to assess the state of oil-paper insulation. Using the proposed methodology, condition monitoring of oil-paper insulation can be performed by analyzing the polarization current profile $i_{pol}(t,T)$ measured at any temperature (T). However, comparing performance parameters derived from $i_{pol}(t,T)$ at different temperatures is challenging, as these parameters are affected by the measurement temperature. Therefore, investigating how measurement temperature impacts TVM parameters is crucial. This paper proposes a methodology to account for the effect of temperature on TVM parameters, allowing for easier comparison of two $i_{pol}(t,T)$ profiles recorded at different temperatures. The present work uses $i_{pol}(t,T)$ of eleven in-service transformers, as shown in Table 1.

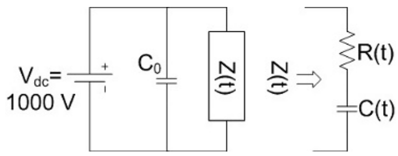

Figure 1. Structure of TVM

Table 1. Details of transformer

Transformer name	Transformer power rating	Operational age (years)
Trafo-1	200 MVA/21 kV	14
Trafo-2	270 MVA/15.75 kV	11
Trafo-3	270 MVA/220 kV	28
Trafo-4	125 MVA/220 KV	26
Trafo-5	250 MVA/420 kV	19
Trafo-6	250 MVA/22 kV	17
Trafo-7	200 MVA/21 kV	26
Trafo-8	220 MVA/22 kV	12
Trafo-9	200 MVA/420 kV	15
Trafo-10	270 MVA/21 kV	17
Trafo-11	200 MVA/15.75 kV	21

Polarization current is a low-amplitude, steadily decreasing signal, with its magnitude affected by the condition of the insulation. To minimize the impact of field noise and capture a response with adequate magnitude, the charging voltage (Vdc) applied during PDC measurement should be maximized. It is mentioned in [4] that the effect of non-linearity in insulation response increases if V_{dc} exceeds 1000 V. As a result, it has become standard practice for utilities to establish Vdc at 1000 V. The same has been followed in the case of the eleven transformers considered in this paper. Figure 2 displays the polarization current profiles for several tested transformers, labeled trafo-1 to trafo-8.

In this paper, insulation diagnosis has been performed using the time domain response of transformer insulation. Data on polarization current over a span of 10,000 seconds is usually employed to assess performance parameters [6], [7]. Nevertheless, utilities tend to favor insulation diagnostic methods that necessitate the shortest data measurement duration. Thus, this study aims to reduce the volume of data required for assessing the condition of insulation. The literature [17] suggests that the profile of the polarization current can be determined using only 600 seconds of recorded polarization current data.

In this examination, the initial 600 seconds of data from different units are utilized to forecast the complete polarization current profile. Subsequently, the aging-sensitive parameter of oil-paper insulation has been determined from the predicted profile. The findings presented in this paper indicate that the suggested method offers enhanced insight into the state of oil-paper insulation.

The study presents time-varying model (TVM) based insulation diagnosis technique. The primary theme is to enhance the precision in assessing the state of insulation made from oil and paper in power transformers. The design and development approach focus on integrating both frequency-domain and time-domain insulation-sensitive parameters, providing a more thorough examination.

The specific goals of the proposed method include:

- Utilizing TVM to predict performance parameters like moisture, regardless of the measurement temperature of polarization current.
- Addressing the temperature dependence of TVM parameters, facilitating the analysis of PDC data not measured at 30 °C.
- Reducing the assessment time of insulation conditions significantly when compared to traditional methods.

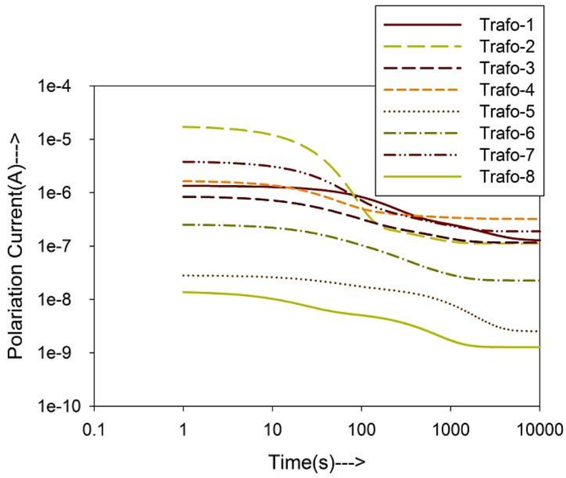

Figure 2. Measured polarization current for trafo-1 through trafo-8

2. THE PROPOSED METHOD

2.1. Condition assessment using TVM

In this paper, the profile of R(t) of TVM is obtained using the methodology depicted in [11]. In [11], the profile of R(t) is fitted with an equation of the form given in (1).

$$R(t) = M_0 + \frac{(a \times t)}{(b+t)} \tag{1}$$

Where M_0 and b are equation coefficients that are evaluated utilizing a least squares curve fitting method. In (1), coefficients M_0, a, and b have units of ohm, ohm, and s, respectively. Polarization current measurement starts after a few seconds of V_{dc} application to avoid transients in recorded data. Since the value of M_0 is affected by the transients, it is not advisable to use M_0 for insulation diagnosis. Consequently, values of a and b are checked to determine whether they can provide any information about insulation conditions. The values of a, b, and moisture corresponding to the different transformers under study are presented in Table 2.

The moisture shown in Table 2 is measured with the IDAX 300. Based on the information provided by utilities, the temperature during PDC measurement was 30 °C (measured with a thermometer having a resolution of 1 °C). The physical dimensions of insulation are expected to be different for each transformer. The coefficients of (1) are tested for insulation diagnosis. To achieve this, it is essential to identify the coefficient that is less responsive to insulation geometry. As, the value of R_0 or $R(t\rightarrow\infty)$, given in (2), is influenced by insulation geometry, condition-sensitive coefficient of (2) should not be affected by the magnitude of leakage current, i_{dc}.

$$R(t \rightarrow \infty) = M_0 + \left(a \times \left\{\left(\frac{b}{t}\right) + 1\right\}^{-1}\right) = M_0 + a; t \rightarrow \infty \tag{2}$$

As M_0 influences the initial value of R(t→0+), it is understood that its value is significantly less than a. This further implies that the magnitude of i_{dc} is affected by a^{-1}. Conversely, it can be argued that the value b in the profile of R(t) is unaffected through the geometry of the insulation. The value of b in (1) is shaped by the consistently decreasing pattern of the polarization current. Previous studies indicate that this polarization current profile is significantly impacted by moisture levels. As insulation deteriorates and moisture content rises, more conductive aging by-products are produced [18]. It is a known fact that the conductive aging by-products influence tanδ.

Table 2. Moisture (measured) and coefficients a and b obtained for different transformers

Trafo	*a* (of (1))	*b* (of (1))	*tanδ*	Moisture
Trafo-1	6.47	137.11	0.58	1.8
Trafo-2	11.34	433.20	0.79	2.3
Trafo-3	8.42	828.10	0.88	2.3
Trafo-4	2.96	116.41	0.21	0.8
Trafo-5	6.62	130.04	0.34	1.2
Trafo-6	8.23	187.42	0.67	1.9
Trafo-7	5.95	810.14	0.80	2.4
Trafo-8	105.65	62.4	0.22	0.8

In literature [11], only the value of b was used to estimate moisture in oil-paper insulation. However, the effect of temperature measurement on this diagnosis technique is not illustrated. In [2], it is reported that the moisture estimation can be improved by including the tanδ information. Hence, in the present work, b and tanδ are collectively used for reliable moisture estimation in a non-invasive way. In the current work, a generalized equation of the form given by (3) is used to estimate moisture corresponding to 30 °C.

$$moisture = a1 \times (b)^{c1} + a2 \times (tan\,\delta)^{c2} \quad (3)$$

Here, $a1$, $a2$, $c1$, and $c2$ are constant coefficients of (3). The values of $a1$, $c1$, $a2$, and $c2$ of (3) are found (using a least square-based iterative technique) to be 0.16, 0.09, 2.52, and 0.96 respectively. It is important to note that both parameters, b and $tan\,\delta$, need to be measured at 30 °C to estimate moisture corresponding to 30 °C using (3).

The measured and estimated value of moisture and their corresponding normalized error (*n_er*) is shown in Table 3. The normalized error is calculated using (4). Based on the data provided by the utilities, power transformers are considered safe to operate until the value of moisture crosses 2.5%. Hence, the normalization correspondence to the maximum moisture value in (4) is shown in Table 3.

$$n\_er = \frac{|measuredvalue - predictedvalue|}{maximumvalueofmoisture} \quad (4)$$

It can be observed from Table 3 that (3) is useful to estimate moisture. However, it should be mentioned here that (3) is only applicable for PDC measured at 30 °C ± 1 °C.

The moisture level can be determined using an equilibrium curve and the moisture content of the oil. Low temperatures render equilibrium curves impractical due to their excessive non-linearity. For instance, at 20 °C, a minuscule error of 4 ppm in the actual oil moisture can lead to a substantial misinterpretation of the moisture content, potentially confusing 0.5% with 5.0% [19]. When the actual oil moisture content is on the order of a few ppm, even negligible errors can lead to substantial deviations in the measured cellulose moisture. Zaengl [20] noted that moisture levels can be estimated using tanδ, which is the minimum tanδ value within the frequency versus tanδ profile. However, it has been observed [20] that this approach can yield errors of up to 35%. This is because tanδ at a given frequency is influenced not only by moisture but also by conductive aging by-products within the system [21]. In fact, moisture impacts the entire low-frequency range of frequency domain spectroscopy (FDS) data [19]. By analyzing the entire FDS dataset and comparing it to an internal database of responses associated with different spacer/barrier ratios, IDAX 300 provides a more reliable moisture prediction than traditional equilibrium curve methods, especially when considering temperature-dependent material behaviors [19]. Therefore, IDAX-predicted moisture is used as the reference value in this work. However, it's important to remember that IDAX 300 results are utilized solely for the identification of the three coefficients.

For an unknown unit, $Trafo_{test}$, (3) and coefficient b (identified from PDC of $Trafo_{test}$) and tanδ are to be used for prediction of moisture present in $Trafo_{test}$. Recent developments have shown that MDM is better suited for modeling the insulation response of power transformers [10]. Unlike the XY model [22], MDM formulation does not need information about spacers (X) and barriers (Y) present in the insulation.

Though oil conductivity [22] can be obtained using the XY model, provided X and Y are known, it is difficult to predict moisture using only X and Y. On the other hand, it is reported in [2], [23] that moisture can be predicted using the transfer function (TF) of MDM. The result obtained from [2] and [23] is dependent upon the number of branches (N) present in MDM. In recent times, TVM parameters have also been used for insulation diagnosis [11]. However, the effect of temperature on the reported technique is not discussed. Any insulation condition monitoring methodology without temperature information is irrelevant. A comparative analysis of the performance of the proposed technique with different methodologies is shown later in this article. It is worth mentioning here that the data of such test unit (trafo-9 to trafo-11) is not used to (3).

It should be mentioned here that (3) is applicable for PDC recorded at 30 °C ± 1 °C. Though in the present case measurement temperature of all transformers was around 30 °C ± 1 °C, it is practically difficult to ensure that all future measurements will be carried out at 30 °C ± 1 °C. Hence, the variation of coefficient b (of (1)) and tanδ with temperature must be studied to understand the full potential of (3). The result of such investigation is reported in the next section.

Table 3. Measured and predicted value (using (3)) of moisture and *n_er*

Trafo.	Moisture (measured)	Predicted value of moisture	*n_er*
Trafo-1	1.8	1.75	0.01
Trafo-2	2.3	2.3	0
Trafo-3	2.3	2.53	0.09
Trafo-4	0.8	0.81	0
Trafo-5	1.2	1.15	0.01
Trafo-6	1.9	1.93	0.01
Trafo-7	2.4	2.34	0.02
Trafo-8	0.8	0.82	0.01

2.2. Variation of b and dissipation factor with temperature

2.2.1. Identifying the value of b at 30 °C

Measuring polarization current, i_{pol}(t, T=30 °C) from all transformers is not always possible. However, i_{pol}(t, T=30 °C) can be calculated using the insulation system's activation energy (E_a). The value of E_a for the transformer can be calculated using the methodology depicted in [5]. It is reported that energy-dissipating elements (R_i; i=0, 1, 2, … N) of CDM are sensitive to measurement temperature, while energy-storing elements (C_i, i=0, 1, 2, ... N) remain relatively unaffected by temperature variation [5]. Dutta *et al.* [5] reported that (5) is capable of modeling variation in CDM parameters (obtained for in-service transformers) due to changes in measurement temperature.

$$R_i^{T2} = R_i^{T1} \times exp\left(\frac{E_a}{K_T} \times \left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right);\ C_i^{T2} = C_i^{T1} \quad (5)$$
$$i = 0, 1, 2, \dots, N$$

Here, K_T is Boltzmann constant (8.6173303E-05 eV/K). R_i^{T1}, C_i^{T1} and R_i^{T2}, C_i^{T2} are the CDM branch parameters of i[th] branch at temperature T_1 and T_2 K. For any test unit, the branch parameters of CDM evaluated at temperature T_1, can be used to identify $i_{pol}(t, T_2)$ using (5) and (6).

$$i_{pol}(t, T_2) = \sum_{i=1}^{N} \frac{V_{dc}}{R_i^{T2}} \times exp(R_i^{T2} \times C_i^{T2} \times t) + \frac{V_{dc}}{R_0^{T2}} \quad (6)$$

The (6) represents the collective behavior of all branches present in CDM and, hence, is less prone to error as far as $i_{pol}(t, T_2)$ profile is concerned. It can be said that i_{pol}(t, T=30 °C) can be obtained from measured polarization current i_{pol}(t, T≠30 °C) for any test unit. Now, using the calculated profile of i_{pol}(t, T=30 °C), b of (1) corresponding to 30 °C can be obtained.

2.2.2. Identifying the value of the dissipation factor at 30 °C

It is also known that tanδ increases with increments in temperature [5]. Unfortunately, tanδ at a temperature other than 30 °C was not available with the utility. However, (3) is applicable only at 30 °C. Insulation resistance (R_0) and geometric capacitance (C_0) are geometry-dependent parameters. However, it can be observed from (7) that their product, known as the insulation pole [24], is less affected by the insulation geometry. It is also known dissipation factor is geometry independent parameter. Insulation pole is reported to increase with an increment in aging by-product [24] and hence with tanδ. Therefore, efforts are made to correlate both the insulation geometry-independent parameters.

$$\left.\begin{aligned} &R0 = \rho\frac{L}{A}; C0 = \varepsilon\frac{A}{L} \\ &Insulationpole = \frac{1}{(R_0 \times C_0)} = \frac{1}{\varepsilon \times \rho} \end{aligned}\right\} \quad (7)$$

According to reference [5], raising the measurement temperature causes both horizontal and vertical shifts in the tanδ profile relative to the frequency axis. An increment in the insulation pole (given in (7)) with temperature deviation, ΔT (=T-30 °C) should be interpreted as the result of an increase in tanδ. The insulation pole for different ΔT is calculated using (5) and (7). Table 4 tabulates the insulation pole sensitivity to temperature variations, considering three temperature differentials (0 °C, 15 °C, and 26 °C) with respect to a 30 °C reference point. Table 4 suggests that the insulation pole's value increases with measurement temperature increase. It is observed rate of change of insulation poles at temperature T (>30 °C) is exponential in nature (shown by (8)).

$$Insulationpole(atT2) = Insulationpole(atT1) \times exp\left(rate_{po} \times \Delta T\right) \quad (8)$$

It is observed that $rate_{po}$ is strongly correlated with tanδ (measured at 30 °C) given in (9).

$$\%\,tan\,\delta = 0.0940\text{-}9.2244 \times rate_{po} + 119.7943 \times \left(rate_{po}\right)^2 \quad (9)$$

The fitted curve obtained from (9) along with data points ($tan\,\delta, rate_{po}$) is shown in Figure 3.

Table 4. Variation of insulation pole (scaled by 10^3) and b with ΔT

Trafo Name	Temperature deviation, ΔT 0 °C pole	15 °C pole	26 °C pole	$rate_{po}$
Trafo-1	7.14	39.75	127.06	0.1066
Trafo-2	9.84	61.87	235.14	0.1218
Trafo-3	12.34	87.44	359.24	0.1292
Trafo-4	7.68	30.69	79.97	0.0891
Trafo-5	27.68	125.4	361.5	0.0985
Trafo-6	45.96	264.4	863.3	0.1085
Trafo-7	28.43	185.7	731.4	0.1245
Trafo-8	0.57	3.88	15.31	0.0873

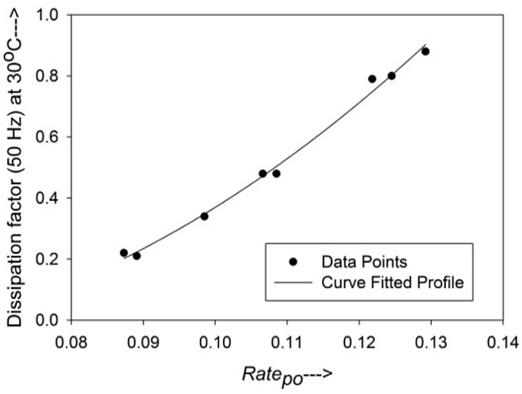

Figure 3. Plot between $rate_{po}$ of (8) and tanδ

Now, it is possible to apply (3) on data i_{pol}(t, T≠30 °C). This can be done in four steps: First, (1) is used to evaluate CDM parameters at measurement temperature, followed by application of (5) and (6) to find i_{pol}(t, T=30 °C). Thereafter, R(t) and b are evaluated at 30 °C. The value of $rate_{po}$ (computed using i_{pol}(t, T≠30 °C) and i_{pol}(t, T=30 °C)) can be readily used to evaluate tanδ at 30 °C using (9). Finally, (3) is applied to compute moisture at 30 °C. The proposed method is limited to data obtained from equipment that has stabilized thermally. As reported by the utilities, each transformer examined in this work was given sufficient time to cool before PDC measurement. A good correlation between moisture and b reinforces the fact the measurement of PDC data was carried out at near thermal equilibrium. The flowchart of whole process is given in Figure 4.

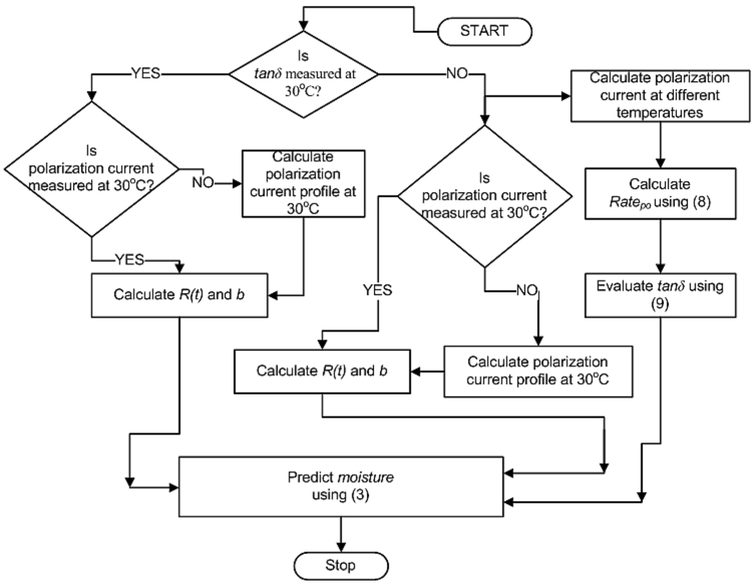

Figure 4. Flowchart of the proposed methodology

3. RESULTS AND DISCUSSION

The transfer function (TF) of the modified Debye model (MDM) has been employed to predict moisture, as described in [2], [23]. However, the accuracy of these methods is dependent on the number of branches (N) in the MDM, which is challenging to identify. On the other hand, TVM has only 2 branches. Temperature constraints limit the applicability of the reported method [11]. The present method is capable of estimating moisture from polarization current measured at any temperature (T). According to [25], the data measurement time required to assess the condition of oil-paper insulation is greater than 50 minutes. The proposed method eliminates all drawbacks or ambiguities found in the above-mentioned reported techniques. Table 5 presents a comparative analysis of the current method alongside other reported techniques. Results shown in Table 5 show that the present method works more preciously compared to other methods. It is worth mentioning here that the data, tabulated in Table 5, is not used to (3). Table 6 presents a comparison of the data measurement time of various reported methods and the proposed method. The proposed method is shown to require significantly less data to diagnose insulation conditions.

Table 5. Comparative analysis of the performance of the present method with other previously reported techniques

Reported methods-		Method 1 [17] (N=7)		Method 2 [20]		Method 3 [2] (N=6)		Method 4 [11]		Proposed methodology (using (3))	
Trans. name	Measured %pm	Estimated	%error	Estimated	%error	Estimated	%error	Estimated %pm	%error	Estimated %pm	%error
Trafo-9	1.5	1.14	24	1.20	20.00	1.31	12.66	1.32	12.0	1.47	2.00
Trafo-10	1.7	1.31	22.94	1.22	28.23	1.48	12.91	1.44	15.2	1.76	3.5
Trafo-11	2.1	1.53	27.14	1.55	26.17	1.74	17.14	1.77	15.7	2.17	3.33

Table 6. Comparative analysis of proposed work with other reported methodologies based on required data measurement time

Method name	Required data measurement time
Method 1 [17]	2.77 hours
Method 2 [20]	Greater than 50 minutes
Method 3 [2]	2.77 hours
Method 4 [11]	2.77 hours
Proposed methodology	10 minutes

4. CONCLUSION

A technique for insulation diagnosis based on a time-varying model (TVM) is proposed. Based on the findings of this study, the following conclusions can be drawn. The suggested approach comprises both time domain as well as frequency domain insulation sensitive parameters to evaluate the condition of oil-paper insulation more precisely. TVM can be employed to estimate performance parameters, including moisture content irrespective of the measurement temperature of polarization current. Temperature dependence of TVM parameters, reported in this paper, makes it easier to analyze PDC data that is not measured at 30 °C. The IDAX 300 requires approximately 50 minutes to assess the insulation condition. Moisture predicted through TVM, on the other hand, has an acceptable correlation (evaluated using data from multiple real-world in-service power transformers) with results collected from commercial equipment (IDAX 300) utilizing only 10 minutes of insulation response data. The strong correlation between b and moisture ensures a reliable and straightforward approach, free from the issues associated with the non-linearity of the equilibrium curve. The suggested approach has been created and tested on a number of in-service, real-world power transformers. As a result, it could be relied on by utilities.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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