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Fractal Analysis of Time Domain Dielectric Response to Reduce Complexity of Insulation Condition Diagnosis Methodology

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ABSTRACT

The health of cellulosic insulation, present in a power transformer, continuously degrades due to its exposure to paper moisture and high temperature. The moisture content of such insulation further accelerates the ageing phenomena. Recent developments made in the field of power transformer insulation diagnosis show that condition-based maintenance of power transformers is more important rather than time-based maintenance. On the other hand, utilities always prefer to monitor the condition of power transformers in short measurement time. The present work proposes a fractal analysis-based condition monitoring technique. The method utilizes only a 600 s measured profile of polarization current. This paper estimates various ageing-sensitive performance parameters evaluated from fractal features for insulation diagnosis. The suggested technique can be used in a non-intrusive way to estimate performance measures such as *%pm* and paper conductivity. With the least amount of shutdown time, this technique quickly assesses the insulating state of power transformers. This strategy has shown to be more successful than existing approaches for monitoring insulation status.

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1. INTRODUCTION

Insulation diagnosis of power transformer is an important task to provide uninterrupted power supply to consumers. Polarization and depolarization current (PDC) measurement is one of the well-known methods to diagnose oil paper insulation present inside a transformer tank [1]. To measure the polarization current, a constant voltage is applied across the insulation. As a result, the dipoles in the oil paper insulation try to line up with the direction of the applied field. The resulting current during this phase is termed polarization current. The oil paper insulation's terminal is quickly shorted out after the polarization stage. In this phase, the short-circuited channel is traversed by reverse current direction as the oriented dipoles attempt to return to their original places. This current phenomenon is referred to as depolarization current.

The magnitude of current flowing through any insulation is greatly affected by its aging, dielectric condition [23]. The oil-paper insulation in transformers typically does not degrade during the installation phase. Instead, degradation occurs over time during the operational lifespan of the transformer due to aging by-products, which compromise the quality of the insulation. The dielectric properties, durability and reliability of insulating oil can be enhanced by adding suitable nanoparticles [24, 25, 27]. Literature reported various methodologies based on PDC measurement to assess the health of oil-paper insulation [1, 2]. Among them, insulation model-based analysis, de-trapped charge-based analysis and insulation pole calculations are popular [3,4,5]. However, each of these methods has some disadvantages, which are detailed later in the paper.

Available literature reported that the response of insulation is affected by moisture present in insulation [1,2]. In the recent past, the monotonically decreasing nature of the dielectric relaxation function, *φ(t)*, has been modelled by a sum of exponential decay functions [3,6]. Researchers have reported many insulation models based on simple combinations of resistances and capacitances that are capable of analyzing *φ(t)*. Among available two-parameter circuits, the Classic Debye Model (CDM) or Maxwell model is quite popular and has been extensively used by many researchers to assess insulation conditions in the past decade [3,6]. In the recent past, the effects of long-term exposure to the radial and axial temperature gradient (causing non-uniform ageing of cellulosic material) have been modelled by the Modified Debye Model (MDM) and Modified Maxwell Model (MMM) [6,7]. In the Time-Varying Model (TVM), the instantaneous values of resistance and capacitance are obtained from a given polarization current [8]. During formulation of either CDM, MDM, MMM or, TVM, the relaxation procedure of a dipole is assumed to be in nature. However, available literature reported debye nature continues during the polarization process for initial few seconds [9]. In fact, the polarization process of solid insulation rarely follows a debye nature. Hence, estimating moisture present in solid insulation using a model-based technique might provide erroneous results.

The PDC profile is useful to calculate the de-trapped charge in oil paper insulation [5]. Such a de-trapped charge amount is useful to sense the health of oil-paper insulation [5]. As per the reported literature, the de-trapped charge is impacted by the charge accumulated at the oil-paper as well oil-metal interface [10]. It is difficult to determine the charge de-trapped from the oil-paper interface only. Hence, it is difficult to know the actual health of paper insulation. Available methodology reported that dipole relaxation follows the time-dependent power law [9, 11]. However, the nonlinearity present in dielectric response can not be modelled by above stated method at a higher time instant. Fractal geometry describes the power laws nature of any data more thoroughly. Available literature [12] shows that Fractal Analysis can better demonstrate issues with nonlinearity and irregularity in any signal. Fractals have been found to be effective in describing naturally arising signals and shapes where conventional and existing mathematical models have proven insufficient.

It is known that paper moisture, dissipation factor and paper conductivity mainly offer an idea about any insulation's quality. However, it is difficult to determine these parameters through non-invasive methods. A unique methodology is proposed in this paper to address the above-stated problem, which is analysis using data from real-life in-service transformers. In this paper, different performance parameters are evaluated from the Fractal Analysis of polarization current and used for successful insulation diagnosis.

In this paper, fractal features were extracted from the time-domain response of insulation. As per general convention, polarization current data spanning 10000 s is used to estimate performance parameters [5, 6]. However, utilities always prefer to apply any insulation diagnosis technique requiring the least data measurement period. Hence, efforts are made to minimize the required measured data for insulation condition diagnosis in the present analysis. Literature [13] reported that the profile of polarization current can be estimated using only polarization current data measured for only 600s. In the present analysis, the first 600s data of different units are used to predict the whole profile of polarization current. Then, the Fractal features, i.e. Fractal Dimension (FD) and lacunarity, are calculated from the forecasted polarization current profile. Results presented in this article demonstrate that these features provide better clarity about the health of oil-paper insulation. The motivation of the paper is to have an effective and reliable diagnosis within a short duration of time using a cost-effective system. It is understood that costly commercial equipment like IDAX cannot be deployed on a large scale. On the other hand, the 6517 B-based setup is much less capital intensive and hence can be deployed at a larger number. Further, literature [13] shows that the entire polarization current can be predicted using data recorded for 10 min. It is a known fact that IDAX takes a much longer time to operate [18]. Later on, it is shown that the proposed method can be used to predict %pm which is close to that estimated by IDAX.

2. DIELECTRIC RESPONSE MEASUREMENT

To study the above analysis, polarization currents of 12 real-life in-service units are measured for 600s. The ratings of the 12 units are shown in Table 1.

Polarisation current is a low amplitude monotonically decaying DC signal, the magnitude of which is determined by the ageing state of the insulation. As a result, the applied voltage during such time domain response measurement should have high magnitude to curtail the effect of noise and to measure the response current with adequate amplitude (so that it can be satisfactorily analyzed). However, literature [14] mentions that if the charging voltage exceeds 1000 V, the effect of nonlinearity on insulation response increases. As a result, it has become standard practice for utilities to set the charging voltage to 1000 V during PDC measurements. This is also the case for the 12 transformers, used in this paper. Here, the KEITHLEY 6517B Electrometer-based measurement setup (shown in Figure 1) was used to measure these profiles. To control the Electrometer effectively, a LabVIEW script is employed to transmit appropriate control signals through the GPIB port. Both the built-in voltage source and the current sensing module within the Electrometer are operated suitably for the purpose of measurement. The specification of this measuring unit is given in [26]. The measured polarization current of some real-life in-service test units is shown in Figure 2.

In the present analysis, insulation condition-sensitive parameters like *dissipation factor*, *%pm* were measured using IDAX 300. Literature shows that different models must be used to assess various performance parameters. For instance, paper-conductivity can be predicted by employing XY model [15], while assessment of paper moisture *(%pm)* needs to employ models like, CDM or, TVM [6,8]. It is shown in this paper that all these commonly measured performance parameters can be easily evaluated by using only fractal features without using any insulation model.

Table 1: Details of the Transformer

Transformer Name	Transformer Power Rating	Operational age (years)
Trafo1	240 MVA/400 kV	19
Trafo2	150 MVA/220 kV	26
Trafo3	270 MVA/220 kV	11
Trafo4	200 MVA / 420 kV	19
Trafo5	125 MVA/220 KV	16
Trafo6	167 MVA/ 400 kV	14
Trafo7	200 MVA /420 kV	15
Trafo8	250 MVA /15.7 kV	28
Trafo9	220 MVA/22 kV	12
Trafo10	250 MVA / 420 kV	19
Trafo11	250 MVA /22 kV	17
Trafo12	270MVA/21 kV	17

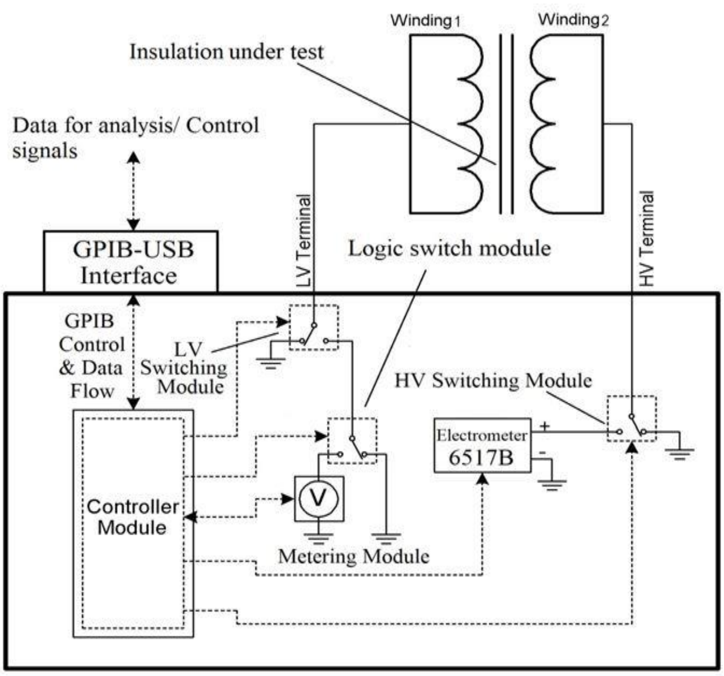

Figure 1. Measurement set up of polarization current using electrometer 6517B

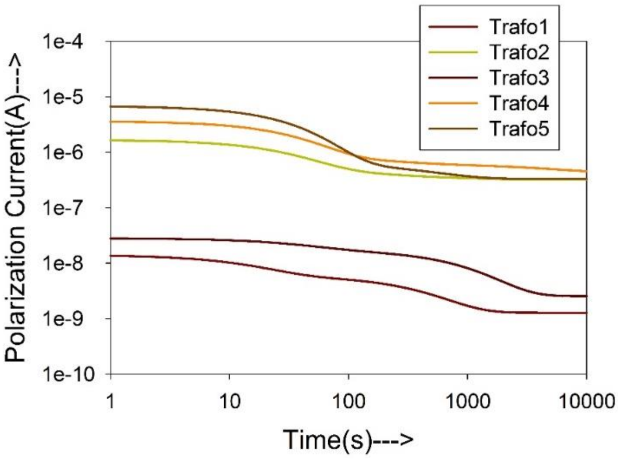

Figure 2. Measured Polarization Current Profile

3. FRACTAL ANALYSIS

Fractal analysis is based on the fractal-dimension concept, which measures the complexity of a fractal object [16]. The fractal dimension provides quantitative information about the self-similarity and scale-invariance properties of a fractal. A higher fractal dimension means a higher order of complexity or irregularity, while a low value of fractal dimension indicates a smoother or less complex structure.

Box counting is the most commonly used method in the fractal analysis due to its simplicity and ease of implementation. In box-counting, the fractal object is covered with a grid box of decreasing size. Thereafter, the quantity of boxes intersecting with the fractal object is counted. The fractal dimension is then evaluated as the slope of the logarithmic graph of the number of boxes against the size of the boxes [16].

Let, set A is in Euclidean n-space. It is said to be self-similar if it is the union of *N* distinct copies of itself, each scaled down by a ratio *r* in all coordinates. The following expression gives the fractal dimension, *FD* of set A.

$$Nr^{FD} = 1 \tag{1}$$

Let us suppose that the data set A is covered by an n-dimensional box having L_{max} size (manifold of the X-Y plane's span *L*). If the set A is now cut down by ratio r, the quantity of box of size $L = r*L_{max}$, required to enclose the entire area, needs to be identified. To find this, (1) can be written as (2).

$$N(L) = \frac{1}{r^{FD}} = \left[\frac{L}{L_{max}}[]^{FD}\right] \tag{2}$$

Here, *N(L)* is the quantity of occupied boxes for a given *L*. For various values of *L*, the non-empty boxes, *N(L)* is calculated. Thereafter, the data points *N(L)* and *L* in log log pot is curve fitted to identify their slope. The slope (shown by (3)) is called the fractal dimension FD. [16]:

$$FD = \frac{log(N(L))}{log(L)} \tag{3}$$

4. LACUNARITY

Details about lacunarity are given in [17]. Let *P(m,L)* denote the possibility that *m* points exist within a box of side *L* (i.e. the square of side *L*) that is centred on an arbitrary point on the waveform. Then, for each *L*, *P(m,L)* is normalized as shown below.

$$\sum_{n=1}^{m} P(m,L) = 1 \tag{4}$$

where *n* is the quantity of points inside the *L*-sided box. Voss [17] defined lacunarity (*LC*) as a function of *Q(L)* and $Q^2(L)$. The expression of *Q(L)* , $Q^2(L)$ and *LC* is given below.

$$\left.\begin{aligned} Q(L) &= \sum_{m=1}^{N} mP(m,L) \\ Q^2(L) &= \sum_{n=1}^{N} m^2P(m,L) \\ LC &= \frac{Q^2(L)-[Q(L)]^2}{[Q(L)]^2} \end{aligned}\right\} \tag{5}$$

The above-stated fractal-based algorithms are applied to the measured polarization current profile to extract fractal features. An investigation has been done to check whether these parameters are insulation condition sensitive or, not. The result of such investigation is presented in the following section.

5. RESULT AND DISCUSSION

5.1 Estimation OF Dissipation Factor (*%tanδ*)

The fractal dimension determines the scaling property of any signal. The present work calculates the fractal dimension of different in-service power transformers' measured polarization current profiles. Now, it is important to know whether fractal dimension (*FD*) is geometry dependent or, not. Hence, a scatter plot between the dissipation factor (corresponding to 50 Hz) and FD is shown in Figure 2. Taking into account the fluctuation of the data points as depicted in Figure 2, the following criteria (6a)–(6f) are evaluated to determine the most suitable expression for modelling these data points. The effectiveness of each equation in representing the relationship within the measured data can be assessed by examining the correlation coefficient, denoted as R. A value of R approaching unity indicates that the equation being tested can accurately model the measured data. The correlation coefficients R associated with these profile using equations (6a)–(6f) are determined. It is found that (6b) has the highest value of R (=0.9931). Therefore, it can be inferred that (6b) most effectively describes the variation of *FD* with *tanδ*. It can be observed that the fractal dimension maintains a clear relationship with *tanδ* (corresponding to 50 Hz) given in (7).

The polarization current arises from various dipole clusters within oil-paper insulation, with each cluster's behaviour resembling that of a Debye model [1,2]. With the introduction of aging by-products, the behaviour of these dipole clusters becomes more intricate, significantly affecting the dissipation factor [8]. Consequently, as the insulation deteriorates, both the dissipation factor and the insulation's response become more complex. Fractal Dimension (FD) serves as a measure of complexity for fractal objects. Therefore, the relationship between FD and *tanδ* (or other condition-sensitive parameters) should exhibit an incremental pattern.

$$tan\delta = \alpha_0 + (\gamma \times FD)/(FD + \beta) \tag{6a}$$

$$tan\delta = \alpha_0 + \beta \, ln(\gamma \times FD - \lambda) \tag{6b}$$

$$tan\delta = \alpha_0 \times (1 - exp(-\beta \times FD)) \tag{6c}$$

$$tan\delta = \alpha_0 \times (1 - exp(-\beta \times FD))^{\gamma} \tag{6d}$$

$$tan\delta = \frac{\alpha_0}{\left(1 + exp\left(\frac{\beta - FD}{\gamma}\right)\right)} \tag{6e}$$

$$tan\delta = \alpha_0 + ln(FD - \beta) \tag{6f}$$

$$\% \tan\delta = 0.0447 + 2.0399 \ln\left(FD\right) \tag{7}$$

The fitted curve obtained from (7) along with data points (*tanδ*, *FD*) are shown in Figure 3. It is known that the dissipation factor of any insulation does not depend upon insulation geometry [2, 8]. So, it can be concluded that the *FD* is a condition-sensitive parameter.

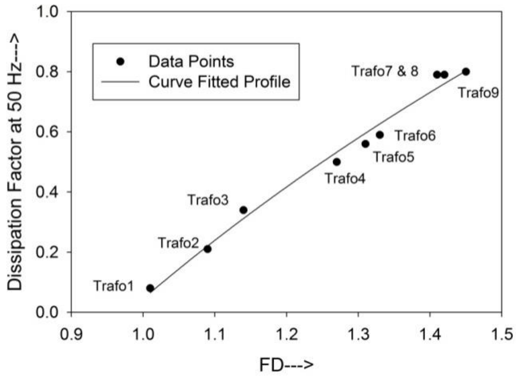

Figure 3. Variation of dissipation factor with %*tanδ*

5.2 Estimation of Paper Moisture (*%pm*)

Paper moisture (*%pm*) is one of the key factors responsible for the degradation of insulation conditions. According to the utilities, power transformers are prone to failure once the moisture content exceeds 2.5%. Available literature suggests that the profile of polarization current is strongly influenced by *moisture* [2, 6]. The variation of *FD* with *%pm* is shown in Figure 4. The correlation coefficient R, obtained by fitting the measured *%pm* with equations of the form (6a)–(6f), is evaluated. It is observed that equation in the form of (6b) yields the highest value of R (=0.9993). Consequently, it can be concluded that equation in the form of (6b) provides the most accurate description of the relationship between Fractal Dimension (FD) and *%pm* variation.

It can be observed that the *FD* maintains a good relationship with *%pm*. The relation between these two parameters is best modelled by (8). For an unknown unit, the *FD* of measured polarization current needs to be identified to estimate *%pm* using (8).

$$\%pm = 3.0167 + 2.6446\ln\left(FD - 0.6520\right) \tag{8}$$

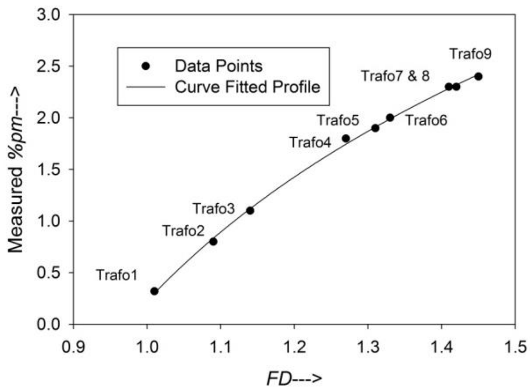

Figure 4. Variation of *FD* with %*pm*

5.3 Estimation of Paper Conductivity (σ)

Paper-conductivity *(σ_c)* is one of the key indicators of oil-paper insulation degradation [15]. According to the available literature, the X-Y model can be used to calculate paper conductivity [15]. The value of such transformer design parameters, X and Y, of any real-life transformer is not always available to the utility. Hence, there is a requirement to find an alternative method to estimate paper conductivity by skipping the X-Y model.

Efforts have been made to estimate the paper conductivity of any oil paper insulation using lacunarity, *LC* of measured polarization current. It is observed that *LC* maintains a good relationship with paper conductivity (shown in Figure 5). The relation is modelled using the least square-based curve fitting technique. It is observed that (9) is best suitable to model the data points. It is worth mentioning here that the value of measured paper conductivity is obtained using X-Y model-based methodology depicted in [15]. For an unknown test unit, *LC* of measured polarization current needs to identify to estimate *paper conductivity* using (9).

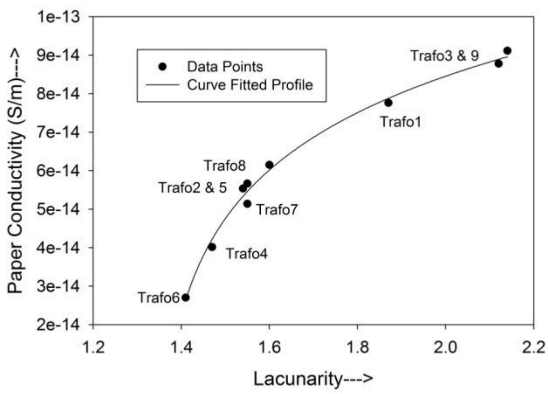

Figure 5. Variation of dissipation factor with *lacunarity*

$$\sigma_c = 9.53\text{E-}014 + 2.63\text{E-}014\, ln(LC - 1.33) \quad (9)$$

6. APPLICATION OF PROPOSED METHOD ON FEW REAL-LIFE UNITS

To validate the proposed methodology, performance parameters of a few units (Trafo10 to Trafo12) have been estimated using fractal analysis. The Fractal Dimension (*FD*) and *LC* of the polarization current from these units are determined following the procedures outlined in Sections 3 and 4, respectively. Subsequently, (8) and (9) are applied to assess the moisture content and paper conductivity of these units. Conversely, the percentage paper moisture (*%pm*) and paper conductivity were measured using IDAX 300 equipment. It's recognized that expensive commercial instruments like IDAX are impractical for widespread deployment. Conversely, setups based on 6517B are more cost-effective and thus can be deployed on a larger scale.

It is worth mentioning here that data corresponding to these transformers were not used during the formulation of the proposed method. The estimated values of *%pm* and *paper conductivity* are shown in Table 3. According to the utility requirements, a 10% margin of error between the estimated paper moisture, paper conductivity, and the values obtained using commercial equipment is deemed acceptable [3,4]. It can be observed that the estimated and measured value of such condition-sensitive parameters is close to each other. The value of *%error* column of Table 2 strengthens that the proposed method is applicable for health monitoring of in-service power transformers.

Table 2. Validation of the proposed methodology

Trans name	Measured *%pm*	Estimated *%pm*	%error	Measured σ_c	Estimated σ_c	%error
Trafo10	1.8	1.77	1.6	5.16e-14	5.22e-14	1.1
Trafo11	2.2	2.24	1.8	6.24e-14	6.31e-14	1.1
Trafo12	1.1	1.14	3.6	8.18e-14	8.28e-14	1.2

7. COMPARATIVE ANALYSIS OF THE PROPOSED WORK

Table 3. Comparison of the performance of the proposed method with other reported methods

Method →		*Method 1* (in [22])		*Method 2* (in [19])		*Method 3* (in [21])		*Method 4* (in [8])		(proposed) Eqn (7)	
Trafo ↓	*Measured %pm*	*%pm*	%error	*%pm*	%error	*%pm*	%error	*%pm*	%error	*%pm*	%error
Trafo1	0.30	0.38	26.66	0.61	103.3	0.4	33.33	0.37	23.33	0.30	0.16
Trafo2	0.80	0.52	35	1.32	65.00	1.04	30.00	0.92	15.00	0.83	4.22
Trafo3	1.10	0.92	16.36	1.42	29.09	1.44	30.90	1.17	6.36	1.11	1.78
Trafo4	1.80	1.62	10	1.44	20.00	1.54	14.44	1.7	5.55	1.74	3.10
Trafo5	1.90	2.27	19.47	1.55	18.42	1.81	4.73	1.94	2.10	1.91	0.52
Trafo6	2.00	1.67	16.5	1.78	11.00	1.74	13.00	1.65	17.50	1.98	0.54
Trafo7	2.30	1.81	21.30	2.02	12.17	1.81	21.30	2.01	12.60	2.28	0.69
Trafo8	2.30	2.01	12.60	1.89	17.82	1.87	18.69	2.04	11.30	2.31	0.81
Trafo9	2.40	1.93	19.58	2.07	13.75	2.15	10.41	2.21	7.91	2.42	0.83

The amount of moisture in cellulose can be estimated using an equilibrium curve and the oil-moisture relationship. Equilibrium curves become too non-linear to be useful at low temperatures [18]. For example, at 20°C, 0.5% moisture can be misinterpreted as 5.0% if the actual oil-moisture is affected by a 4 ppm error [18]. This is especially true when the actual oil-moisture content is only a few ppm. In such cases, a few ppm error in determining moisture in cellulose becomes significant. According to Zaengl [19], moisture can be predicted using $tan\delta_m$ (minimum value of dissipation factor in $tan\delta$ vs frequency plot). However, this relationship [19] is observed to provide results with up to 35% error [19]. This occurs because conductive ageing by-products (in addition to moisture) present in the system affect $tan\delta$ (at a specific frequency) [20]. In fact, the whole low frequency region of Frequency Domain Data (FDS) has been reported to be affected by moisture [18]. To determine moisture content, IDAX 300 compares the measured FDS data-set to its database, which contains responses corresponding to different proportions of spacers/barriers. The analysis also considers the temperature dependence of various materials [18]. As a result, moisture predicted by IDAX is more likely to be accurate than moisture predicted by an equilibrium curve [18]. As a result, the moisture obtained by IDAX is assumed to be the measured value in the current work. It should be noted that IDAX 300 results are used only during the identification of (7) coefficients.

Several non-invasive methodologies [22, 8, 19, 21] for estimating *%pm* have been reported. A performance comparison of the present work with other reported methods is shown in Table 3. It can be observed from Table 2 that the proposed methodology works more precisely than other reported methods.

A comparison of different reported methods with the proposed method based on required data measurement time is tabulated in Table 4. It can be monitored that the proposed method required less amount of information to diagnose insulation conditions preciously.

Table 4. Comparative analysis of proposed work with other reported methodologies based on required data measurement time

Method Name	Required Data Measurement Time
Method 1 [22]	2.77 Hours
Method 2 [19]	Greater than 50 minutes
Method 3 [21]	Greater than 50 minutes
Method 4 [8]	2.77 Hours
Proposed Methodology	10 minutes

8. CONCLUSIONS

This paper proposes a fractal analysis-based technique to estimate different insulation condition-sensitive parameters using only 10 minutes of insulation response data. The subsequent points can be concluded from the above discussion.

1. Fractal analysis, appropriately designed, can be utilized to analyze forecasted polarization current data considering only 600 seconds of recorded polarization current. Through this method, various parameters sensitive to insulation condition can be computed.
2. The *FD* can be employed to estimate performance parameters like *%pm* and *%tanδ* in a non-invasive way.
3. The proposed method requires a very small amount of shutdown period of the power transformer and less computation time to diagnose insulation conditions.
4. The proposed method works more preciously than other reported insulation condition monitoring methods.
5. While conventional Frequency Domain Spectroscopy (FDS) typically takes approximately 12 hours to complete, IDAX significantly reduces this time to around 50 minutes for diagnosing oil-paper insulation. The proposed method further shortens the time required for diagnosing oil-paper insulation, offering even greater efficiency in assessment.
6. Validation of the proposed method using real-life data collected from in-service transformers lends credibility to its reliability. As a result, utility companies can confidently employ this method for diagnosing oil-paper insulation in transformers.

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