# Estimation of Moisture in Transformer Insulation Using Dielectric Frequency Response Analysis by Heuristic Algorithms

Mehdi Bigdeli, Jafar Aghajanloo, Davood Azizian

***Abstract*—Transformers are one of the most valuable assets of power systems. Maintenance and condition assessment of transformers has become one of the concerns of researchers due to a huge number of transformers has been approached to the end of their lifetimes. Transformer's lifetime depends on the life of its insulation and the insulation's life is strongly influenced by its moisture attraction as well. Thus, regarding the importance of moisture analysis, in this paper, a new method is introduced for moisture content determination in the transformer insulation system. The introduced method uses the dielectric response analysis in the frequency domain based on heuristic algorithms such as genetic algorithm and particle swarm optimization. First, the master curve of the dielectric response is modeled. Afterward, using the proposed method the master curve and the measured dielectric response curves are compared. By analyzing the comparison results, the moisture content of the paper insulation, the electrical conductivity of the insulating oil, and the dielectric model dimensions are determined. Finally, the proposed methods are applied to several practical samples and their capabilities are compared to the well-known conventional method.**

***Keywords*—Transformer Insulation, Moisture, Dielectric Frequency Response (DFR) Analysis, Genetic Algorithm (GA), Particle Swarm Optimization (PSO).**

## I. Introduction

Nowadays, a large fleet of transformers are working at the end of their life expectancy [1]. Due to the high prices and the tremendous impact of transformers on the reliability of power networks, monitoring and condition assessment of power transformers has been widely regarded by power system experts. The lifetime of a transformer depends on the insulation's condition. One of the most important factors that are harmful to insulation (particularly cellulose-type insulations) is moisture. Eventually, moisture in a transformer may be penetrated due to three main reasons:

- Remaining moisture in the rigid and large parts of insulations from the drying process
- Moisture com from cellulose and cellulose aging (oxidation)
- Moisture absorption during the breathing of the transformer

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Moisture can cause bubbles, partial discharge, breakdown voltage reduction, and aging in insulation [2]. Insulation's moisture determination has been performed by two general methods: chemical and electrical methods [3]. Chemical methods are not accurate enough and cause some errors [4]. In recent decades, new techniques based on the dielectric response analysis have been introduced which are called electrical methods. Three main methods for measuring a dielectric response can be listed as follows [5]:

- Polarization and Depolarization Currents (PDC)
- Recovery Voltage Measurement (RVM)
- Dielectric Frequency Response (DFR) or Frequency Domain Spectroscopy (FDS)

PDC and RVM methods are based on time-domain measurements. These techniques determine the insulation's condition by measuring the polarization and the depolarization current [6-7]. Insulation's dielectric response measurement in the frequency domain (DFR) is a conventional test for measuring the dissipation factor (tan δ), the complex dielectric constant, and complex capacitance in a wide range of frequencies [7]. The importance of DFR is that the dielectric properties of the insulating systems are revealed in different frequencies. Insulating system parameters such as moisture amount of the paper, the electrical conductivity of the oil (which represents its moisture content), and the insulation model dimensions can be determined by comparing the insulation dielectric response with its master curves [8].

The DFR in oil-impregnated pressboards, moisture content as well as test temperature, was monitored carefully, and a new dielectric characteristic parameter for the diagnosis of moisture content was proposed in [9]. Some of the related studies [10-11] improved the monitoring method based on the FDS principle to implement the dielectric measurement on energized transformers. As an application of intelligent methods, the use of two types of neural networks for the analysis of the FDS results to help to discriminate the impact of moisture and aging done in [12].

Usually comparing the insulation dielectric response with its master curves is done by separating the frequency ranges (SFR) [13]; however practically, this method has significant errors and cannot accurately assess the condition of the insulation [14]. Hence, in this paper, a new method is proposed to determine the parameters of the transformer insulating system using the genetic algorithm (GA) and particle swarm optimization (PSO). To evaluate the performance of the proposed methods, four transformers with different design conditions, have been selected and their frequency responses have been measured. Afterward, the transformer insulation's condition (moisture content of the insulating paper, electrical conductivity of the insulating oil, and the dielectric model dimensions) is determined using the proposed methods and their results are compared to the SFR method.

It is shown that the presented heuristic algorithms can estimate the moisture content rapidly and accurately. The PSO method has better results and it is faster than GA. Therefore, the introduced method based on PSO can be employed as a reliable method for determining the moisture amount in the transformer's insulation.

## II. Background of the DFR Theory

To measuring the dielectric response in the frequency domain, a sinusoidal voltage has been applied to the insulating material and its impedance has been measured (by measuring the current and voltage carefully). Given the phase difference between the voltage and the current due to the polarization, the impedance of the insulation can be expressed as follows:

$$\bar{Z}(\omega)=Z'(\omega)+iZ''(\omega)=\frac{\bar{u}(\omega)}{\bar{I}(\omega)} \quad (1)$$

Assuming that the tested dielectric material is a complex capacitance, insulation's impedance can be expressed as [15]:

$$\bar{Z}(\omega)=\frac{1}{i\omega\bar{C}(\omega)} \quad (2)$$

Combining the equations (1) and (2), the relation between the voltage and the current will be explained as follows:

$$\bar{I}(\omega)=i\omega\bar{C}(\omega)\bar{u}(\omega) \quad (3)$$

The complex capacitance can be explained as two real and imaginary parts as follows [15]:

$$\bar{C}(\omega)=C'(\omega)-iC''(\omega) \quad (4)$$

Since the dielectric material's capacitance depends on the dielectric constant, the complex dielectric constant can be determined according to the following equation [16]:

$$\bar{\varepsilon}(\omega)=\varepsilon'(\omega)-i\varepsilon''(\omega) \quad (5)$$

And the dielectric dissipation factor may be defined as (6) [16].

$$\tan\delta=\frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}=\frac{C''(\omega)}{C'(\omega)} \quad (6)$$

## III. The Master (Reference) Curve Determination

One of the benefits of the insulation's condition assessment based on DFR is the master curve modeling. For a specified amount of moisture in the insulating paper, the electrical conductivity of the oil, the geometry dimensions, and the dielectric response of the insulating system can be achieved. To form a master curve, the dielectric response of each component in the insulating system must be determined first.

Afterward, using the XY model, the dielectric response of the whole system is achieved. The XY model of the Insulating system (consisting of the oil and paper insulations) is shown in Figure 1 [5-6]. The parameter X is the relative amount of the solid insulation (barriers) in the radial direction and Y is the relative amount of the spacers.

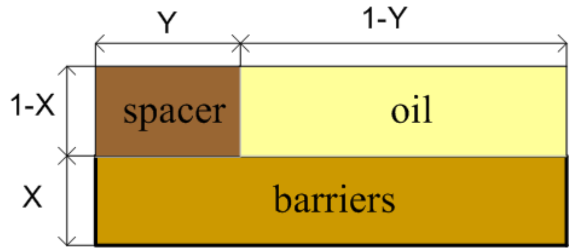


Fig 1. The geometric arrangement of the insulation system (XY model)

Given XY dimensions of the insulating system and the complex permittivity of any insulating materials, equivalent permittivity of the insulating system can be obtained from equation (7) [17].

$$\bar{\varepsilon}(\omega,t)=\frac{Y}{\frac{1-X}{\bar{\varepsilon}_{spacer}}+\frac{X}{\bar{\varepsilon}_{barrier}}}-\frac{1-Y}{\frac{1-X}{\bar{\varepsilon}_{oil}}+\frac{X}{\bar{\varepsilon}_{barrier}}} \quad (7)$$

Where: $\bar{\varepsilon}(\omega,t)$ is the complex permittivity of the whole system, $\bar{\varepsilon}_{spacer}$ is the complex permittivity of the spacers, $\bar{\varepsilon}_{barrier}$ is the complex permittivity of the paper, and $\bar{\varepsilon}_{oil}$ is the complex permittivity of oil.

The complex permittivity of the oil is composed of two real and imaginary parts. Its real part is a constant value equal to 2.2 and the imaginary part depends on the frequency and the electrical conductivity. Thus, the complex permittivity of the oil can be expressed by the following equation:

$$\bar{\varepsilon}_{oil}(\omega,t)=2.2-i\frac{\sigma_{dc}}{\omega\varepsilon_{\circ}} \quad (8)$$

Where: $\sigma_{dc}$ is the Electrical conductivity, $\omega$ is the angular velocity, and $\varepsilon_{\circ}$ is the permittivity of vacuum.

The complex permittivity of the paper saturated with oil is very complex and highly depends on the frequency, the temperature, and the moisture content; it can be obtained by the experimental results [18]. To do this, several samples of the moisture included papers under different conditions are provided; and by measuring their dielectric responses in a wide range of frequency (0.1mHz-1KHz) a database is created [19]. If the temperature of the measured master curve is not equal to the transformer's temperature, the master curve results must be transferred to the temperature of the transformer under test. If the dielectric response is plotted on a logarithmic scale, temperature changes will not modify the overall shape of the curve, but the curve will be displaced in the same direction of the frequency axis [20]. The amount of frequency shift can be obtained from equation (9) [21],

$$shift=\log(\omega_1)-\log(\omega_2)=-\frac{e}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \quad (9)$$

Where: e is the activation energy in electron-volt, *k* is the Boltzmann constant and *T* is the temperature in Kelvin.

By creating a master curve and compare it with the measured insulation curves, the insulating system parameters are determined.

## IV. DFR ANALYSIS USING SFR

Dielectric response in the frequency domain (if it is drawn in logarithmic scale) will be approximately S-shaped [22-25]. This S-shaped curve includes a minimum and a maximum at low frequencies (typically below 1Hz) and a local minimum at high frequencies (usually above 10Hz). Figure 2 shows an example of this response.

The moisture content of the paper, the electrical conductivity of oil, and the X and Y dimensions of the insulation model affect the different parts of the insulating system response. Moisture in paper affects the curve at frequencies below 0.1mHz and above 1Hz. Thus, with an increase in the amount of moisture, the curve moves upward, and insulation losses increase, and vice versa. The amount of X and Y affects the local maximum at low frequencies and the local minimum at high frequencies. So, an increase in dimensions decreases the maximum and increases the minimum point. The effect of the oil's electrical conductivity can be seen in the frequencies between the minimum and maximum points; by increasing its value, this part of the curve moves towards the higher frequencies. The temperature will not change the overall shape of the curve but by increasing the temperature, the curve moves towards the higher frequencies.

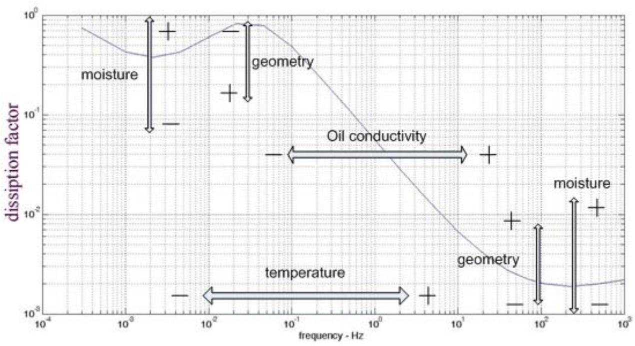


Fig 2. DFR measurements (the effect of various parameters) [22]

In the analysis using SFR, by comparing the measured dielectric response with the master curve, the insulating system parameters can be determined for each frequency range, separately. In this way, by changing the parameters of the insulating system, the closest master curve that has the smallest difference from the measured curve is generated.

## V. DFR ANALYSIS USING HEURISTIC METHODS

DFR analysis using SFR has errors in some cases. For example, in some measurements, the dielectric response curve has not been fully established and the local minimum and maximum points will not be visible. This can be related to the condition of insulation such as the amount of moisture in the paper, oil, and dimensions (X and Y). Moreover, the parameters' frequency ranges are not always similar and vary with the condition of the insulation. Therefore, the results are strongly influenced by the choice of frequency ranges. In the following, heuristic methods based on GA and PSO are proposed to analyze the measured insulation curves regardless of the frequency ranges.

### *A. DFR analysis based on the Genetic Algorithm (GA)*

GA is a method that can be used for solving nonlinear equations and complex optimizing problems. GA is based on natural selection, providing solutions by generating a set of chromosomes referred to as a generation and repeatedly modifies a population of initial solutions. In contrast to more traditional numerical techniques, the parallel nature of the stochastic search done by GA often makes it very effective to arrive at global optimum. In the GA approach, each design variable represented as a binary string (chromosome) of fixed length is evaluated by using a fitness function. If the search has to continue, the GA creates a new generation from the old one until a decision is made on the convergence. A crossover operator exchanges information contained in two-parent individuals to produce two offspring and then replace the parents. The number of times the crossover operator is applied to the population is determined by the probability of crossover and the population size. A mutation operator randomly selects an individual from the population and then chooses two elements in this individual to exchange positions. A binary tournament selection strategy is used to select the fittest individuals where two individuals are selected at random from the population, and the better one is duplicated in the next generation. This cycle is repeated until an optimization criterion is reached [26].

GA is originally a binary algorithm, but depending on the nature of problems it might be used as a real-coded algorithm. In a real-coded GA (RCGA) the solution is directly represented as a vector of real parameter variables [27].

### *B. DFR analysis based on the Particle Swarm Optimization (PSO)*

PSO is an efficient algorithm and developed in recent years. PSO is one of the new algorithms invented by Kennedy and Eberhart in 1995 [28-29]. This algorithm was inspired by the social behavior of animals such as bird flocking or fish schooling. In comparison with other optimization algorithms, PSO has a considerable search for complex optimization problems with a faster convergence rate. As an advantage in programming, PSO requires fewer parameters for regulation than other optimization algorithms. Implementation steps of this algorithm are as follows:

1-Random generating of primary population,

2-Particles fitness calculation respect to their current positions,

3-Comparison current fitness of particles with their best experience:

If $F(P_i) \geq pbest_i \rightarrow \begin{cases} pbest_i = F(P_i) \\ \overrightarrow{xpbest_i} = \overrightarrow{x_1(t)} \end{cases}$

(10)

4-Comparison of the current fitness of particles with the best experience of all particles

If $F(P_i) \geq gbest_i \rightarrow \begin{cases} gbest_i = F(P_i) \\ \overrightarrow{xgbest_i} = \overrightarrow{x_1(t)} \end{cases}$

(11)

5-Change in velocity of each particle according to (12).

$$\vec{v}_1(t) = \vec{v}_1(t-1) + \rho_1 \, (\overrightarrow{xpbest_i} - \vec{x}_1(t)) + \rho_2 \, (\overrightarrow{xgbest_i} - \vec{x}_1(t))$$

(12)

6-The particle position change to a new position according to (13).

$$\vec{x_1}(t) = \vec{x_1}(t-1) + \vec{v_1}(t) \quad (13)$$

7-The algorithm is iterated from step 2 until convergence is obtained.

In the above algorithm $\vec{x_1}(t)$, F(P$_i$), Pbesti, and $\overrightarrow{xpbest_t}$ are position, fitness, best fitness, and best fitness position of the i-th particle. Also Pbesti, and $\overrightarrow{xgbest_t}$ are the best fitness of the population and its position.

### C. General Notes on Implementation of PSO

**The number of particles:** The number of particles in search space is chosen by the trial and error method to get better convergence. Since PSO application is relatively based on swarm intelligence, more particles lead to a better response. On the other hand, more particles require more calculations and therefore the method will be time-consuming.

**Velocity limitation:** One higher limit for velocity prevents that particles jump at high speed in the searching region. Consequently, Space is searched to reach a better region accurately. Additionally, this limitation prevents algorithm divergence due to the high velocities of particles. After updating the velocity vector, the following conditions are checked:

$$\text{If } V_i(t) \geq V_{\max} \rightarrow V_i(t) = V_{\max} \quad (14)$$

$$\text{If } V_i(t) \leq -V_{\max} \rightarrow V_i(t) = -V_{\max} \quad (15)$$

The maximum value of velocity is selected concerning the change of position vector parameters. However, researchers [30-31] have shown that if the equation (12) is applied for updating velocity vector (as follows); it doesn't require checking previous conditions.

$$\vec{v_1}(t) = k(\vec{v_1}(t-1) + \rho_1(\overrightarrow{xpbest_t} - \vec{x_1}(t)) + \rho_2(\overrightarrow{xgbest_t} - \vec{x_1}(t))) \quad (16)$$

where,

$$k = \frac{2}{\left|2-\rho-\sqrt{\rho^2-4\rho}\right|}, \quad \rho = (\rho_1+\rho_2) > 4 \quad (17)$$

**Inertia weight:** This parameter controls the effect of the previous velocity on current velocity. Its large certainly causes wide search space and vice versa. Implementation of inertia weight can be done by using equation (18):

$$\vec{v_1}(t) = \phi\vec{v_1}(t-1) + \rho_1(\overrightarrow{xpbest_t} - \vec{x_1}(t)) + \rho_2(\overrightarrow{xgbest_t} - \vec{x_1}(t)) \quad (18)$$

Preliminarily inertia weights are initialized by 1 value and reduce along with the algorithm. Also, the equation (16) must be true. If not, PSO's behavior becomes oscillatory and maybe divergence [30-31]:

$$\phi > \frac{1}{2}(C_1+C_2) - 1 \quad (19)$$

### D. Implement heuristic Algorithms

As was mentioned earlier, the model's parameters can be determined using artificial optimization methods such as GA and PSO. These algorithms overcome inaccuracies that arise mostly due to errors in analytical formulae. Heuristic algorithms, for each model with a specified number of model units, are used to determine the model parameters optimally, starting with the initial values. Besides initial values, a suitable fitness function is required for any optimization algorithm, to find the model parameters that most improving the accuracy of the original model. For our purpose a proper fitness function yielding satisfactory optimizations is formulated as follows:

$$\text{O\_F} = \sum_{i=1}^{m}[(\log10(\tan\delta_1(i)) - (\log10(\tan\delta_2(i))]^2 \quad (20)$$

Where; O-F is the objective function, m is the number of measured samples, $\tan\delta_1$ and $\tan\delta_2$ are the measured dissipation factor and reference dissipation factor, respectively.

## VI. Results and discussion

### A. Field measurements

To evaluate the effectiveness of the proposed methods, four transformers with different design parameters were selected and the frequency responses were measured using DIRANA-OMICRON. Then the results obtained by the different methods (SFR, GA, and PSO methods) are analyzed and insulating system parameters were specified. Specifications of the studied transformers are shown in Table 1.

Table I.
Specification of case studies

| Transformer name | T1 | T2 | T3 | T4 |
|---|---|---|---|---|
| Power (MVA) | 2.5 | 0.25 | 160 | 90 |
| Voltage (KV) | 0.4/6.3 | 0.55/20 | 63/230 | 63/230 |
| Year produced | 2001 | 2008 | 2007 | 1996 |

### B. Comparison of the methods

To compare the difference between the estimated master curves with measured curves, the following functions are used:

1-The absolute sum of logarithmic error (ASLE) [32]

ASLE, as expressed in (21), compares the data on a logarithmic scale. The ideal value of ASLE is 0. The ASLE is considered to be an effective parameter to identify the deviation between two sets of data.

$$\text{ASLE} = \frac{\sum_{i=1}^{m}\left|(\log_{10}\tan\delta_1(fi) - \log_{10}(\tan\delta_2(fi)\right|}{m} \quad (21)$$

2-Correlation coefficient (CC) [33]

The CC (see (22)) is defined as the potency of linear association between two data variables. Its value varies from -1 to +1.

$$\text{CC} = \frac{\sum_{i=1}^{m}\left|\tan\delta^*1(fi).(\tan\delta^*2(fi)\right|}{\sqrt{\sum_{i=1}^{m}\left|[\tan\delta^*1(fi)]^2.[(\tan\delta^*2(fi)]^2\right|}} \quad (22)$$

Where;

$$\tan\delta^*1(fi) = \left|\tan\delta_1(fi)\right| - \frac{1}{m}\sum_{i=1}^{m}\left|\tan\delta_1(fi)\right| \quad (23)$$

$$\tan\delta^*2(fi) = \left|(\tan\delta_2(fi)\right| - \frac{1}{m}\sum_{i=1}^{m}\left|(\tan\delta_2(fi)\right| \quad (24)$$

It is clear that for removing the difference between the reference curve and a measured curve, the ASLE value comes close to zero, and the CC approaches 1.

### C. Discussion

The flowchart of transformers moisture estimation using heuristic algorithms is given in Figure 3.

Figures 4 to 7 show the obtained curves by SFR and the proposed methods for each of the transformers. In Tables 2 to 5, the analysis results are given for different methods, as well.

TABLE II.
ESTIMATION OF INSULATION PARAMETERS BY DIFFERENT METHODS IN TRANSFORMER T1

| Method | SFR | GA | PSO |
|---|---|---|---|
| Paper moisture (%) | 5.2 | 5.1 | 5 |
| Oil conductivity (ps/m) | 7.8 | 7.9 | 8.2 |
| X | 15 | 15 | 15 |
| Y | 14 | 14 | 14 |
| ASLE | 0.0243 | 0.0235 | 0.0215 |
| CC | 0.9923 | 0.9955 | 0.9982 |

TABLE III.
ESTIMATION OF INSULATION PARAMETERS BY DIFFERENT METHODS IN TRANSFORMER T2

| Insulation parameters | SFR | GA | PSO |
|---|---|---|---|
| Paper moisture (%) | 1.4 | 1.5 | 1.3 |
| Oil conductivity (ps/m) | 2.6 | 2.7 | 2.5 |
| X | 14 | 14 | 15 |
| Y | 14 | 14 | 14 |
| ASLE | 0.0707 | 0.0753 | 0.0604 |
| CC | 0.9945 | 0.9933 | 0.9981 |

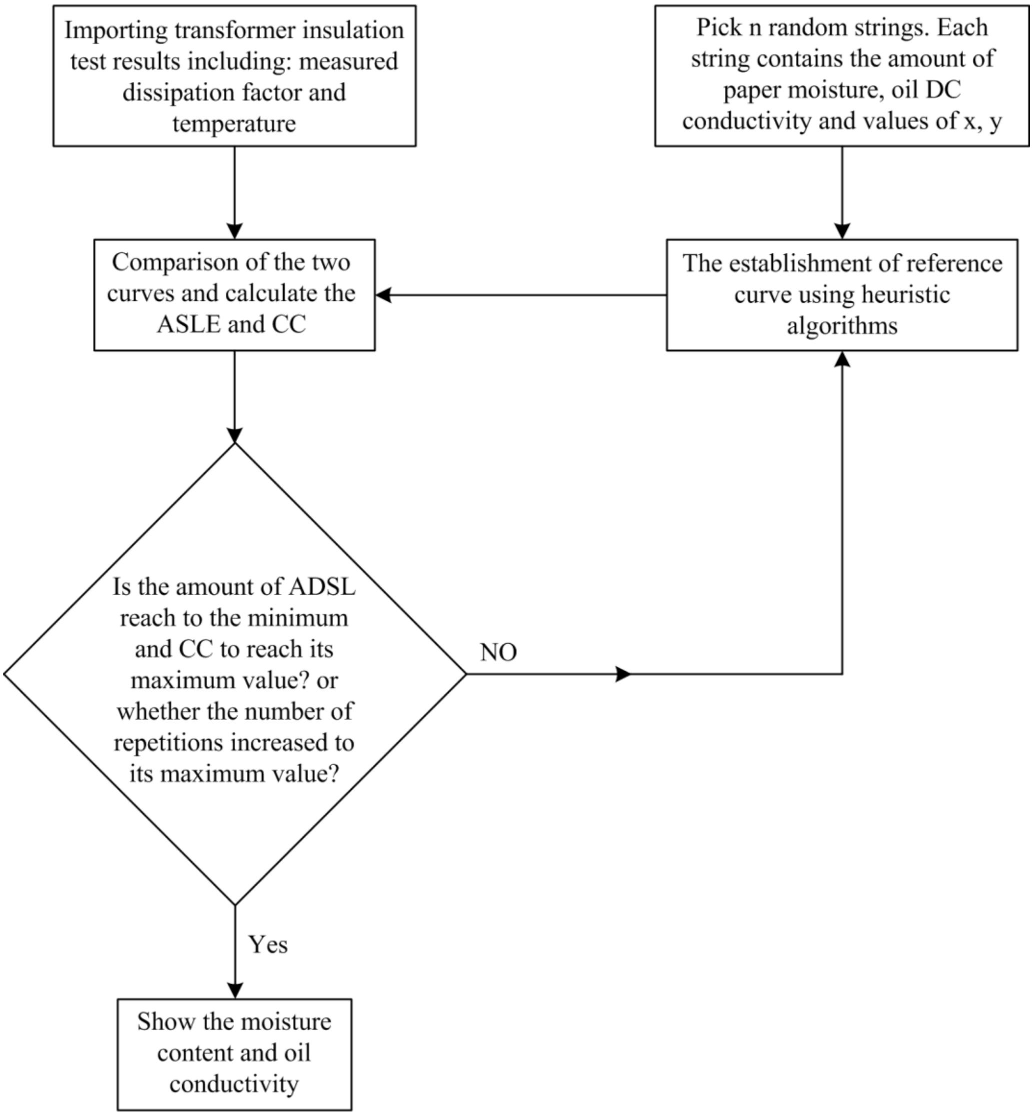


Fig 3. Flowchart of the proposed method

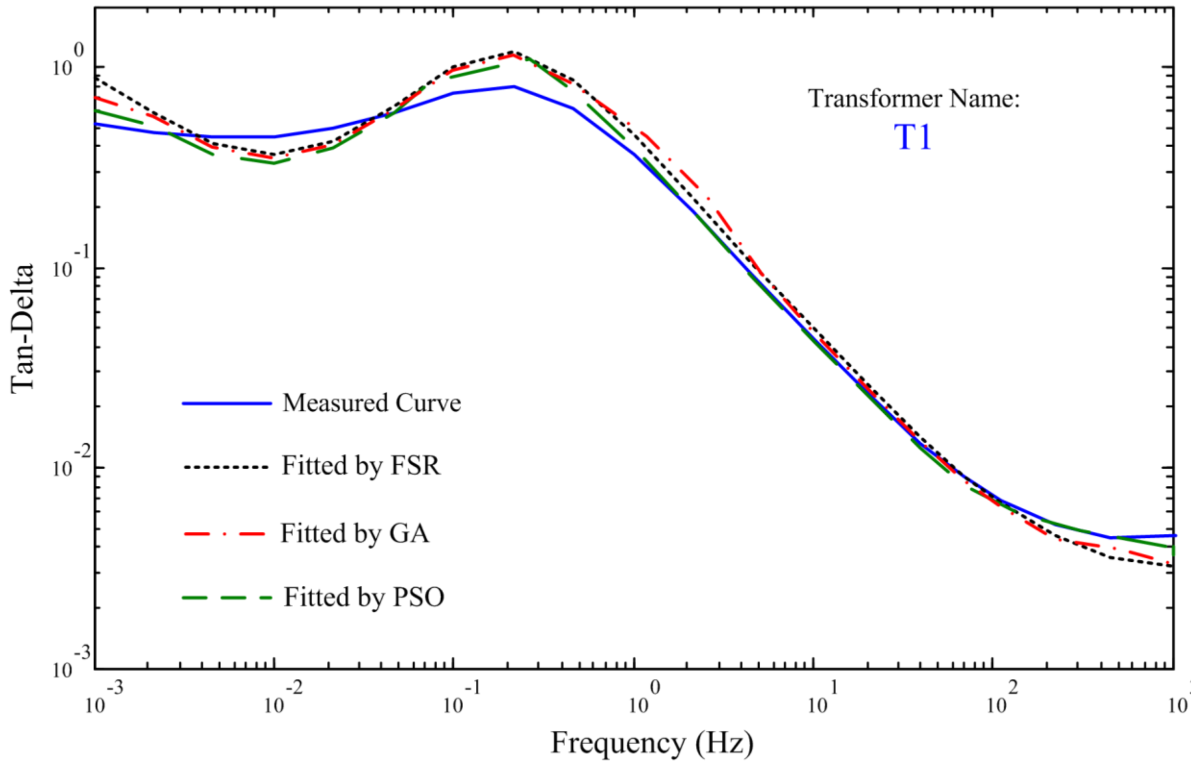


Fig 4. The measured and estimated dielectric response curves of transformer T1

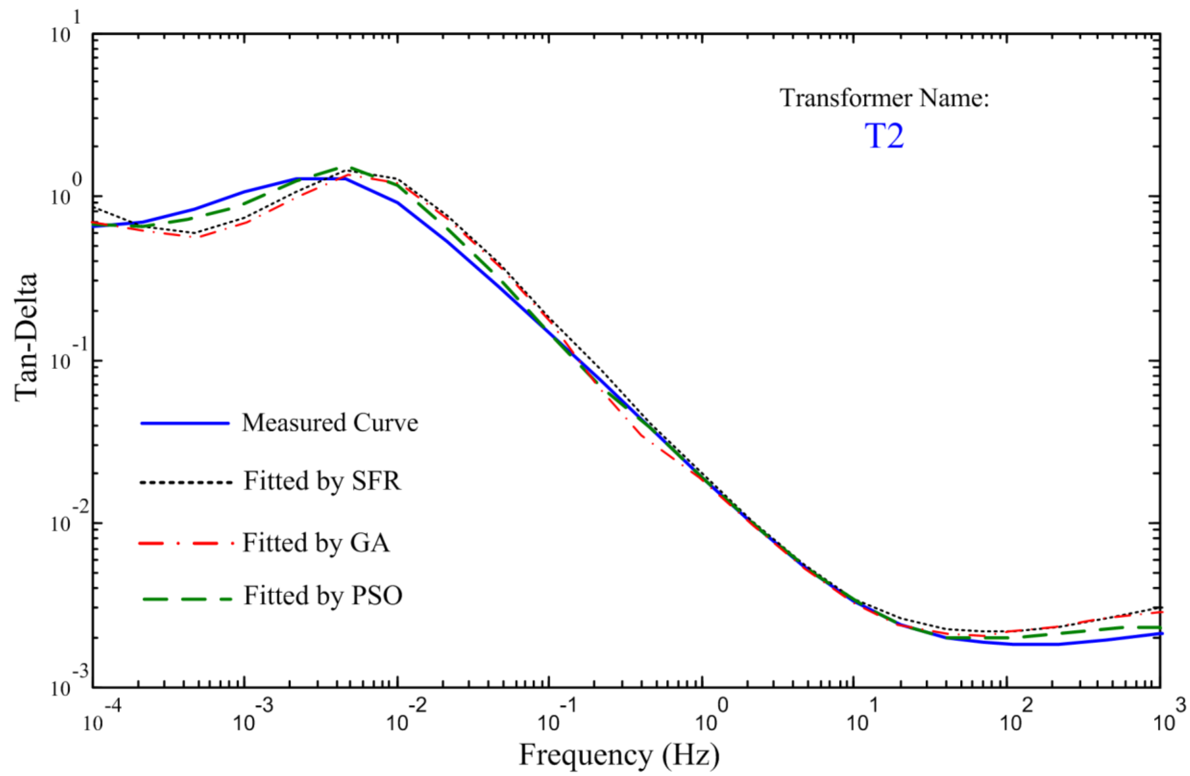


Fig 5. The measured and estimated dielectric response curves of transformer T2

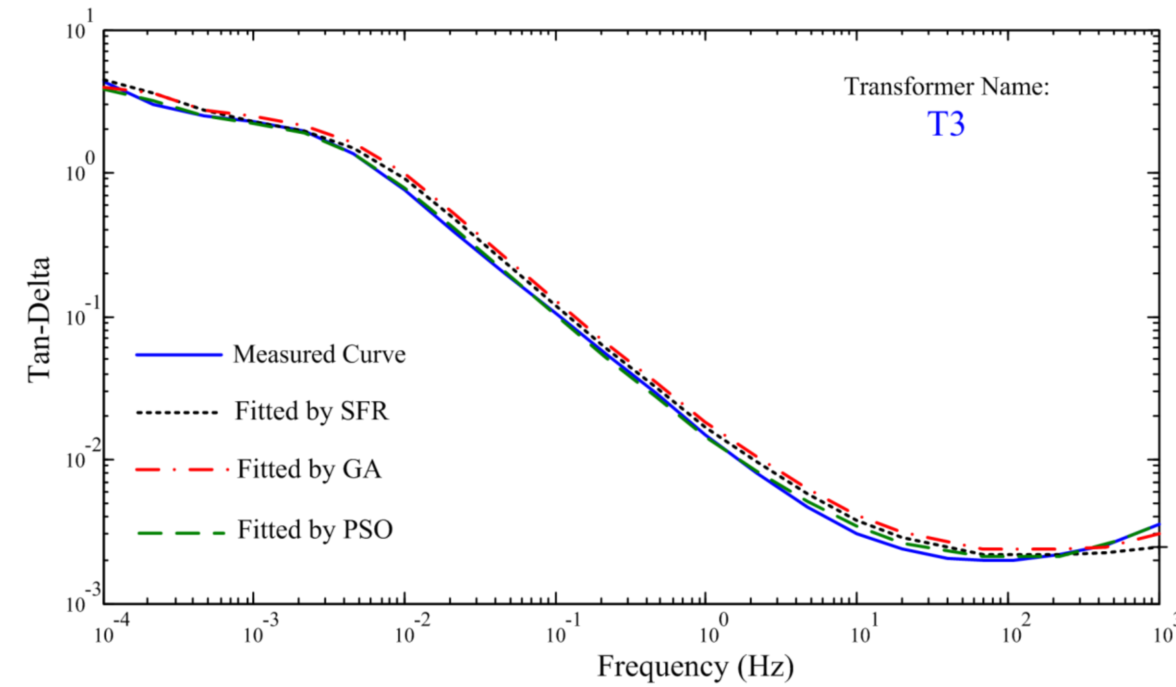


Fig 6. The measured and estimated dielectric response curves of transformer T3

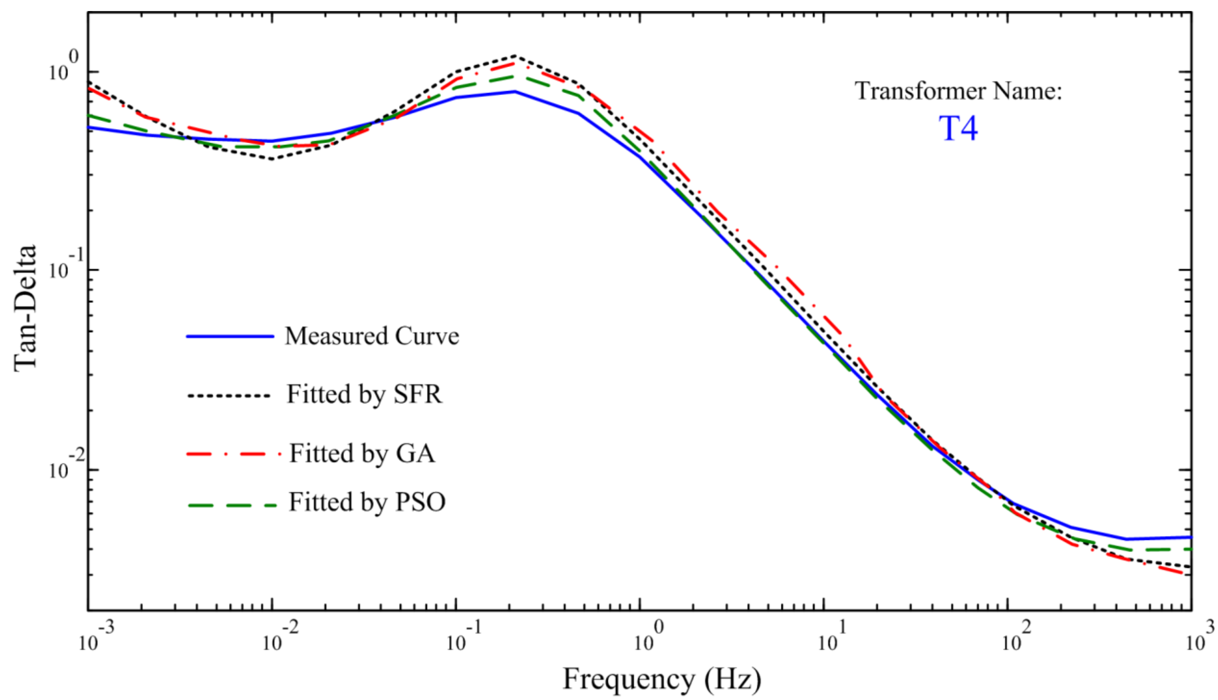


Fig 7. The measured and estimated dielectric response curves of transformer T4

TABLE IV.
ESTIMATION OF INSULATION PARAMETER BY DIFFERENT METHODS IN TRANSFORMER T3

| Method | SFR | GA | PSO |
|---|---|---|---|
| Paper moisture (%) | 1.2 | 1.2 | 1.2 |
| Oil conductivity (ps/m) | 1.7 | 1.7 | 1.8 |
| X | 15 | 15 | 15 |
| Y | 24 | 24 | 25 |
| ASLE | 0.0297 | 0.0313 | 0.0278 |
| CC | 0.9972 | 0.9966 | 0.9994 |

TABLE V.
ESTIMATION OF INSULATION PARAMETER BY DIFFERENT METHODS IN TRANSFORMER T4

| Method | SFR | GA | PSO |
|---|---|---|---|
| Paper moisture (%) | 0.8 | 0.8 | 0.8 |
| Oil conductivity (ps/m) | 92 | 91 | 90 |
| X | 23 | 23 | 20 |
| Y | 25 | 25 | 25 |
| ASLE | 0.0657 | 0.0646 | 0.0637 |
| CC | 0.9959 | 0.9964 | 0.9979 |

While the method is not always constant SFR and depending on insulation, varies.

The comparisons show that all three methods can create the reference curve well. Nonetheless, the values obtained for ASLE and CC show that the reference curve created by the PSO method is closer to the measured curve and better fitted to it. Furthermore, the method based on SFR is not always constant and it is varied depending on the insulation conditions. And different frequency ranges for various transformers may be considered. However, the proposed methods based on GA and PSO algorithms use the entire frequency range. Another advantage of these methods is the elimination of errors associated with the selection of frequency ranges. Regardless of that the local maximum or minimum points are visible or not, the dielectric response curves are analyzed with considerable accuracy.

To have a better comparison between the proposed methods, the simulation duration and the number of iterations of the proposed algorithms are provided in Table 6. Considering the previous points and studying the results of Table. 6, it is preferred to use the PSO for estimating the moisture content of transformer insulation, at least in the case examined here.

TABLE VI.
COMPARE THE PERFORMANCE OF GA AND PSO

| Index | Method | |
|---|---|---|
| | GA | PSO |
| Simulation duration (s) | 123 | 88 |
| Iteration | 8726 | 3451 |

## VII. CONCLUSIONS

In this research, the reference curve of the dielectric dissipation factor (dielectric response) was formed for transformer insulation's moisture detection. Then, new methods based on heuristic algorithms (GA and PSO) were proposed. The proposed algorithms could compare the measured curve with the reference curve and they can determine the insulation model parameters. The results show that not only the proposed algorithms do not need to specify the frequency ranges (unlike the SFR), but also reference curves that are estimated using these methods are closer to the measured curve. Moreover, the dielectric parameters, such as the insulating paper's moisture content, the oil conductivity, and the dielectric model dimensions were determined with good accuracy.

The introduced method based on PSO has the best performance according to a better convergence speed and lower simulation duration when it is compared to GA. Thus, it is proposed to employ PSO as an efficient method to estimate the moisture content in transformer insulation.

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