Condition assessment of transformer insulation using dielectric frequency response analysis by artificial bee colony algorithm

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Abstract: Transformers are one of the most important components of the power system. It is important to maintain and assess the condition. Transformer lifetime depends on the life of its insulation and insulation life is also strongly influenced by moisture in the insulation. Due to importance of this issue, in this paper a new method is introduced for determining the moisture content of the transformer insulation system using dielectric response analysis in the frequency domain based on artificial bee colony algorithm. First, the master curve of dielectric response is modeled. Then, using proposed method the master curve and the measured dielectric response curves are compared. By analyzing the results of the comparison, the moisture content of paper insulation, electrical conductivity of the insulating oil and dielectric model dimensions are determined. Finally, the proposed method is applied to several practical samples to demonstrate its capabilities compared with the well-known conventional method.

Key words: artificial bee colony (ABC) algorithm, condition assessment, dielectric frequency response (DFR), transformer insulation

1. Introduction

Nowadays, a large fleet of transformers are close to the final years of their lives [1]. Due to high prices and tremendous impact of transformers on the reliability of the network and power systems, maintenance, monitoring and condition assessment of transformers has become one of the critical issues for the power systems. The lifetime of a transformer depends on lifetime of its insulation and insulation destruction is the most expensive type of defect. One of the most important factors damaging insulation, particularly cellulose insulations, is moisture. Moisture in the transformer will eventually come under three main reasons:
- remain moisture in rigid and large parts of insulation in the drying step of transformer,
- moisture from cellulose and cellulose aging (oxidation),
- absorb moisture from the environment due to the breathing of transformer.

Moisture causes the aging in transformer cellulose, reducing the breakdown voltage of insulation, bubbles and creates a partial discharge [2]. Insulation moisture determination is performed by two general methods: chemical and electrical methods [3]. Chemical methods are not accurate and have error [4]. In recent decades, new techniques have been introduced so-called electrical methods. These methods are based on the dielectric response analysis. Three main methods of measuring dielectric response are 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 measuring in time domain. These methods determine the insulation condition by measuring the polarization and depolarization current [6-7]. Insulating dielectric response measurement in the frequency domain or DFR is the conventional measurement of dissipation factor (tan δ) or measurement of complex dielectric constant or complex capacitance in a wide frequency range [7].

The importance of DFR method is that the dielectric properties of the dielectric material which forms the insulation composite systems in different frequencies is revealed. Insulation parameters such as moisture of insulation paper, electrical conductivity of the oil (which represents the moisture content of oil) and insulation model dimensions (if not known), is determined using comparison of the insulation dielectric response with master curves [8]. Usually this is done by separating frequency ranges (SFR) [9], which in practice has a significant error and also this method can not accurately assess the condition of the insulation [10].

In recent years, in most cases, heuristic algorithms are used to solve parameter estimation problems. Any optimization algorithm has its own advantages and disadvantages. In general, algorithms with smaller number of parameters (to be adjusted by user by trial and error), faster convergence and higher probability of skipping from local optimums are identified as more effective algorithms. Among the various smart methods, artificial bee colony (ABC) is very fast and the number of parameters that need to adjust is fewer than other heuristic algorithms [11]. In [12] the effectiveness of ABC algorithm compared to other well-known smart techniques is proven. Hence, in this paper a new method to determine the parameters of the transformer insulation system using ABC algorithm is proposed. To evaluate the effectiveness of the proposed method, four transformer with different design conditions have been selected and their frequency responses are measured and then the transformer insulation condition (moisture content of paper insulation, electrical conductivity of the insulating oil and dielectric model dimensions) using SFR and proposed method are determined and compared. The results show the high accuracy and speed of the proposed algorithm in comparison with past well-known method. Therefore, it can be used as a reliable method to determine the amount of moisture in transformer insulation. To satisfy this objective, the paper is structured in the following manner.

Section 2 provides a review on DFR theory. It also discusses about determination of the master (reference) curve in detail. Section 3 focuses on the DFR analysis by past well-known method (SFR). Section 4 introduces the ABC algorithm as a reliable method to assess transformer insulation system. Results of the measurements and analysis of the results are showed

in section 5. The conclusion to this research is given in section 6 including a summary of the results.

2. Background of the DFR

2.1. DFR theory

To measure the dielectric response in the frequency domain, the insulation impedance by applying a sinusoidal voltage to the insulation material, current and voltage of insulation is carefully measured. Given the phase difference between voltage and current due to the polarization, impedance of insulation material can be expressed as follows:

$$\overline{Z}(\omega) = Z'(\omega) + iZ''(\omega) = \frac{\overline{u}(\omega)}{\overline{I}(\omega)}. \tag{1}$$

Assuming that the tested dielectric material is a complex capacitance, insulation impedance is equal to [13]:

$$\overline{Z}(\omega) = \frac{1}{i\omega\overline{C}(\omega)}. \tag{2}$$

Combining relations (1) and (2), relation between $U(\omega)$ and $U(\omega)$ will be as follows:

$$\overline{I}(\omega) = i\omega\overline{C}(\omega)\overline{u}(\omega). \tag{3}$$

Complex capacitance, which is composed of two real and imaginary parts, expressed as the following equation [13]:

$$\overline{C}(\omega) = C'(\omega) - iC''(\omega). \tag{4}$$

Since the complex capacitance of the dielectric material is dependent on the complex dielectric constant, complex dielectric constant can be determined according to the following equation [14]:

$$\overline{\varepsilon}(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega). \tag{5}$$

And dielectric dissipation factor is defined according to Equation (6) [14]:

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

2.2. Determining the master (reference) curve

One of the benefits of insulation condition assessment using the measured dielectric response in the frequency domain is that the master curve can be modeled. For a specified amount of moisture in the insulation paper, electrical conductivity of oil and geometry dimen-

sions, the dielectric response of insulation system can be achieved. To form a master curve, dielectric response of each component of the insulation system must first be determined.

To form a master curve, the dielectric response curve for each component of insulation system must be determined first. Then, using the *XY* model dielectric response of the system is achieved. The *XY* model of Insulation system consisting of oil and paper insulations is shown in Figure 1 [5-6]. The parameter *X* is the relative amount of solid insulation (barriers) in the radial direction and *Y* is the relative amount of spacers.
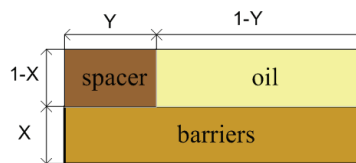

Fig. 1. Geometric arrangement of insulation system (*XY* model)

Given *XY* dimensions of insulation system and complex permittivity of the any insulating materials, equivalent permittivity of the insulation system can be obtained from Equation (7) [15]:

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

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

Complex permittivity of oil is composed of two real and imaginary parts. its real part is constant and equal to 2.2 and its imaginary part depends on frequency and electrical conductivity. It can be expressed in the following equation:

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

where: σ_{dc} is Electrical conductivity, ω is angular velocity and ε_o is permittivity of vacuum.

Complex permittivity of paper saturated with oil is very complex and highly dependent on the frequency, temperature and moisture content of the paper. It is obtained by the experimental results [16]. To do this, several samples of insulation paper with moisture and different conditions are provided and their dielectric response are measured in a wide frequency range (0.1 mHz-1 KHz). Then data obtained provide a database [17]. If the temperature of measured master curve is not equal to temperature of the tested transformer, the results of master curve must be transferred to temperature of the transformer under test. If the dielectric response is plotted on a logarithmic scale, temperature changes does not modify the overall shape of the curve, but the curve is displaced in the direction of the frequency axis [18]. The amount of frequency shift can be obtained from equation (9) [19]:

$$shift = \log(\omega_1) - \log(\omega_2) = -\frac{e}{k}(\frac{1}{T_1} - \frac{1}{T_2}), \qquad (9)$$

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

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

3. DFR analysis by SFR

Dielectric frequency response in the frequency domain (if it is drawn in logarithmic scale) would be approximately *S*-shaped [20-23]. This *S*-shaped curve includes a minimum point and a point of local maximum at low frequencies (typically below 1 Hz) and a local minimum point at high frequencies (usually above 10 Hz). Figure 2 shows an example of this response. Moisture of insulation paper, electrical conductivity of oil, and dimensions of the *X* and *Y* in insulation model affect the different parts of the insulation system response. Moisture of insulation paper affects the curve at frequencies below 0.1 m Hz and above 1 Hz. Thus, with the increase in the amount of moisture, the curve moves upward and insulation losses increases, and vice versa. Amount of *X* and *Y* affects the local maximum at low frequencies and the local minimum at high frequencies. So that the increase in *X* and *Y*, decreases the maximum point and increases the minimum point. The effect of electrical conductivity of the oil is in the frequency range between the minimum and maximum points. By increasing it, this part of the curve moves towards higher frequencies. Temperature will not change the overall shape of the curve and with increasing temperature, curve moves towards higher frequencies.

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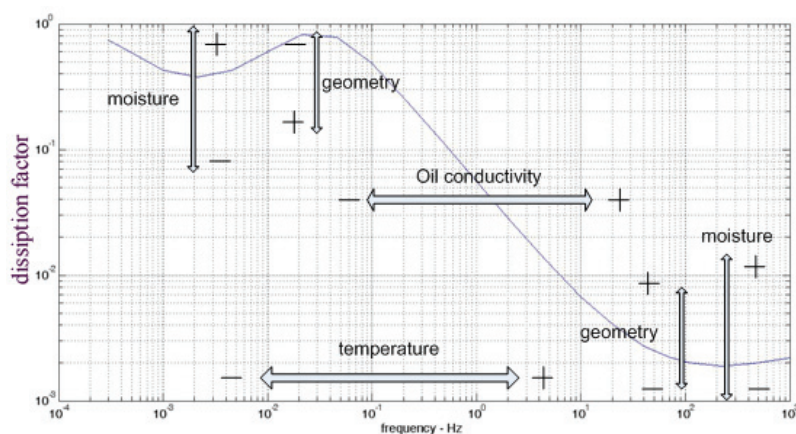

Fig. 2. DFR measurements (the effect of various parameters) [20]

4. DFR analysis by proposed method

DFR analysis using SFR have errors in some cases. For example, in some measurements, dielectric response curve has not been fully established and local minimum and maximum points are not visible. This is related to condition of insulation such as amount of moisture in the paper, oil and dimensions of X and Y. Moreover, the frequency ranges of the parameters of the insulation is not always constant and vary depending on condition of insulation. Therefore, the results strongly influenced the choice of frequency ranges. In the proposed method, regardless of frequency ranges, the entire curve by optimization method based ABC algorithm are analyzed.

4.1. Summary of ABC algorithm

The ABC algorithm, which belongs to the family of nature-inspired meta-heuristic optimization algorithms, was first introduced in 2005 by [24]. This algorithm is inspired from the behavior of honey bees in nature and provides us with a powerful tool for solving complex optimization problems. In the ABC algorithm artificial bees in the colony are divided into three parts: employed bees, onlooker bees, and scout bees. Employed bees (whose number is equal to onlooker bees) discover the food sources, bring the food to hive and share its location with other bees. Onlooker bees stay in the hive and decide to follow the employed bees based on the quality of the food sources they have discovered. Scout bees randomly search the outdoor (independent of employed bees) to find (probably better) unseen food sources. In ABC algorithm the location of each food source identifies a point in the domain of problem (i.e., a potential solution) and points with smaller value for cost function are assumed to be better food sources (better solutions).

The ABC algorithm flowchart is given in [24-26], at the first step, each employed bee looks for new position (v_m) by searching and surrounding a food source around its old position (x_m), as shown in (10).

$$v_{mi} = x_{mi} + \phi_{mi}(x_{mi} - x_{ki}),$$ (10)

where, m is the number of current bee, k is a random integer number between 1 to SN (number of bees), and ϕ_{mi} is a random number with uniform distribution controlled by a neighborhood radius.

After determining a new food source, proportion rate (equivalent to the objective function presented in the next section) is accounted. Onlooker Bees make their choice based on the probabilistic values generated by employed bees. The probability of onlooker bee's choice for xm can be expressed as following:

$$P_m = \frac{fit(x_m)}{\sum_{k=1}^{SN} fit(x_k)}.$$ (11)

Afterward, all onlooker bees can find one of the food sources in the previous repeat by the above equations: the position of neighbor food source is found by (10) and then proportion rate is calculated. This process continues till the finishing condition is met. After some iter-

ations, employed bees could not be able to find a successful way. In this case, in order to increase the effectiveness, employed bees are converted into scout bees and all arrived solutions are ignored. Number of these iterations, lack of better result and converting employed bees into scout bees are named abandonment criteria [26].

4.2. Objective function

As it was mentioned earlier, parameters of the transformer insulation system can be determined using artificial optimization methods such as ABC. This algorithm, for each model with specified number of model units, is used to determine the model parameters optimally, starting with the initial values. Beside initial values, a suitable fitness function is required for any optimization algorithm. In the proposed method, sum of square of logarithmic difference of measured dielectric response curve with master curve is chosen as objective function (according to (12)). Thus the problem of determining the parameters of the insulation system by choosing a reference curve that has the highest correlation with the measured curve, becomes an optimization problem and dielectric parameters are determined.

$$O\_F = \sum_{i=1}^{m} [(\log 10(\tan \delta_1(i))) - (\log 10(\tan \delta_2(i)))]^2, \tag{12}$$

where: O_F is objective function, m is number of measured samples, $\tan\delta_1$ and $\tan\delta_2$ are the measured dissipation factor and reference dissipation factor, respectively.

4.3. The main steps of the algorithm

In general, the analysis of the curve and determine the parameters of transformer insulation model can be expressed as follows:
1) Assign initial values to SN, and other parameters of algorithm.
2) Allocate random values to unknown parameters containing moisture of insulation paper, oil conductivity, *X* and *Y*.
3) Create a reference curve for each answer vector.
4) Determine the fitness of any answer vector using the objective function.
5) Iteration = 1.
6) Calculate the new position of employed bees from (10).
7) Replace new answer vector with the old vector.
8) Onlooker bees select the employed bees of next iteration from (11).
9) Memorize the position of the bee with the highest fitness.
10) Set the position of scout bee equal to the best position obtained so far.
11) Iteration = Iteration + 1.
12) If the termination condition is satisfied then stop the algorithm, else go to step 6.

5. Results and discussion

5.1. Field measurements

To evaluate the effectiveness of the proposed method, four transformers with different designs were selected and the frequency responses are measured using DIRANA-OMICRON.

Then results obtained by the different methods (SFR and ABC methods) are analyzed and insulation system parameters are specified. Specifications of analyzed transformers are according to Table 1.

Table 1. 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

5.2. Comparison method

To compare the difference of master curves with measured curves the following functions are used:

5.2.1. Absolute sum of logarithmic error (ASLE) [27]

ASLE, as expressed in (13), 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.

$$\text{ASLE} = \frac{\sum_{i=1}^{m} \left| (\log_{10} \tan \delta_1(fi) - \log_{10}(\tan \delta_2(fi)) \right|}{m}. \tag{13}$$

5.2.2. Correlation coefficient (CC) [28]

The CC (see (14)) is defined as the potency of linear association between two data variables. Its value varies from −1 to +1.

$$\text{CC} = \frac{\sum_{i=1}^{m} \left| \tan \delta_1^*(fi).(\tan \delta_2^*(fi) \right|}{\sqrt{\sum_{i=1}^{m} \left| [\tan \delta_1^*(fi)]^2.[(\tan \delta_2^*(fi)]^2 \right|}}, \tag{14}$$

where

$$\tan \delta_1^*(fi) = \left| \tan \delta_1(fi) \right| - \frac{1}{m} \sum_{i=1}^{m} \left| \tan \delta_1(fi) \right|. \tag{15}$$

$$\tan \delta_2^*(fi) = \left| (\tan \delta_2(fi) \right| - \frac{1}{m} \sum_{i=1}^{m} \left| (\tan \delta_2(fi) \right|. \tag{16}$$

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

5.3. Discussion

Figures 3 to 6 show the obtained curves by SFR and proposed method for each of the transformers. Also in Tables 2 to 5, the results of the analysis by different methods are given.
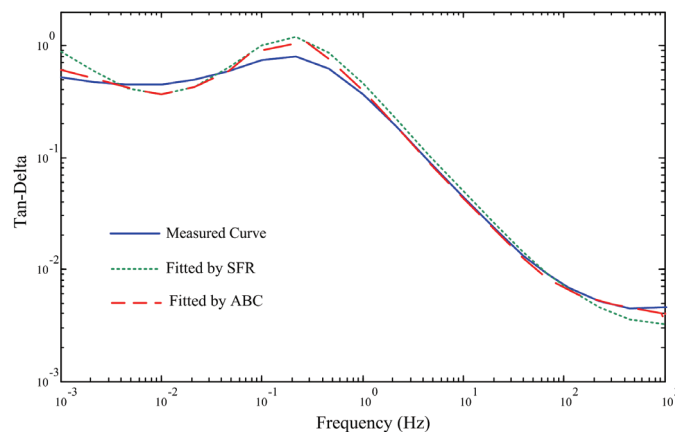
Fig. 3. The measured and estimated dielectric response curves of transformer T1

Table 2. Estimation of insulation parameter by different methods in transformer T1

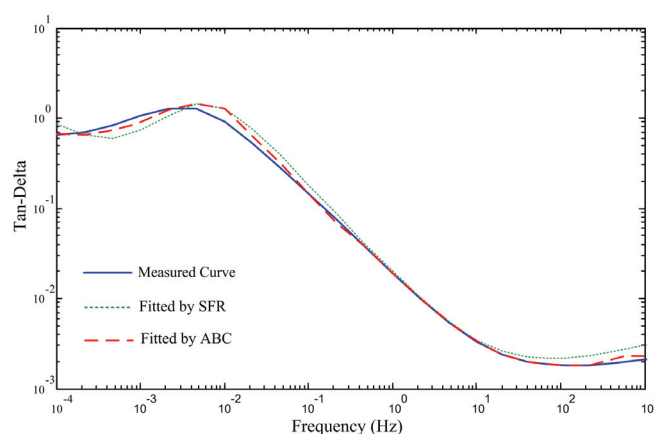| Insulation parameters \ Method	SFR	ABC
paper moisture (%)	5.2	5
oil conductivity(*ps/m*)	7.8	8.1
X	15	15
Y	14	14
ASLE	0.0243	0.0210
CC	0.9923	0.9987

Fig. 4. The measured and estimated dielectric response curves of transformer T2

The values obtained for ASLE and CC suggest that the reference curve created by the ABC method is closer to measured curve and better fitted to it. And also the amount of moisture in the insulation paper, oil conductivity and values of X and Y in both methods are close and the difference is little. This confirm the accuracy of the proposed method and its effectiveness.

Furthermore, the method based on SFR is not always constant and vary depending on insulation conditions and different frequency ranges for various transformers may be considered. However, the proposed method based on ABC algorithm uses the entire frequency range.

Another important result is that ABC algorithm has smaller errors in the determination of the insulation parameters in comparison to SFR. Therefore, the ABC algorithm as a reliable method for determining the dielectric parameters of transformer is proposed.

Table 3. Estimation of insulation parameter by different methods in transformer T2

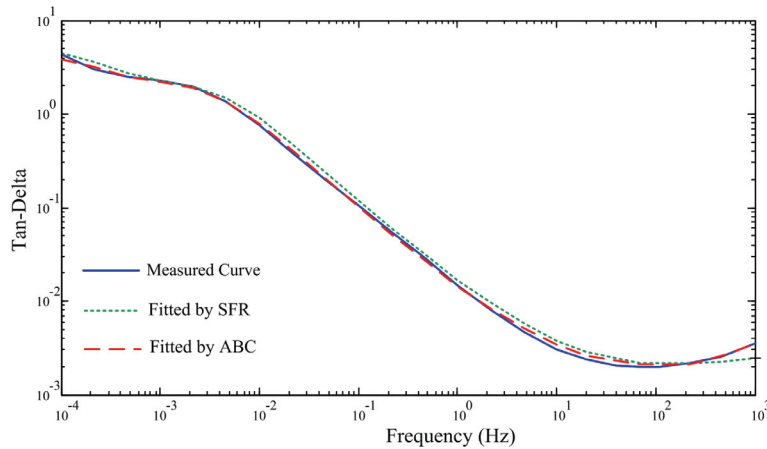| Insulation parameters \ Method	SFR	ABC
paper moisture (%)	1.4	1.3
oil conductivity(*ps/m*)	2.6	2.5
X	14	15
Y	14	14
ASLE	0.0707	0.0549
CC	0.9945	0.9983

Fig. 5. The measured and estimated dielectric response curves of transformer T3

Table 4. Estimation of insulation parameter by different methods in transformer T3

Insulation parameters \ Method	SFR	ABC
paper moisture (%)	1.2	1.2
oil conductivity(*ps/m*)	1.7	1.8
X	15	15
Y	24	25
ASLE	0.0297	0.0213
CC	0.9972	0.9995

The main advantage of proposed method is the elimination of errors associated with the selection of frequency ranges. Meanwhile, regardless of the local maximum or minimum points are visible or not, dielectric response curves are analyzed with a considerable accuracy.

6. Conclusions

In this paper, the reference curve of dielectric dissipation factor (dielectric response) was formed for transformer insulation moisture detection. Then, new method based on ABC algorithm was proposed. The proposed method can compare the measured curve with reference curve and it can determine the insulation model parameters. The results show that the proposed method not only the no need to specify the frequency ranges (unlike the SFR method), but also reference curves are closer to measured curve. Moreover, the dielectric parameters such as insulation paper moisture, oil conductivity and dielectric model dimensions are determined with good accuracy.
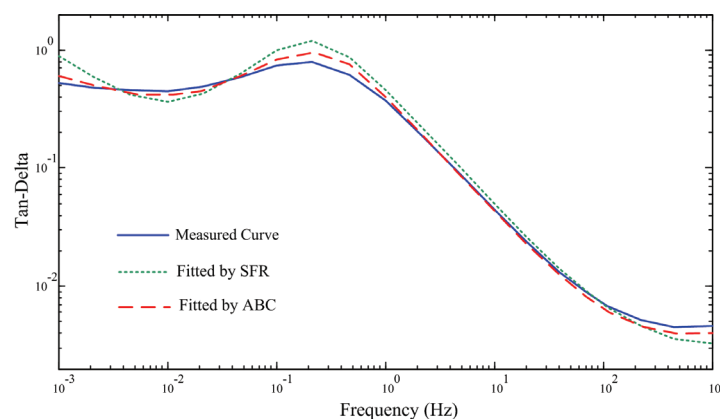

Fig. 6. The measured and estimated dielectric response curves of transformer T4

Table 5. Estimation of insulation parameter by different methods in transformer T4

Insulation parameters / Method	SFR	ABC
paper moisture (%)	0.80	0.81
oil conductivity(*ps/m*)	92	90
X	23	20
Y	25	25
ASLE	0.0657	0.0513
CC	0.9959	0.9981

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