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An Improved Mathematical Model using PSO for Estimating Polarization Parameters of Power Transformer Oil-Paper Insulation with FDS data

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Abstract-The life of a transformer is associated with the state of the insulation system, one of the techniques used to measure the insulation system is frequency-domain spectroscopy (FDS), which measures the dielectric properties in the frequency domain. This work establishes a mathematical model with the data of the FDS to estimate the parameters of the equivalent circuit of the dielectric response of the paper-oil isolation system of the transformer, which is a group of non-linear equations that make its resolution complex. The equations are transformed into an optimization problem using the least squares technique, and using the Particle Swarm Optimization (PSO) to solve them. In order to test the efficiency of the proposed method, the parameters of the electrical circuit of the isolation system in two transformers were estimated and the curves of the dissipation factor (tanδ) were compared with the values obtained by the measured by the FDS method. The relative error obtained between the measured and calculated curves was less than 0.8%, which means that the proposed method for estimating the parameters of the dielectric circuit equivalent to the oil-paper insulation system is valid.

Keywords *— Frequency Domain Spectroscopy (FDS), Particle Swarm Optimization(PSO), dissipation factor(tanδ).*

1. Introduction

The distribution transformer is a vital and relatively expensive element in the power system. Economic and technical reasons supported the widespread interest in studying the life of the transformer. In general, the life of a transformer is associated with the state of its insulation [1,2]. The characterization techniques for dielectric materials have been considered promising for a non-destructive assessment of the quality of transformers insulation, as measures in the frequency domain (Frequency Domain Spectroscopy) and in the time domain (Polarization and Depolarization Current "PDC" and Return Voltage Measurement "RVM") [3,4]. Measurements in the frequency domain can be obtained using an impedance analyzer, which measures the dielectric properties of materials as a function of frequency. Through the study of the obtained curves, it is possible to make a distinction between the different types of phenomena.At the moment, the researchers are mainly focused on the effect of temperature, moisture, and aging on the isolation system of the transformers [5-6]. Few are papers analyze a mathematical model to estimate the equivalent circuit of the dielectric polarization of the oil-paper insulation system. To estimate the equivalent circuit parameter of the power transformer is needs to choose the appropriate mathematical model. In reference [7]calculates the parameters of the equivalent circuit, by the method of nonlinear least-squares optimization using the RVM data. However, its integration process is complex and ignores some parameters of the mathematical model, which greatly influences the final result. The reference [8] the mathematical model to estimate the circuit parameters using data from the initial slope, good results were obtained for new transformers. However, the recovery voltage data takes a long time to measure, the insulation resistance needs to be calculated after the estimated bias parameter. In addition, the result is not always accurate for distribution transformers and high moisture transformers. In reference [9] the parameters of the equivalent circuit of the oil-paper isolation system are determined from the data of the RVM measurements using a method based on a genetic algorithm. The method showed good results although the computation time was long. In reference [10], the PSO algorithm is used to estimate the parameters of the insulation system's circuit of the power transformer, from data obtained by the RVM method, the results of which were not very accurate for the old transformers. the reference [11] calculates the parameters of the equivalent circuit of the insulation system using the method of Bacterial Foraging Optimization (BFO), using data from the FDS method. the results were accurate mainly for the distribution transformer, although it is a complex algorithm. Currently, few researchers study equivalent circuit parameters based on FDS. The mathematical model of parameters established by PDC or RVM data is non-linear exponential function equations that make your calculations complex. This article presents an improved method of estimating parameters of an equivalent circuit for transformer oil insulation. In the improved model, the equations of the mathematical model of the theory of Debye are transformed into a problem of optimization by using the method of square minimums. The PSO algorithm is used to estimate the equivalent circuit parameters. The advantage of the model establishes only one equation, using data dissipation factor (tanδ) obtained by the FDS. It is suitable for large power transformers and distribution transformers.

2. The measurement principle and circuit model of oil-paper insulation system

Measurements in the frequency domain (FDS) can be obtained using an impedance analyzer (IDAX300) Fig.1, which measures the dielectric properties of materials as a function of frequency typically from 1mHz to 1kHz. Through the study of the obtained curves, it is possible to make a distinction between the different types of phenomena. Impedance (magnitude and angle) can be calculated accurately by measuring voltage and current. Thus, several parameters can be calculated, such as capacitance (*C*), dissipation factor (*tanδ*), complex capacitance (*C′* and *C″*), and complex permittivity (*ε′* and *ε*") [12- 13].

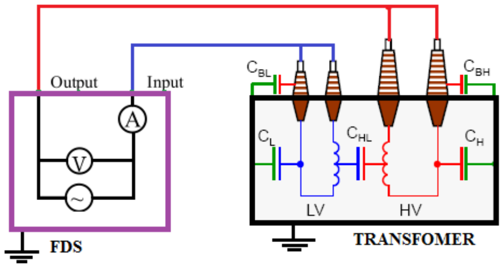

Figure 1. Dielectric measurement circuit using FDS

The dielectric polarization of the power transformers can be modeled by an equivalent circuit that can represent an infinite number of dipolar arrangements [11]. According to the linear dielectric theory, the oil-paper insulation in power transfomer can be replaced by Debye model extended in Fig.2 [14-15].

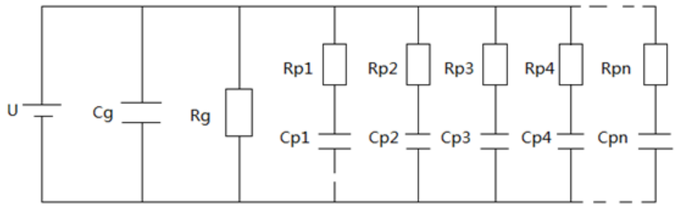

Figure 2. Equivalent circuit model of the oil-paper isolation system in the power transformers.

Where: R_g: equivalent insulation resistance; C_g: the geometric capacitance of the insulation system; R_{pi}-C_{pi}: polarization processes in different time constant.

Therefore, whether the equivalent circuit parameters of the oil-paper insulation system of the power transformer can be determined.

3. The mathematical model of equivalent circuit based on FDS

Applying an alternating voltage *U(ω)* to measure the insulation in the transformer using FDS, Fig.1, a current *I(ω)* will flow from the insulation system, which can be written as [11,16]:

$$I(\omega) = j\omega\left\{C^{'}(\omega) - jC^{''}(\omega)\right\}U(\omega) \qquad (1)$$

Where, *C '(ω)* and *C''(ω)* is the real part and the imaginary part of the complex capacitance, respectively. The dielectric loss factor equation *tanδ* (dissipation factor "DF") can be written as [11, 17]:

$$DF = \tan\delta = \frac{C^{''}(\omega)}{C^{'}(\omega)} \qquad (2)$$

And the complex capacitance will be: $C^{*}(\omega) = C^{'}(\omega) - jC^{''}(\omega)$ (3)

The real and imaginary component of the capacitance can be written as [17, 18]:

$$C^{'}(\omega) = C_g + \sum_{i=1}^{n} \frac{C_{pi}}{1+(\omega R_{pi} C_{pi})^2} \qquad (4)$$

$$C''(\omega) = \frac{1}{\omega R_g} + \sum_{i=1}^{n} \frac{\omega R_{pi} C^2{}_{pi}}{1+(\omega R_{pi} C_{pi})^2} \quad (5)$$

And *tanδ* (dissipation factor "DF") will be:

$$\tan\delta(\omega) = \frac{C''(\omega)}{C'(\omega)} = \frac{\dfrac{1}{\omega R_g} + \sum_{i=1}^{n} \dfrac{\omega R_{pi} C^2{}_{pi}}{1+(\omega R_{pi} C_{pi})^2}}{C_g + \sum_{i=1}^{n} \dfrac{C_{pi}}{1+(\omega R_{pi} C_{pi})^2}} \quad (6)$$

Replacing in Eq.(5) and Eq. (5) with the measured FDS data we have a system of non-linear equations.

4. Parameters identification based on Particle Swarm Optimization (PSO)

The extended Debye equivalent circuit has six branches of relaxation in this article, which contain 14 variables. Therefore, it is necessary to establish a set of equations composed of 14 non-linear equations. The least square method will be used to solve the equations, transforming it into an optimization problem with the objective equation (G):

$$G = \min \left\{ \sum_{i}^{n} \left[\tan\delta_c - \tan\delta_m \right]_i^2 \right\} \quad (7)$$

Where: $tan\delta_c$: can be calculated using Eq. (6), and $tan\delta_m$: value measured by the FDS.

The PSO is based on the behavior of groups, such as birds or swarms, that start searching for food at random, but that quickly organize themselves to create a collective search pattern [19]. Given its robustness and processing speed, several authors have used PSO as an optimization tool in supply chain analysis problems [20-21]. The method is based on the behavior of groups of birds. In this way, the position occupied by each particle represents a possible solution, X. Initially, this position, as well as the speed of each particle, V, are determined at random. At each time step (iteration), the quality of the position of each particle is evaluated according to the objective function, and a new speed is calculated from three parameters: its inertia, its best position already occupied (cognitive portion), P, and the best position already found by the swarm (social parcel), G, as shown in Eq. (8). Then, the position of the particles is updated according to Eq. (9). Thus, randomness in the search process is guaranteed, in addition to considering the individual performance of each particle and the overall performance of the group, which makes the method fast and efficient.

$$V_i^{k+1} = \omega \cdot V_i^k + c_1 \cdot rand_1 \cdot \frac{\left(P_i^k - X_i^k\right)}{\Delta t} + c_2 \cdot rand_2 \cdot \frac{\left(G - X_i^k\right)}{\Delta t} \quad (8)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \cdot \Delta t \quad (9)$$

Where: V : particle velocity; X : particle position; P : the best position occupied by the particle; G: the best position occupied by the group; Δt: iteration. Each of the terms in Eq. (8) is weighted according to a dimensionless coefficient: the coefficient of inertia, *w* indicates the particle's ability to maintain its current trajectory; the cognitive coefficient c_1 represents the memory of the particle, causing it to return to the best places ever visited; and the social coefficient c_2 demonstrates the influence of the group in the trajectory of the particle, directing its displacement to the best place already occupied by the group. Fig.2 Shows the flowchart of the optimization process using the PSO.

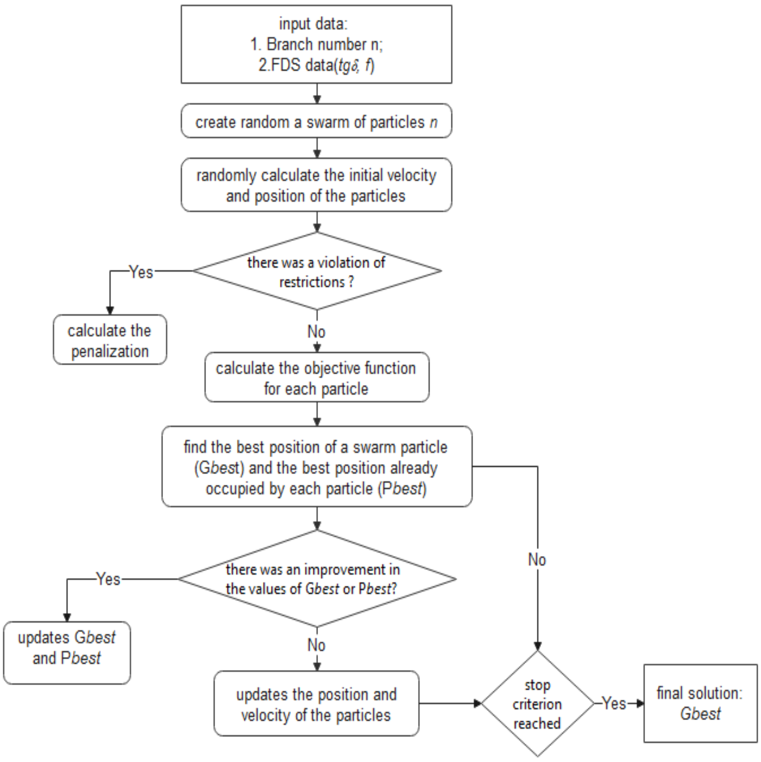

Figure 3: Flowchart of the optimization process using PSO.

5. Application of the Method for Calculation of Polarization Parameters Of Transformer Insulation.

To test the applicability of the method for calculating the polarization parameters of the transformer insulation using the PSO optimization method, the dielectric response measurement data was used using the FDS method of reference [22]. the two transformers have the same characteristics (35 MW, 6.3 / 35kV) and different lifetime. The results of FDS measurement of transformer 1 are shown in Table 1[22].

Table 1. Dielectric response measurement data using FDS for transformer 1 with 3.1% of moisture.

$f\,(Hz)$	$C\,(nF)$	$\tan\delta\,(abs)$
1000	24.054	0.00189
470.59	24.076	0.00212
222.22	24.099	0.00241
90.3954	24.127	0.0032
60.15	24.144	0.00381
40	24.164	0.00468
20	24.209	0.00663
10	24.269	0.00961
4.6417	24.37	0.01489
2.1546	24.531	0.02322
1	24.788	0.0357
0.4642	25.216	0.05379
0.2154	25.829	0.0801
0.1	26.741	0.11816
0.0464	27.918	0.17574
0.0215	29.817	0.26205
0.01	32.757	0.38465
0.0046	37.527	0.53516
0.0022	44.789	0.71438
0.001	54.613	0.90339
0.0005	64.7	1.095
0.0002	77.726	1.3423

The data in Table 1 was obtained by the FDS method, the polarization parameters of the transformer insulation system were calculated using the PSO optimization method. The algorithm was implemented using the Matlab tool. The minimum reached for the objective function was 0.0003 after 20 iterations. The results are shown in Table 2

Table 2. the values of branch parameter in transfomer 1 using PSO.

Branch	$\tau_{pi}\,(s)$	$C_{pi}\,(nF)$	$R_{pi}\,(G\Omega)$
1	69.7313	5.5428	12.5805
2	436.8311	30	14.561
3	0.739	0.4001	1.8471
4	470.9901	16.6749	28.2454
5	194.7918	30	6.4931
6	10.6596	1.9798	5.3842
Rg	9.44521		
Cg	17.393		

To check the effectiveness of the PSO method for obtaining the circuit parameters of the transformer oil-paper insulation system. The FDS curve was calculated using the data from the equivalent circuit obtained by the PSO method and compared with the curve measured. The results were satisfactory, as shown in Fig 4.

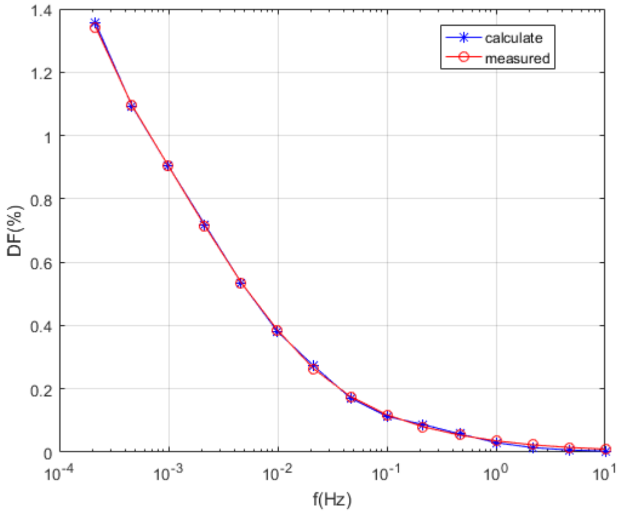

Figure 4. comparison of the measured and calculated dissipation factor value.

The error shown between the two curves was acceptable, with a small margin of error, as shown in Fig. 5.

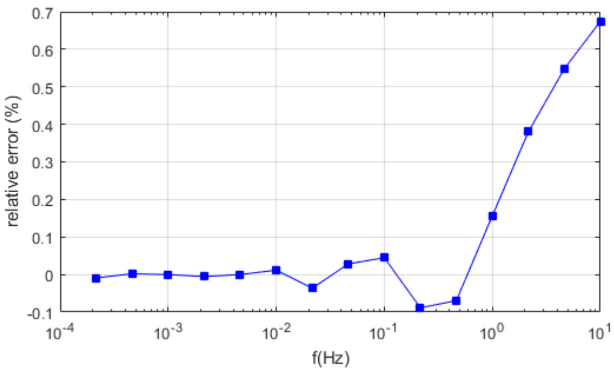

Figure 5. relative error curve between the measured and calculated value by the FDS.

The proposed method was also applied to the second transformer with relatively low moisture compared to the first transformer, the measurement results using the FDS method are shown in Table 3 [22]

Table 3. Dielectric response measurement data using FDS for transformer 2 with 2,9% of moisture.

$f\left(Hz\right)$	$C\left(nF\right)$	$\tan\delta\left(abs\right)$
1000	13.108	0.00199
470.59	13.122	0.00224
222.22	13.136	0.00249
90.3954	13.153	0.00299
60.15	13.162	0.00333
40	13.172	0.0038
20	13.191	0.00492
10	13.215	0.00688
4.6417	13.254	0.01047
2.1546	13.317	0.016
1	13.416	0.02416
0.4642	13.571	0.03616
0.2154	13.795	0.0544
0.1	14.09	0.0817
0.0464	14.645	0.11991
0.0215	15.557	0.16698
0.01	17.023	0.21172
0.0046	19.091	0.23789
0.0022	21.463	0.24316
0.001	23.586	0.25412
0.0005	25.438	0.30101
0.0002	27.415	0.39526

Using data from Table 3, the polarization parameters of the isolation system were calculated using the PSO optimization method. The minimum in the objective function was reached was 0.0001 after 300 iterations. The results are shown in Table 4

Table 4. the values of branch parameter in transformer 2 using PSO.

Branch	$\tau_{pi}\left(s\right)$	$C_{pi}\left(nF\right)$	$R_{pi}\left(G\Omega\right)$
1	11.3368	0.912	12.4307
2	310.8556	20.8248	14.9256
3	0.173702	0.0994	1.7475
4	114.0778	3.9608	28.8017
5	157.3893	24.3799	6.4557
6	2.1698	0.4154	5.2233
Rg	28.8283		
Cg	17.3256		

To check the effectiveness of the PSO method ,the FDS curve of the transformers was calculated using the data from the equivalent circuit obtained by the PSO method and compared with the curve obtained by the measurements using FDS, the two curves obtained are illustrated in Fig.6.

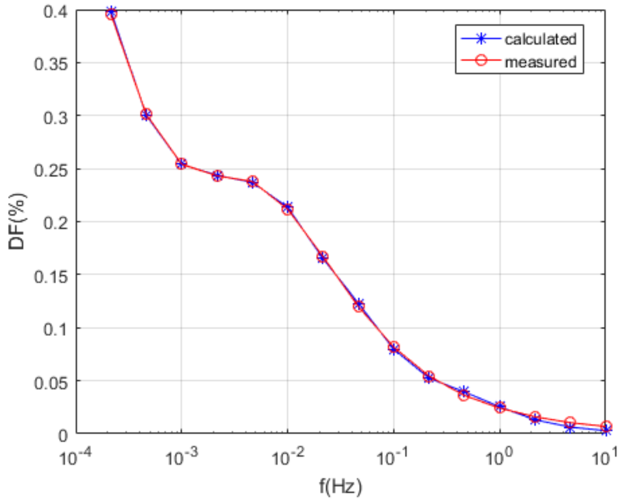

Figure 6. comparison of the measured and calculated dissipation factor value.

The results were satisfactory, the Fig. 7 shows the relative error between the two curves, the maximum error was 0.6%.

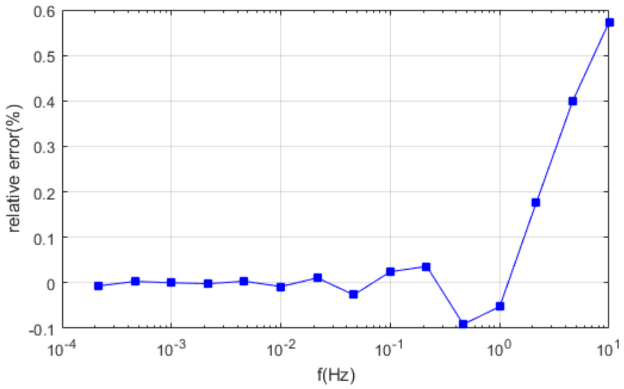

Figure 7. relative error curve between the calculated and measured value by the FDS.

The analysis of the results from Table 2 and Table 4 obtained from the polarization parameters of the isolation system of the two transformers showed that: The geometric capacitance (C_g) is basically unchanged under different moisture because of the structure and size of the oil-paper insulation system are not affected by the moisture. Insulation resistance (R_g) decreases with increasing of moisture and is very sensitive to changes in water content. This is due to the high conductivity of the water containing impurities itself and can also act as a catalyst to accelerate the decomposition of impurities and further increase the number of charge within the insulator, thus significantly increasing the conductivity of the insulating medium, and the insulation resistance corresponding is significantly reduced. For each polarization branch (R_{pi}-C_{pi}), the polarization capacitance basically increases with increasing moisture, while the polarization resistance tends opposite to the polarization capacitance, that is, it becomes monotonous with increasing content of water. Increased capacitance, because the impurity introduced due to increased moisture increases the polarization of the insulating dielectric interlayer so that macroscopically it shows the increase in the relative permittivity and polarization capacitance of the system [22]. The polarization time constant shows a tendency to increase with increasing moisture.
The analysis of the results obtained in the two transformers and the comparison of the dissipation factors measured and calculated using the equivalent circuit of the insulation system where it presented a relatively small error, proved the effectiveness of the method in estimating the parameters of the equivalent circuit of the oil-paper insulation system of transformer.

6. Conclusion

The results of measurements obtained by the FDS method, such as the dissipation factor and complex capacitance, are extremely useful to be able to estimate the parameters of the circuit equivalent of the oil-paper insulation. In this article, a mathematical model based on the extended Debye theory and the PSO optimization algorithm was used, to estimate the parameters of the equivalent circuit of the dielectric response of the oil-paper insulation system using data from the FDS method. The results obtained with the equivalent circuit of the insulation system estimated by the proposed model compared with the measured curve by FDS proved to be effective, with a relative error less than 0.8%. Therefore, it can be concluded that the proposed method to estimate the parameters of the equivalent circuit is feasible and effective. The modeling of the equivalent circuit of the insulation system allows analyzing the relationship between the state of insulation and the parameters of the equivalent circuit of the transformer. it also allows the analysis of the insulation system by other methods, such as PDC or RVM, without the need to make new measurements and, thus, improve the quality of the diagnosis of the insulation system.

References

1. Maik Koch Michael Krüger, "The negative dissipation factor and the interpretation of the dielectric response of power transformers", 16th International Symposium on High Voltage Engineering, Austria, Series A, Vol. 73, Iss. 3, 2014, , pp 402-422.
2. Belén García, et al "Determination of water content in transformer solid insulation by frequency-domain spectroscopy", proc. of the 5th wseas/iasme int. conf. on electric power systems, high voltages, electric machines, tenerife, spain, december , 2015,pp16-19.
3. K. Bandara, C. Ekanayake, et al "Modeling the Dielectric Response Measurements of Transformer oil" IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 22 ,pp. 1283 - 1291 , April， 2015,
4. R. Scholz, "Avaliação do comportamento dielétrico dos materiais isolantes utilizados em transformadores de distribuição por meio de espectroscopia dielétrica", PhD dissertation,Uniparana,Parana,Brazil, 2013.[online].Available: http://hdl.handle.net/1884/36893.
5. S. Wang, J. Wei, S. Yang, M. Dong and G. Zhang, "Temperature and thermal aging effects on the frequency domain spectroscopy measurement of oil-paper insulation" in Proc.International Conference on Properties and Applications of Dielectric Materials, Harbin,2009, pp.329-332.
6. C.Ekanayake, S.M. Gubanski, K.D.Mularachchi and M.A.R.M. Fernando, "Diagnostic of power transformers in Sri Lanka application of dielectric spectroscopy in frequency domain"in Proc. Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference, Cincinnati, 2001, pp.593-596.
7. X. Shuzhen, M. Rick, F. Fred, et al. "A comparison of return voltage measurement and frequency domain spectroscopy test on high voltage insulation," Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials. Nagaya, pp. 351—355, Jun. 2003.
8. T.K. Saha, P. Purkait, F. Muller, "Deriving an equivalent circuit of transformers insulation for understanding the dielectric response measurements," IEEE Transactions on Power Delivery. vol.20, no.1, pp.149-157, 2005.
9. B. Filipovi, et al, "Modeling of Polarization in Oil-Paper InsulationUsing Recovery Voltage Measurements" International Review of Electrical Engineering (I.R.E.E.), Vol. 6, N. 1 January-February 2011.
10. Tao Zhang et al "An Improved Mathematical Model for Estimating Polarization Parameters of Transformer Oil-Paper Insulation, energies 2016.
11. Tao Zhang,et al, "Parameter Identification and Calculation of Return Voltage Curve Based on FDS Data" IEEE, 2016.
12. M. Ohlen, P. Werelius "Dielectric Frequency Response and Temperature Dependence of Power Factor", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 8, pp.301-310, Jan, 2012.
13. R. Scholz, "Avaliação do comportamento dielétrico dos materiais isolantes utilizados em transformadores de distribuição por meio de espectroscopia dielétrica", PhD dissertation,Uniparana,Parana,Brazil, 2013.[online].Available: http://hdl.handle.net/1884/36893.
14. T. Zhang, J. Cai, "Research on parameters identification for dielectric response equivalent circuit of transformers with oil-paper insulation" Adv.Tech. of Elec.Eng.&Energy, vol.29, no.4, pp.35-39, Oct. 2010.
15. W. S. Zaengl. "Applications of dielectric spectroscopy in time and frequency domain for HV power equipment,¡± IEEE Electrical Insulation Magazine, vol.19, no.6, pp.9-22, Nov. 2003.
16. P.K. Poovamma, T.R. Afzal Ahmed, C. Viswanatha, K. Mallikarjunappa and A. Sudhindra, "Evaluation of transformer oil by frequency domain technique" in Proc. IEEE International Conference on Dielectric Liquids, France.2008,pp. 1-4.
17. U. Gafvert, L.Adeen, M. Tapper, P. Ghasemi and B. Jonsson, "Dielectric spectroscopy in time and frequency domain applied to diagnostics of power transformers", in Proc. 6th Intern. Conf. Properties and Applications of Dielectric Materials, Xi¡¯an,2000, vol.2, pp.825-830.
18. C.Ekanayake, S.M. Gubanski, K.D.Mularachchi and M.A.R.M. Fernando, "Diagnostic of power transformers in Sri Lanka application of dielectric spectroscopy in frequency domain" in Proc. Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Conference, Cincinnati, 2001, pp.593-596.
19. Eberhart, R. C., Kennedy, J. "A new optimizer using particle swarm theory".In: Proceedings of the sixth international symposium on micro machine and human science (1995), Vol. 1, pp. 39-43.
20. Brentan B. M., Luvizotto J¨²nior, E. "PSO applied to reduce the cost of energy in water supply networks". Applied Mechanics and Materials, No. 409¨C410, pp. 703¨C706, 2013.
21. V. Ramakichenan, R.K. Jain, et al., "Experiences of dielectric response measurements in frequency domain for diagnostics of transformer insulation system" in Proc. International Conference on Condition Monitoring and Diagnosis, Beijing, 2008, pp.914-918.
22. Y. Feng, et al "Analyzing the Moisture State of Oil-Paper Insulation System Using an Equivalent Circuital Model ", Transactions of china electrotechnical society, Vol.35, No. 21, Nov, 2020.

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