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Parameter Identification of Mixed Polarization Equivalent Model of Oil-paper Insulation Based on Frequency Domain Spectroscopy

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Abstract. Based on the extended Debye model, the interface polarization branch is introduced to make the oil-paper insulation mixed polarization equivalent model more suitable for the actual polarization process. The mixed polarization equivalent model parameter identification method using frequency domain dielectric spectrum is studied. Firstly, the relationship between the frequency domain spectrum and the circuit parameters is derived based on the mixed polarization equivalent circuit. Secondly, the objective function of the equations for solving the multivariate parameters is established, and the artificial intelligence algorithm is used to solve the parameters. Finally, the method is used to verify the identification of the method. Feasibility and accuracy of mixed polarization equivalent model parameters. The calculation results show that the mixed equivalent model considering interface polarization can more accurately reflect the relaxation process of oil-paper insulation. Compared with the time domain dielectric spectrum parameter identification method, the identification method based on frequency domain dielectric spectrum has the advantages of simple solving process and accurate and reliable parameter calculation results.

1. Introduction

Oil-paper insulation system is the main insulation structure of oil-immersed transformer, and the accurate evaluation of its insulation state is of great significance to the reliable operation of transformer[1]-[2]. In order to achieve a better study of the aging and damping state of oil-paper insulation in theory, we constructed an equivalent circuit model more matching with the actual polarization response process of oil-paper insulation and designed corresponding parameters calculation methods

About the construction of the equivalent model of oil-paper insulation, scholars at home and abroad have conducted research[3]-[4], in which the Extended Debye Model (EDM) can reasonably explain the relaxation response of oil-paper insulation. EDM is the most widely used oil-paper insulation equivalent model has also been extensively studied for its model parameters[5]-[6]. In addition, some scholars have improved the model based on EDM[7]-[8]. Among them, Huang Yuncheng and others also introduced the equivalent circuit, which can reflect the interface polarization characteristics, and proposed a mixed polarization circuit model which can better fit the actual relaxation process of oil-paper insulation system.

The equivalent model parameter identification methods are mainly based on the test data of recovery voltage method or polarization depolarization current method, and the accuracy and feasibility of results are verified by an example. However, the derivation formula of the solution



process is generally more complex and the calculation is large. At the same time, the test data based on the time domain dielectric response method will be disturbed by different factors such as electromagnetic environment[9]. Although the parameter identification results can reach a high agreement with the test data, they cannot be equivalent to the real oil-paper insulation structure. In contrast, the Frequency Domain Spectroscopy (FDS) method has the advantages of strong anti-interference ability and wide measurement bandwidth, and less disturbed by field factors [9]. Therefore, based on the frequency domain dielectric spectrum and mixed polarization equivalent model of oil-paper insulation, the equivalent model parameter identification method was studied and proposed. The parameters of FDS are applied through the verification of measured data. The method compares the time domain identification method, the formula derivation process is more simple, and can find all the parameters at one time, and the result is accurate and reliable. At the same time, it is proved that the equivalent model with interface polarization more realistically reflects the polarization process of oil-paper insulation.

2. Mixed polarization equivalent model and frequency domain spectrum of oil-paper insulation

2.1. Mixed polarization equivalent model of oil paper insulation

As the actual oil-paper insulation system is composed of composite dielectric materials, the polarization response of the dielectric includes not only the relaxation process of transformer oil and insulation paper, but also the relaxation response process of various products related to insulation aging, such as air gap, acid, micro-water and furfural. At the same time, oil-paper and various aging products will interact with each other to form more complex interface reactions. In order to better conform to the polarization response process of actual oil-paper insulation, the interface polarization branches are introduced base on EDM to simulate interface polarization response of the oil-paper insulation system, then a mixed polarization circuit model of oil-paper insulation system as shown in figure 1 is established.

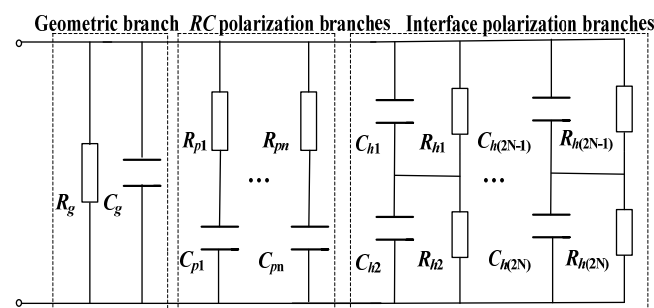


Figure 1. Mixed polarization equivalent circuit of oil-paper insulation system

The mixed polarization circuit model in figure 1 consists of geometric equivalent circuit, RC series polarization branches and interface polarization branches. Among them, R_g is a strict physical sense of insulation resistance, C_g is the geometric capacitance of an insulating system. RC series polarized branch elements R_{pi} and C_{pi} ($i=1, 2, \dots, n$) represents the polarization resistance and polarization capacitance of a homogeneous medium, and represents the dielectric polarization equivalent element at different relaxation times $\tau_i = R_{pi}C_{pi}$. R_{hj} and C_{hj} ($j = 1, 2, \dots, 2N$) of N interface polarization branches represent the polarization resistance and polarization capacitance of dielectric in the process of interface polarization response, respectively. They are used to simulate the complex interface polarization process of oil-paper insulation system.

2.2. Frequency domain dielectric spectroscopy of oil-paper insulation

Frequency domain dielectric spectroscopy (FDS) mainly measures the polarization response of dielectric excited by alternating electric field by applying alternating current sinusoidal voltage at both

ends of dielectric. Measuring the different of voltage frequency(ω), the relationship between the polarization parameters (e.g., complex capacitance $C^*(\omega)$ and dielectric loss factor $\tan\delta(\omega)$) and the measurement frequency can be obtained. Many studies have proved that the dielectric spectra in frequency domain of oil-paper insulation system can effectively reflect the aging and dampness of oil-paper insulation system[10]. Therefore, based on the frequency domain dielectric spectroscopy of oil-paper insulation, the equivalent circuit model parameters and the degree of aging dampness have certain theoretical basis.

3. Parameter calculation of mixed polarization equivalent circuit based on FDS

3.1. Relationship between dielectric spectrum and equivalent circuit parameters in frequency domain

It is assumed that there are n series polarization branches and N interface polarization branches in the mixed polarization equivalent model. According to figure 1, the equivalent admittance Y at both ends of the medium can be obtained, as shown in Formula (1).

$$Y = Z^{-1} = j\omega C_g + \frac{1}{R_g} + \sum_{i=1}^n \frac{1}{R_{pi} + (j\omega C_{pi})^{-1}} + \sum_{i=1}^N \frac{1}{R_{h(2i-1)}(R_{h(2i-1)} \cdot j\omega C_{h(2i-1)} + 1)^{-1} + R_{h(2i)}(R_{h(2i)} \cdot j\omega C_{h(2i)} + 1)^{-1}} \quad (1)$$

Through the formula (1) operation, its complex capacitance C^* is:

$$C^*(\omega) = (j\omega Z)^{-1} = C_g + \frac{1}{j\omega R_g} + \sum_{i=1}^n \frac{C_{pi}}{1 + j\omega R_{pi} C_{pi}} + \sum_{i=1}^N \frac{1}{j\omega [R_{h(2i-1)}(R_{h(2i-1)} \cdot j\omega C_{h(2i-1)} + 1)^{-1} + R_{h(2i)}(R_{h(2i)} \cdot j\omega C_{h(2i)} + 1)^{-1}]} \quad (2)$$

The real part C' and imaginary part C'' of the upper middle capacitor C^* are:

$$C'(\omega) = C_g + \sum_{i=1}^n \frac{C_{pi}}{1 + (\omega\tau_i)^2} + \sum_{i=1}^N \frac{(\omega^2\tau_{2i-1}\tau_{2i} - 1)(R_{h(2i-1)}\tau_{2i} + R_{h(2i)}\tau_{2i-1}) - (\tau_{2i-1} + \tau_{2i})(R_{h(2i-1)} + R_{h(2i)})}{\omega^2(R_{h(2i-1)}\tau_{2i} + R_{h(2i)}\tau_{2i-1})^2 + (R_{h(2i-1)} + R_{h(2i)})^2} \quad (3)$$

$$C''(\omega) = \frac{1}{\omega R_g} + \sum_{i=1}^n \frac{\omega\tau_i C_{pi}}{1 + (\omega\tau_i)^2} - \sum_{i=1}^N \frac{(R_{h(2i-1)} + R_{h(2i)})(1 - \omega^2\tau_{2i-1}\tau_{2i}) - \omega^2(R_{h(2i-1)}\tau_{2i} + R_{h(2i)}\tau_{2i-1})(\tau_{2i-1} + \tau_{2i})}{\omega^3(R_{h(2i-1)}\tau_{2i} + R_{h(2i)}\tau_{2i-1})^2 + \omega(R_{h(2i-1)} + R_{h(2i)})^2} \quad (4)$$

In formula (3) and formula (4), $\tau_i = R_{pi}C_{pi}$, $\tau_{2i} = R_{h(2i)}C_{h(2i)}$, $\tau_{2i-1} = R_{h(2i-1)}C_{h(2i-1)}$.

According to the theory of dielectric physics, the dielectric loss factor is equal to the ratio of imaginary part to real part of complex capacitor.

$$\tan\delta(\omega) = \frac{C''(\omega)}{C'(\omega)} \quad (5)$$

3.2. Equivalent parameter calculation method using FDS

Assuming that there are n RC series polarization branches and N interface polarization branches in figure 1, there are $(2+2n+4N)$ circuit parameters to be solved. The parameters of the equivalent model can be solved by establishing a multivariate nonlinear equation (6).

$$\begin{cases} C'_t(\omega_1) - C'(\omega_1) = 0, \dots, C'_t(\omega_l) - C'(\omega_l) = 0 \\ C''_t(\omega_{l+1}) - C''(\omega_{l+1}) = 0, \dots, C''_t(\omega_k) - C''(\omega_k) = 0 \\ \tan\delta_t(\omega_{k+1}) - \tan\delta(\omega_{k+1}) = 0, \dots, \tan\delta_t(\omega_m) - \tan\delta(\omega_m) = 0 \end{cases} \quad (6)$$

In equation (6), $C'_t(\omega)$, $C''_t(\omega)$ and $\tan\delta_t(\omega)$ are the results of dielectric spectrum measurement in frequency domain at each corresponding frequency(ω), $C'(\omega)$, $C''(\omega)$ and $\tan\delta(\omega)$ are the concrete calculation expressions of formula (3)-(5).

If the equation (6) is solved, at least $(2+2n+4N)$ values of complex capacitance and dielectric loss factor are required, so $m > 2+2n+4N$ in the equation is obtained. Considering the fact that the measured complex capacitance data of oil-paper insulation FDS span a large order of magnitude in a wide frequency range, and the optimization process also considers the real and imaginary parts of complex capacitance, the identification of equivalent model parameters is a relatively complex multi-objective optimization problem. In this paper, genetic algorithm and improved particle swarm optimization are combined to optimize and identify the solution parameters. The multi-objective optimization problem

is transformed into a single-objective optimization problem, and the overall optimization objective function is established, as shown in equation (7).

$$y = \min \sum_{i=1}^m [(\tan \delta_1(\omega_i) - \tan \delta(\omega_i))^2 + (C'_1(\omega_i) - C'(\omega_i))^2 + (C''_1(\omega_i) - C''(\omega_i))^2] \quad (7)$$

In equation (7), $\tan \delta(\omega_i)$, $C'(\omega_i)$ and $C''(\omega_i)$ are calculated by formula(3)-(5), while $\tan \delta_1(\omega_i)$, $C'_1(\omega_i)$ and $C''_1(\omega_i)$ are the second corresponding measured data of FDS.

Genetic algorithm has good global searching ability. Combining particle swarm optimization with genetic algorithm based on compression factor can give full play to their advantages and further improve the searching ability. For the objective equation (7) to be optimized, the genetic algorithm is first used to search for a certain number of iterations, and then the resulting particle swarm is put into the improved particle swarm optimization to continue iterative optimization until the optimal solution is found. When the objective function is close to 0, all element parameters in the equivalent model can be calculated at a time.

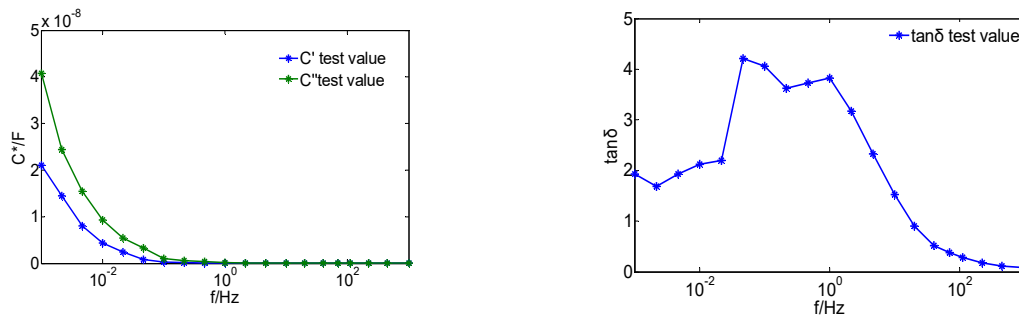


Figure 2. Test results of FDS of oil immersed voltage regulator

4. Example

4.1. FDS test of oil-paper insulation equipment

In this paper, the DIRANA dielectric response analyzer of Omron Company is used to test the dielectric spectrum of oil-paper insulation. The oil-paper insulation equipment to be tested is a decommissioned oil-immersed inductance voltage regulator (TSJA-20/0.5). According to the testing principle and wiring mode of DIRANA analyzer, test wiring is carried out for the testing equipment. The measuring frequency range is $10^{-4} \sim 10^3$ Hz, the AC voltage amplitude is 100 V, and the frequency sampling point is the default point. The measured dielectric loss factor $\tan \delta$ and complex capacitance C^* are shown in figure 2.

4.2. Calculation and verification of mixed polarization equivalent model parameters

There are differences in the number of RC series polarization and interface polarization branches in the oil-paper insulation equivalent circuit considering different aging conditions[11]. In this paper, the parameter identification is carried out according to the different types of polarization branches that may exist in the total of 6 polarization branches. The calculation of the frequency domain spectrum is obtained based on the parameter identification results. A higher degree of agreement with the measured line indicates that the corresponding equivalent model is more closely related to the actual situation, and the number of different types of polarization branches is determined.

Assumes that the number of branches of different polarization types in the mixed polarization equivalent model is the following 4 cases. RC series polarization number n and interface polarization branch N are $n=3, N=3, n=4, N=2, n=5, N=1, n=6, N=0$, respectively. Then according to the dielectric loss factor and the complex capacitance measured data of figure 2, the parameters of the mixed

polarization equivalent model are calculated according to the method of Section 3.2. The results are shown in table 1 to table 4.

Table 1. Calculation results of $n=3, N=3$

Equivalent branch	$R_i/G\Omega$	C_i/nF
$n=3$	1	2.0351
	2	1.5749
	3	3.7272
$N=3$	1	845.5637
		1403.4588
	2	1460.3626
		1141.4960
	3	802.5713
		1303.6397
Geometric branch	5.0604	0.014552

Table 2. Calculation results of $n=4, N=2$

Equivalent branch	$R_i/G\Omega$	C_i/nF
$n=4$	1	1.5737
	2	2.0869
	3	7.7873
	4	3.8765
$N=2$	1	939.6659
		1105.0485
	2	1367.7945
		1239.0066
Geometric branch	10.7136	0.017301

Table 3. Calculation results of $n=5, N=1$

Equivalent branch	$R_i/G\Omega$	C_i/nF
$n=5$	1	1.5963
	2	957.4885
	3	7.2785
	4	3.7598
	5	2.1719
$N=1$	1	1091.282
		2528.0165
Geometric branch	11.0449	0.017211

Table 4. Calculation results of $n=6, N=0$

Equivalent branch	$R_i/G\Omega$	C_i/nF
1	387.9278	406.8853
2	1.5871	0.1624
3	485.2859	299.5282
4	2.1601	3.7669
5	3.7800	15.0071
6	8.9044	77.9314
Geometric branch	8.9268	0.017319

Based on the calculation results of the parameters in table 1 to table 4, the calculated values of the frequency domain dielectric spectrum can be obtained by equations (3)-(5). The frequency domain spectrum comparison of the different types of polarization branches is shown in figure 3. Comparing the different frequency domain dielectric spectrum test values with the calculated values in figure 3, it can be seen that when the number of RC series polarization branches and the number of interface polarization branches are 4 and 2 respectively, the line of test and calculation has the highest degree of coincidence. It can be explained that the equivalent model containing the interface polarization branch is more consistent with the actual situation.

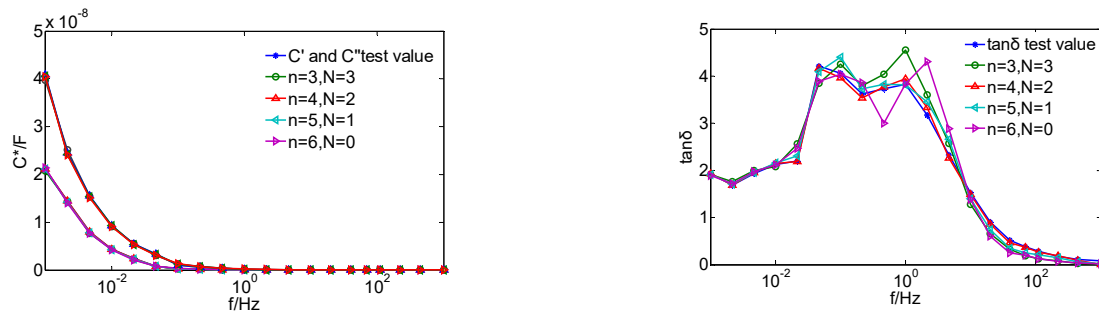


Figure 3. FDS contrast of different types of polarization branch

In order to more intuitively show the degree of spectral line matching of different polarization branches, the coincidence degree and the average coincidence degree W_a of different frequency domain spectra can be calculated according to formula (8). The specific results are shown in table 5.

$$W = \left(1 - \frac{\sum_{k=1}^m |X_{ck} - X_{tk}|}{\sum_{k=1}^m X_{tk}} \right) \times 100\% \quad (8)$$

In formula (8), X_{tk} is the frequency domain spectral test value of the k^{th} frequency sampling point, X_{ck} is the corresponding frequency domain spectrum calculation value, and m is the frequency sampling frequency.

Table 5. Result of coincidence of different types of polarization branches

(n, N)	$C'(\%)$	$C''(\%)$	$\tan\delta(\%)$	$W_a(\%)$
(3, 3)	97.65	95.92	88.95	94.17
(4, 2)	99.72	99.37	97.65	98.91
(5, 1)	98.46	97.70	94.10	96.75
(6, 0)	96.58	95.43	87.86	93.29

From the calculation results of the matching degree of the different polarization type branch combinations in table 5, it can be seen that the parameter identification results of the oil-paper insulation equivalent model using the frequency domain dielectric spectrum have higher precision. Among them, the coincidence degree of C' and C'' is more than 95%, the degree of coincidence of $\tan\delta$ is 87% or more, and the average degree of coincidence W_a is substantially 92% or more. At the same time, it can be determined by W_a that the mixed polarization equivalent model of the oil-paper

insulation system has 4 RC series polarization branches and 2 interface polarization branches. The extended Debye model ($N=0$) without the interface polarization branch is lower than the equivalent model containing the interface polarization branch, which can further explain the oil-paper insulation mixed polarization equivalent model and actual situation of figure 1, more consistent and more realistic reflection of the aging process of oil-paper insulation.

In the parameter identification results of the time domain dielectric spectrum in the literature[8], the equivalent model of the four RC series polarization branches and the two interface polarization branches, the test and calculation line alignment is only 89.04%, and the average coincidence of the frequency domain method is 98.91%. It can be explained that the parameter identification result based on the frequency domain dielectric spectrum is significantly improved compared with the accuracy of the time domain dielectric spectrum.

5. Conclusion

1) Compared with the time domain dielectric spectrum identification method, the method of applying the frequency domain dielectric spectrum identification equivalent model parameters has the advantages of simple solving process and more accurate and reliable calculation results.

2) According to the comparison of the calculated values of the frequency domain dielectric spectrum and the measured values of the parameter identification results, it can be verified that the oil-paper insulation equivalent model with interface polarization can more accurately reflect the actual polarization response process of the medium.

3) Through the average coincidence degree of different frequency domain lines, the number of branches of different polarization types in the mixed polarization equivalent model can be judged, which is beneficial to further analyze and evaluate the aging of oil-paper insulation status based on the mixed polarization equivalent model.

References

- [1] Tang M.G., Lei M., Bai F., et al. (2014) Parameter identification based on vector fitting method for extended Debye model of oil-paper insulation system. *High Voltage Engineering*, 40: 548-556.
- [2] Gao J., Liao R.J., Wang Y.Y., et al. (2016) Aging characteristic quantities of oil-paper insulation for transformers based on extended Debye model. *Transactions of China Electrotechnical Society*, 31: 211-217.
- [3] Tuncer E., Gubanski S. M. (2000) Electrical properties of filled silicone rubber. *Journal of Physics Condensed Matter*, 12: 1873-1897.
- [4] Saha T.K., Purkait P., Muller F. (2005) Deriving an equivalent circuit of transformer insulation for understanding the dielectric response measurements. *IEEE Transactions on Power Delivery*, 20: 149-157
- [5] Ye R., Cai J.D. (2018) Analytic method of cubic differential in time domain dielectric spectroscopy for oil-paper insulation polarization equivalent circuit. *Chinese Journal of Scientific Instrument*, 39: 112-119.
- [6] Wang Q., Zang C.Y., Zhang M.L. (2012) Research on the method of parameter identification for dielectric response equivalent circuit of oil-paper Insulation. *High Voltage Apparatus*, 48: 7-11+17.
- [7] Li A.N., Cai J.D. (2014) Study on parallel-series equivalent circuit and parameters identification of oil-paper insulation system. *Chinese Journal of Scientific Instrument*, 35: 2130-2136.
- [8] Huang Y.C., Cai J.D., Lu J.Y. (2016) New mixed polarization circuit model and parameters identification of oil-Paper insulation transformers. *Transactions of China Electrotechnical Society*, 31: 170-177.
- [9] Liao R.J., Hao J., Yang L.J., et al. (2010) Simulation and experimental study on frequency-domain dielectric spectroscopy of oil-paper insulation for transformers. *Proceedings of the CSEE*, 30: 113-119.

- [10] Dong M., Liu Y., Ren M., et al. (2015) Explanation study of frequency-domain dielectric spectroscopy for oil-paper insulation system. Proceedings of the CSEE, 35: 1002-1008.