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Optimization of Transformer Winding Deformation Assessment Criterion Considering Insulation Aging and Moisture Content

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Abstract: Frequency response analysis is widely used to diagnose transformer winding deformation faults due to its high sensitivity, strong anti-interference capability, and equipment portability, but the results of frequency response analysis can be affected by insulation aging and moisture in the transformer, leading to errors in the diagnosis of winding deformation faults. Currently, there is no effective method to prevent such errors. This paper focuses on optimizing the criterion for diagnosing winding deformations when insulation aging and moisture are present. First, the winding frequency response curves of oil-paper insulation were determined by combining insulation aging and moisture tests of the oil-paper insulation with frequency response simulations of the transformer winding. Next, the winding deformation criterion predicting the likelihood and extent of errors diagnosing transformer winding deformations due to the insulation aging and moisture content is discussed. Finally, the corresponding criterion optimization method is proposed. The corresponding results show that insulation aging and moisture can lead to errors when using the correlation coefficient R criterion to diagnose the transformer winding deformations. Moreover, the possibility of winding deformation errors caused by the change of insulation state can be reduced by introducing the corresponding auxiliary criterion through comparing the capacitance change rate based on the frequency response method and that based on the dielectric spectrum method.

Keywords: frequency response; aging and moisture; winding deformation; fault diagnosis; criterion optimization

1. Introduction

Oil-immersed power transformers are at the core of energy transmission and distribution in power systems, and their safe operation is of great significance to ensure reliable power delivery [1–3]. Winding deformations are one of the leading causes of transformer faults [4]. If the winding deformation occurs in an operating transformer, the mechanical properties of the winding drop sharply, which damages the transformer and prevents it from operating normally [5]. Therefore, the ability to effectively detect transformer winding deformations is essential to the safe and stable operation of transformers, which has important academic and engineering significance.

The early detection of winding deformations in power transformers is typically performed by inspecting the hanging cover. However, this method is time-consuming and laborious, and atmospheric moisture can enter the transformer and negatively affect the performance of the insulation. In recent years,

the frequency response analysis (FRA) method has attracted significant attention because of its high sensitivity, strong anti-interference capabilities, and measuring equipment portability. The FRA method was first proposed by Dick and Erven [6], since then Jensen [7], Islam [8], and many other scholars [9–11] have done extensive work in this field. Currently, the FRA method has become the main method for diagnosing transformer winding deformations in European countries. Since the 1990s, FRA has received increased attention by scholars and has been applied to the detection of transformer winding deformations in real-world applications [12]. In 2004, the FRA method was written into the power industry standard DL/T 911-2004 [13] as a method for analyzing winding deformations in power transformers. However, the frequency response of transformers is affected not only by winding deformations but also by insulation aging, moisture exposure, internal transformer temperature during measurement, and other factors, which can lead to errors in the analysis [14]. Researchers have confirmed that the insulation state of the oil-paper insulation affects the frequency response of the transformer. A simulation study demonstrated that the aging of the oil-paper insulation does not significantly affect the frequency of the resonance peak of the FRA curve of the winding, but it does affect its peak value [15]. In another study [16], the FRA curves of the winding of a 5 kV transformer were measured before and after drying, and it was found that the FRA curve of the transformer shifted to higher frequencies after being dried. Nevertheless, the insulation state of transformers is still evaluated through the FRA results. Research on the influence of the transformers' oil-paper insulation state on the assessment of winding deformations has been limited to simple qualitative discussions, and a method that can effectively avoid errors when analyzing winding deformations has not been proposed yet.

In this paper, the influence of insulation aging and moisture on the frequency response characteristics of transformer windings is investigated. Since the transformer in long-term operation will be affected by uncontrollable and uneven insulation aging or moisture exposure due to the change of actual working conditions, it is difficult to directly test transformers, so the aging and moisture tests of the oil-paper insulation materials were combined with a winding frequency response simulation to determine the frequency response characteristics of the transformer windings after aging and exposure to moisture. Based on the simulation of winding frequency response curves with different aging and moisture degrees, the possibility and degree of errors when analyzing winding deformations caused by aging and exposure to moisture is discussed by combining with the correlation coefficient R criterion. Finally, two optimization methods of an auxiliary criterion based on the rate of change of the capacitance are proposed and their effectiveness is verified.

2. Theory of Frequency Response and Winding Deformation Diagnosis

2.1. Principle of Frequency Response Analysis

According to the DL/T 911-2004 standard [13], the amplitude-frequency response characteristics in the 1 kHz–1 MHz range should be investigated when diagnosing and analyzing winding deformation faults for transformers with a voltage of 6 kV and above using the FRA method. Due to the influence of the winding on the ground capacitance and longitudinal capacitance, the transformer winding can be represented by a circuit composed of distributed parameters such as inductance, capacitance and resistance [13]. The test circuit for the FRA method is shown in Figure 1. where, R_0 , L_0 , C_0 , and C_s are the distributed resistance, distributed inductance, distributed capacitance to ground, and longitudinal distributed capacitance per unit length of winding, respectively. U_s and R_s are the voltage and output impedance of the excitation signal source, respectively. R is the measured resistance. U_1 and U_2 are the voltages at the excitation and response ends of the winding equivalent circuit, respectively.

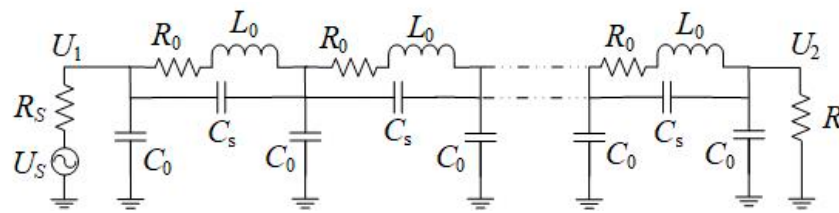


Figure 1. Basic test loop of the frequency response method.

The amplitude–frequency response of the transformer winding can be expressed as in Formula (1).

$$H(f) = 20 \log \frac{U_2(f)}{U_1(f)} \quad (1)$$

where $H(f)$ is the amplitude of the frequency response when the frequency is f ; $U_2(f)$ is the effective or peak value of the voltage at the response end when the frequency is f ; $U_1(f)$ is the effective or peak value of the voltage at the excitation end when the frequency is f .

Two commonly used connection modes for the frequency response method are shown in Figure 2. In Figure 2a, the in-phase non-measurement winding of the tested winding is in a short circuit state, which is called end-to-end open-circuit connection mode. In Figure 2b, the winding is in the end-to-end short-circuit connection mode, where the input signal is applied to one end of one winding, and the output signal is at one end of the other windings in the same phase; aside for these two ends, the other ends of the transformer winding should be in a suspended state. The frequency response in this connection mode is sensitive to radial deformations of the windings. The frequency response measured by both connection modes is the frequency response of a single winding.

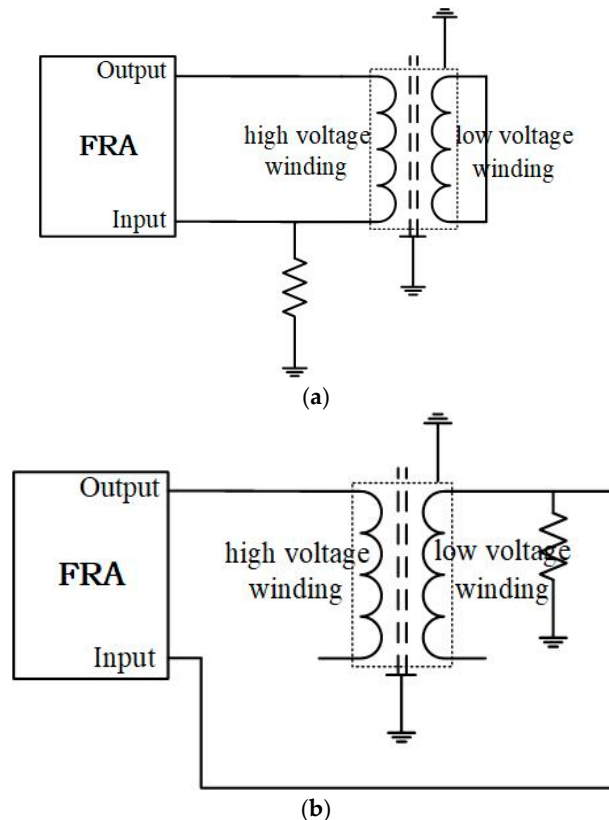


Figure 2. Two wiring methods commonly used in frequency response analysis (FRA). (a) End-to-end short-circuit; (b) capacitive inter-winding.

2.2. Winding Deformation Criterion

Winding deformations in transformers are diagnosed using FRA, which compares the measured winding frequency response characteristic curve with the reference curve to assess the transformer winding [5].

To diagnose winding deformations, the correlation coefficient CC is commonly used and is defined as follows [17]. Assuming that x and y are the first and second frequency response sequences of the transformer, $\bar{x}$ and $\bar{y}$ are the average values of x and y , respectively, and N is the length of x and y , the correlation coefficient CC can be determined using Formula (2).

$$CC = \frac{\sum_{i=1}^N ((x_i - \bar{x}) \times (y_i - \bar{y}))}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2 \sum_{i=1}^N (y_i - \bar{y})^2}} \quad (2)$$

However, there is no unified standard for the relationship between correlation coefficient CC and the degree of transformer winding deformation. The correlation coefficient R criterion was formally put forward in a different power industry standard, the DL/T 911-2004 [13]. The algorithm at the core of the two correlation coefficients is the same, the only difference is that the correlation coefficient R divides the frequency band into three sections, which is better for practical engineering applications.

The correlation coefficient R criterion is one of the most important methods for determining whether a winding is deformed, and has been widely adopted in the field [11,12]. In this method, the measured frequency band in the FRA is divided into three small frequency bands: low frequency (1–100 kHz), medium frequency (100–600 kHz), and high frequency (600–1000 kHz) bands. The degree of winding deformation is determined according to the correlation coefficient in each of the three frequency bands. Assuming that there are two transformer transfer function sequences, $X(k)$ and $Y(k)$ ($k = 0, 1, \dots, N-1$) with length N , and both $X(k)$ and $Y(k)$ are all real numbers, then the correlation coefficient R of the two sequences can be calculated according to Formula (3).

$$R_{xy} = \begin{cases} 10, & (1 - \sigma) < 10^{-1} \\ -\log_{10}(1 - \sigma) \end{cases} \quad (3)$$

where R_{xy} is the correlation coefficient in the low (medium/high) frequency band; σ is the normalized covariance coefficient of the two sequences, where σ can be determined using Formula (4).

$$\sigma(x, y) = \frac{C_{xy}}{\sqrt{D_x D_y}} \quad (4)$$

where C_{xy} is the covariance of the two sequences; D_x and D_y are the standard variances of the two sequences.

The relation between the correlation coefficient R and the degree of transformer winding deformation is presented in Table 1 [13], and the severity of the winding deformation can be assessed according to the correlation coefficients of the different frequency bands.

Table 1. Relation between correlation coefficient R and deformation degree of transformer winding.

Winding Deformation Degree	R
Severe deformation	$R_{LF} < 0.6$
Obvious deformation	$1.0 > R_{LF} \geq 0.6$ or $R_{MF} < 0.6$
Mild deformation	$2.0 > R_{LF} \geq 1.0$ or $0.6 \leq R_{MF} < 1.0$
Normal winding	$R_{LF} \geq 2.0$ and $R_{MF} \geq 1.0$ and $R_{HF} \geq 0.6$

3. Establishment of the Transformer Frequency Response Simulation Model

Owing to the high cost and complexity of performing aging and moisture tests on actual transformers, a method that combines the tests with simulations was adopted. In this method, the aging and moisture tests are carried out on transformer oil-paper insulation materials in a laboratory to measure the dielectric parameters of such materials. Next, the measured results are substituted into a transformer frequency response simulation model. Finally, the transformer frequency response of insulation materials under the condition of the aging and moisture is calculated.

3.1. Transformer Single-Phase Winding Equivalent Circuit Model

According to Figure 1, the equivalent circuit model of a single-phase transformer is established based on the structure of a 10 kV three-phase double-winding transformer, as shown in Figure 3, where C_{10} and G_{10} refer to the capacitance and conductance between the high voltage winding and the transformer wall, respectively; C_{20} and G_{20} are the capacitance and conductance between the low voltage winding and the iron core, respectively; C_{12} and G_{12} refer to the capacitance and conductance between high and low voltage windings, that is, the main insulation of transformer, respectively; C_{s1} and G_{s1} are longitudinal capacitance and longitudinal conductance of high voltage windings, respectively; C_{s2} and G_{s2} are longitudinal capacitance and longitudinal conductance of low voltage winding, respectively; L_1 and R_1 are equivalent inductance and equivalent resistance of high voltage winding, respectively; L_2 and R_2 are equivalent inductance and equivalent resistance of low voltage winding, respectively; and M is the mutual inductance between windings. The structural parameters of the transformer, corresponding to this model, are given in Table A1 (Appendix A).

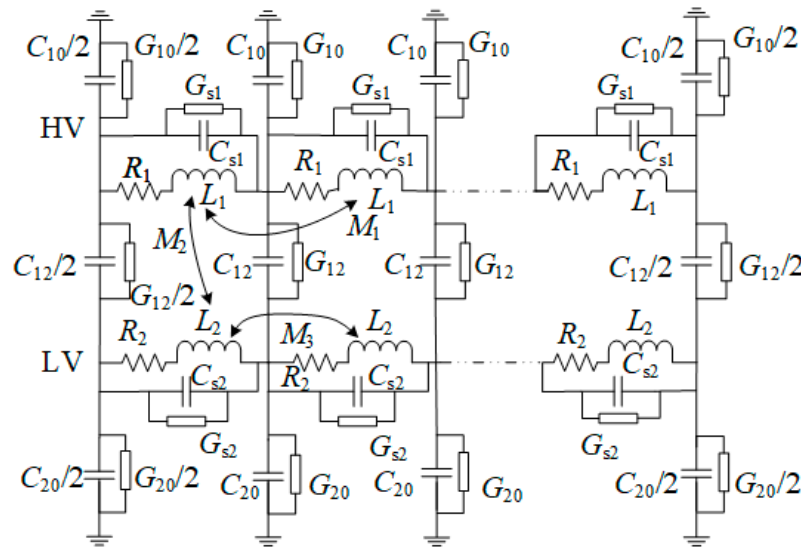


Figure 3. Equivalent circuit model of single-phase transformer.

When constructing the simulation model of the transformer frequency response, the transformer winding is divided into several parts and the lumped parameters of each part are calculated. In order to ensure the constant current flowing through each lumped parameter part, this paper takes a piece of high-voltage winding and other structures with the same height as it as a unit to build the model and calculate the lumped parameters. The specific calculation method and derivation are shown in Appendix B.

3.2. Three-Phase Transformer Frequency Response Simulation Model

Because the transformer simulation model requires sweeps of the frequency values over multiple ranges, and the lumped parameters change as the frequency changes, the model was constructed in Matlab/Simulink, and values were quickly assigned to the parameters. The equivalent circuit model

of a three-phase transformer can be constructed by connecting three equivalent circuit models of single-phase transformer winding, as shown in Figure 3, in a particular way. The frequency domain response simulation model built in Simulink is shown in Figure 4, where R_s is the output impedance of the signal source and its value does not affect the frequency response; R is the measured impedance and its value is set to $50\ \Omega$ in accordance with regulations; I is the current flowing through the response end; $U1$ and $U2$ are the effective voltage values of the excitation and response ends, respectively.

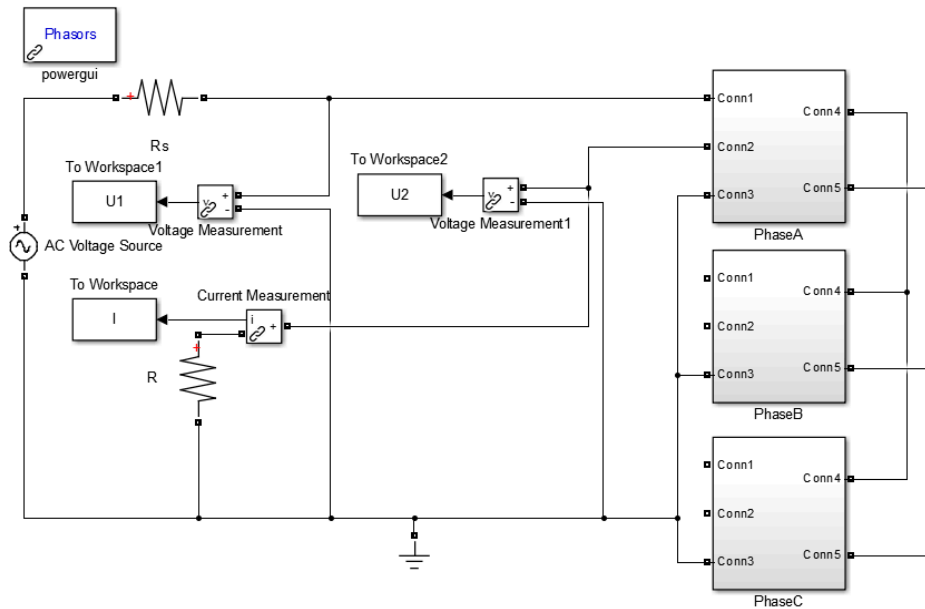


Figure 4. Frequency response simulation model based on Simulink.

Phase A, Phase B, and Phase C are the modules packaged in Figure 3, which respectively represent the A, B, and C phases of the transformer, and their lead-out ends are the two ends of the high and low voltage windings and the ground end. The frequency response curve of the transformer can be obtained by simultaneously changing the frequency of the excitation source and the lumped parameters in the model through programming in Matlab.

4. Frequency Response with Insulation Aging and Moisture

Using the test results of the dielectric parameters of oil-immersed paperboard from Figure A2 (Appendix C) and the corresponding formulas in Appendix B, the lumped parameters in the simulation model were calculated. Subsequently, the frequency response curves under different conditions were obtained using the simulation, and the influence of the oil-paper insulation state change on transformer winding fault diagnosis results was discussed by using the correlation coefficient R criterion.

4.1. Amplitude-Frequency Response and Winding Deformation Assessment Results of Overall Insulation Aging and Moisture Conditions

Figure 5 shows the results of the transformer winding amplitude–frequency response simulation with different degrees of aging and moisture content of the oil-immersed paperboard. This simulation was performed at $30\ ^\circ\text{C}$ and with two connection modes, a and b. It is clear that the resonance points of the amplitude–frequency response curve of the transformer shifted to higher frequencies as the degree of aging of the insulation paperboard was increased, in either connection mode. Combined with the results of the measurement of the dielectric parameters, presented in Figure A2, it was determined that in the frequency range of 1 kHz to 1 MHz, the real part of the relative complex dielectric constant ϵ' decreased as the degree of aging of the oil-immersed paperboard increased, which led to a reduction in the capacitance of the main insulation of the transformer, thus causing the resonance frequency shift to a high frequency.

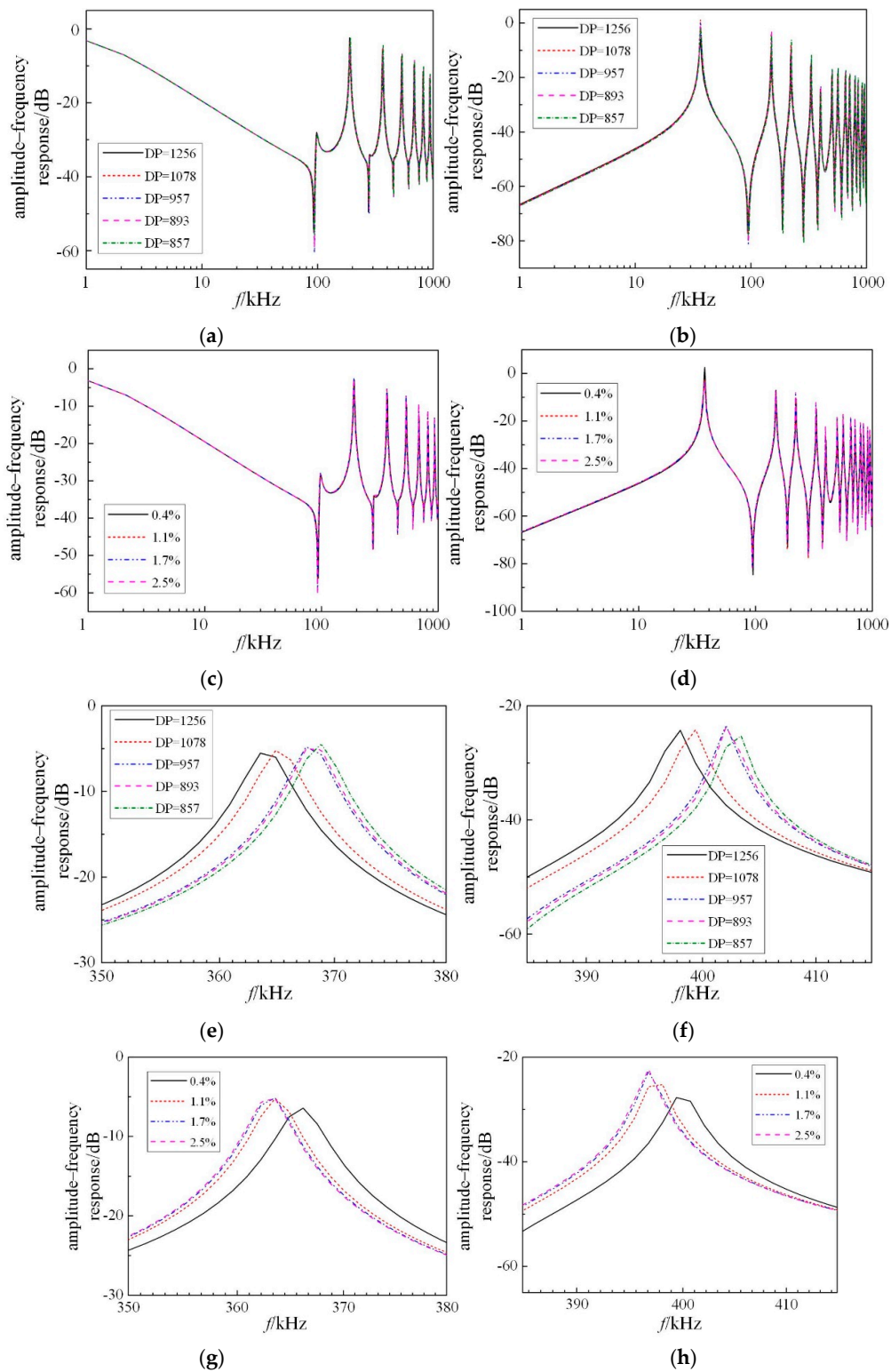


Figure 5. Amplitude-frequency response of windings with different aging degrees and moisture contents. (a) Full-band response of connection mode a under different aging degrees; (b) full-band response of connection mode b under different aging degrees; (c) full-band response of connection mode a under different moisture contents; (d) full-band response of connection mode b under different moisture contents; (e) local-band response of connection mode a under different aging degrees; (f) local-band response of connection mode b under different aging degrees; (g) local-band response of connection mode a under different moisture contents; (h) local-band response of connection mode b under different moisture contents.

The resonance points of the frequency response curve of the transformer shifted to lower frequencies as the moisture content of the insulation paperboard was increased, which is opposite to the trend seen with insulation aging. Combined with the results of the measurement of the dielectric parameters, presented in Figure A2, it was determined that in the frequency range of 1 kHz to 1 MHz, the real part of the relative complex dielectric constant ϵ' of the oil-immersed paperboard increased as the moisture content increased, which led to an increase in the capacitance of the main insulation of the transformer, thus causing the resonance frequency shift to a low frequency.

The influence of the degree of aging of insulation paperboard on the diagnosis of winding deformations is investigated considering the correlation coefficient R criterion. Taking the amplitude–frequency response curve of a transformer with a degree of polymerization (DP) value of 1256 as the reference curve, the correlation coefficient R between the amplitude–frequency response curve with different degrees of aging and the reference curve was calculated, and the result of the assessment of the winding deformation was determined by combining the correlation coefficient R criterion, as shown in Table 2.

Table 2. Correlation coefficient R and winding deformation assessment of aging insulating paperboard.

Connection Mode	DP Value	R			Transformer Status
		Low Frequency	Medium Frequency	High Frequency	
connection mode a (high voltage winding)	1078	2.4716	2.1199	1.7368	Normal winding
	957	1.5443	1.1918	0.8005	Mild deformation
	893	1.5625	1.1585	0.7624	Mild deformation
	857	1.5647	1.0841	0.6853	Mild deformation
connection mode b	1078	2.5705	1.8692	1.4818	Normal winding
	957	2.0547	0.9569	0.5373	Mild deformation
	893	2.0408	0.9174	0.4994	Mild deformation
	857	1.9846	0.8397	0.4213	Mild deformation

Similarly, taking the amplitude–frequency response curve of a transformer with 0.4% moisture content as the reference curve, the correlation coefficient R between the amplitude–frequency response curve with different moisture contents and the reference curve was calculated, and the result of the winding deformation assessment was given by combining the correlation coefficient R criterion, as shown in Table 3.

Table 3. Correlation coefficient R and winding deformation assessment of moist insulating paperboard.

Connection Mode	Moisture Content	R			Transformer Status
		Low Frequency	Medium Frequency	High Frequency	
connection mode a (high voltage winding)	1.1%	1.8193	1.6027	1.2171	Mild deformation
	1.7%	1.6507	1.4476	1.0482	Mild deformation
	2.5%	1.6074	1.4057	1.0028	Mild deformation
connection mode b	1.1%	2.1422	1.3654	0.9339	Normal winding
	1.7%	1.9862	1.2061	0.7641	Mild deformation
	2.5%	1.9459	1.1647	0.7190	Mild deformation

According to the results presented in Table 3, the correlation coefficient decreased as the frequency was increased, in both connection mode a (high voltage winding) and connection mode b, and a normal winding would be misjudged to be slightly deformed. As the degree of aging increased, the correlation coefficient tended to decrease, and the likelihood that the winding was misdiagnosed as deformed increased. In addition, by analyzing the correlation coefficients at low, medium, and high frequencies in different connection modes, it was determined that the degree of aging in connection mode a

(high voltage winding) caused the correlation coefficient in the low frequency band to decrease by a greater amount. The misdiagnosis of winding deformations was mainly caused by the change of the correlation coefficient in the low frequency band from 1 kHz to 100 kHz. However, when the degree of aging changed in connection mode b, the range over which the correlation coefficient varied for low, medium, and high frequencies was relatively consistent. This was mainly affected by the number and amplitude of resonance peaks in the different frequency bands in different connection modes.

Table 4 shows that there was an error in the winding deformation evaluation after a change in the moisture content in both connection modes. As the moisture content increased, the correlation coefficient showed a decreasing trend, and the likelihood that a normal winding was misdiagnosed as being deformed windings increased.

Table 4. Correlation coefficient R and winding deformation assessment of insulating paperboard with localized moisture.

Connection Mode	Moisture-Affected Part	R			Transformer Status
		Low Frequency	Medium Frequency	High Frequency	
connection mode a (high voltage winding)	head part	6.0127	6.8299	5.6905	Normal winding
	middle part	6.3819	4.5294	7.2117	Normal winding
	tail part	10	7.2117	5.6923	Normal winding
connection mode b	head part	4.3688	4.402	3.8419	Normal winding
	middle part	4.7049	4.8085	4.4063	Normal winding
	tail part	7.2982	4.2690	4.8028	Normal winding

Consistent with the results of the degree of aging, the likelihood of a misdiagnosis due to the correlation coefficient of the low frequency band was greater when the moisture content changed in connection mode a (high voltage winding), while the likelihood of misdiagnosis caused by the low, medium, and high frequency correlation coefficients in connection mode b was relatively consistent.

4.2. Amplitude–Frequency Response and Winding Deformation Assessment Results of Local Moisture Conditions

Due to the uneven distribution of the internal electric field, the constant change in load, change in temperature, and other factors, the state of the oil-paper insulation inside the main insulation structure was not consistent everywhere. The moisture content of the transformer insulation was often greater in areas where the electric field was concentrated and where there was significant aging. In this section, the influence of the local concentrated moisture distribution on the transformer frequency response is discussed.

Taking the winding lead-out end as a benchmark, the local insulation moisture-affected parts were the main insulation parts of the head part, the middle part and the tail part. The height of the moisture-affected part was the height of one unit, namely, the height of a piece of high-voltage winding. The moisture contents of the paperboard at insulation moisture part and other locations were 2.5% and 0.4%, respectively. The frequency response of the transformer in both connection modes at 30 °C was calculated via the simulation, as shown in Figure 6. Additionally, the correlation coefficient calculated based on the frequency response without local insulation moisture in the transformer is presented in Table 4. It was determined that the influence of local insulation moisture on the amplitude–frequency response of transformer did not change significantly compared with the overall insulation state and would not affect the winding deformation evaluation results.

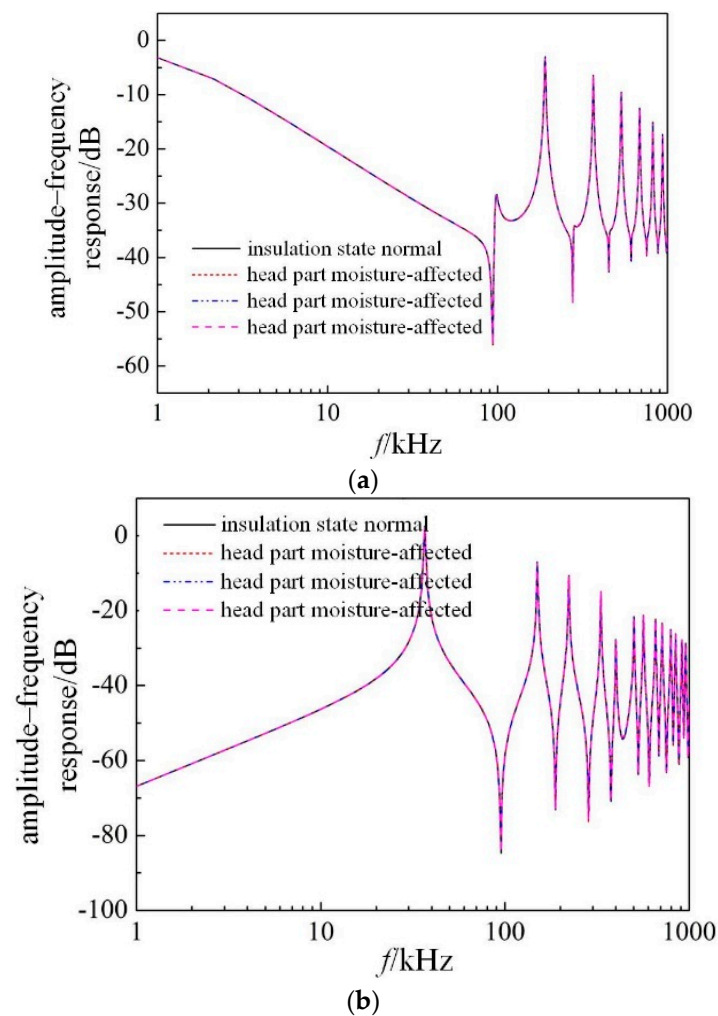


Figure 6. Amplitude–frequency response curve of oil-impregnated paperboard with localized moisture. (a) Connection mode a; (b) connection mode b.

5. Correlation Coefficient Criterion Optimization of Winding Deformation

5.1. Winding Deformation Criterion Optimization Based on Capacitance Change Rate Comparison

The main insulation section between the high and low voltage windings is typically the test object in the frequency domain dielectric response test. This means that the frequency domain spectrum when excessive aging and moisture are present mainly reflects the change of equivalent capacitance of the main insulation section, while the winding deformation affects the equivalent capacitance of other parts, including the main insulation and the longitudinal insulation. Therefore, this section discusses the relationship between the frequency domain spectrum of the transformers main insulation and the rate of change of the capacitance, determined from the transformer winding frequency response, and explores the optimization method for the winding deformation criterion when aging and moisture become a factor.

The resonant frequency f in the equivalent circuit was determined using the equivalent capacitance C and the equivalent inductance L in the circuit, where the relationship is shown in Formula (5).

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

It was reported that the inductance of the transformer winding did not change significantly with the change in frequency, so the shift of the resonance peak in the frequency response curve was mainly

caused by the change in capacitance in the equivalent circuit of the transformer [14]. Assuming that f_1 and f_2 were the frequencies of a particular resonance peak in the first and second tests, and C_1 and C_2 were the corresponding equivalent capacitances, respectively, the equivalent capacitance change rate ΔC_{FRA} , based on the frequency response curve, can be expressed as Formula (6).

$$\Delta C_{FRA} = \left| \frac{C_2}{C_1} - 1 \right| \times 100\% = \left| \frac{f_1^2}{f_2^2} - 1 \right| \times 100\% \quad (6)$$

It is difficult to carry out quantitative aging and moisture treatment on the main insulation system of a transformer. Therefore, a finite element simulation model was established in Comsol based on the dielectric parameters in Figure A2, according to the structural parameters of the transformer presented in Table A1, as shown in Figure 7. Subsequently, the complex capacitance frequency domain spectrum of the transformer's main insulation is calculated via simulation. The capacitance change rate ΔC_{FDS} , based on the frequency domain spectrum of the transformer's main insulation, can be determined through its complex capacitance frequency domain spectrum.

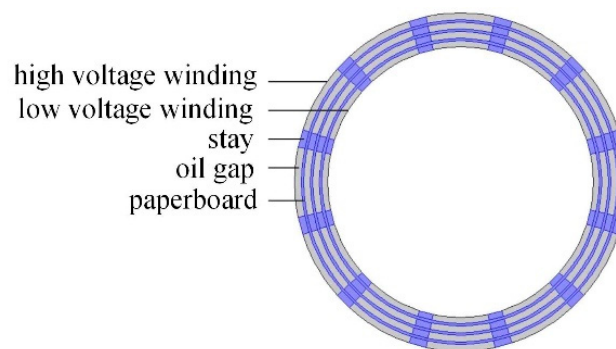


Figure 7. Finite element simulation model of 10 kV transformer.

Using the points at each resonance peak in the winding amplitude–frequency response curve with an insulation DP value of 1256 and moisture content of 0.4% as the reference frequencies, the capacitance change rate at each resonance peak frequency point, in both connection modes, could be determined, and the capacitance change rate at different resonance peak frequency points could be averaged. The results are presented in Table 5. Due to the difference in the two connection modes, the positions of the resonance peaks were also different. Therefore, there were some differences in the average values of ΔC_{FDS} between the two connection modes.

Table 5. Capacitance change rates under different insulation aging degrees and moisture contents.

Influence Factor		Connection Mode A		Connection Mode B	
		ΔC_{FRA}	ΔC_{FDS}	ΔC_{FRA}	ΔC_{FDS}
DP value	1078	0.56	1.27	0.50	1.26
	957	1.85	4.30	1.77	4.29
	893	1.96	4.55	1.87	4.54
	857	2.22	5.13	2.03	5.11
moisture content	1.1%	1.33	2.68	1.13	2.68
	1.7%	1.43	3.29	1.43	3.30
	2.5%	1.51	3.47	1.48	3.48

The capacitance change rate in the different connection modes was compared, as shown in Figures 8 and 9. As can be seen, the capacitance change rate (ΔC_{FRA}) calculated by the frequency response of the transformer was smaller than the capacitance change rate (ΔC_{FDS}) calculated by the

frequency domain dielectric spectrum at the same reference resonance frequency. This is because the capacitance of the main insulation measured by frequency domain spectrum (FDS) was only a part of the capacitance in the frequency response model of transformer, and the change of transformer insulation state mainly affected the capacitance of the main insulation. Essentially, the capacitance of other parts did not change like the main insulation, which was reflected in the overall frequency response of transformer in that the overall capacitance change rate was less than that of the main insulation part. In addition, ΔC_{FRA} and ΔC_{FDS} increased significantly as the degree of aging increased and increased slightly as the moisture content increased. It can be seen from these figures that the difference in capacitance change rate between the a and b connection modes was very small.

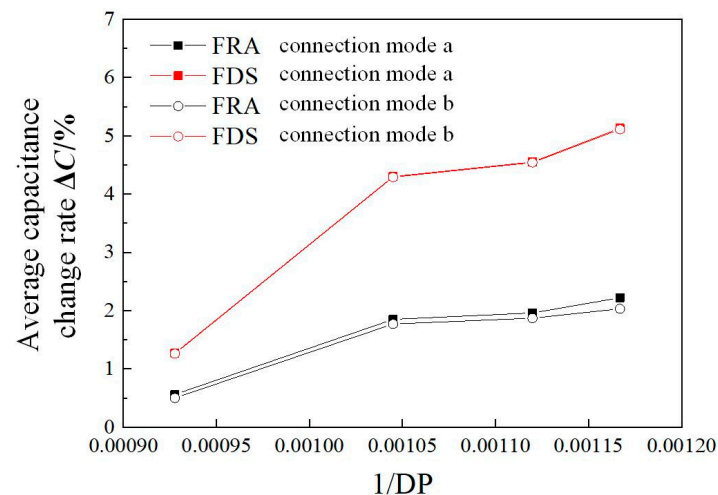


Figure 8. Capacitance change rate obtained by FRA and FDS with different degrees of aging.

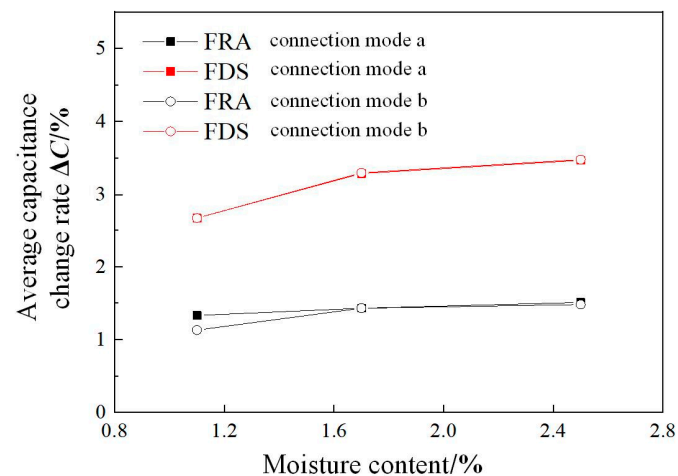


Figure 9. Capacitance change rate obtained by FRA and FDS with different moisture contents.

The ΔC_{FRA} and ΔC_{FDS} with different degrees of aging, moisture content, and different connection modes were plotted in the same figure, and the relationship between ΔC_{FRA} and ΔC_{FDS} was fit based on the method of least squares. The result is shown in Figure 10, where the correlation coefficient reaches 0.991, indicating that there was a significant correlation between ΔC_{FRA} and ΔC_{FDS} , which was independent of the connection mode. In the figure, A is the slope of the fitted straight line and the constant related to the transformer structure, and $A = 0.425$.

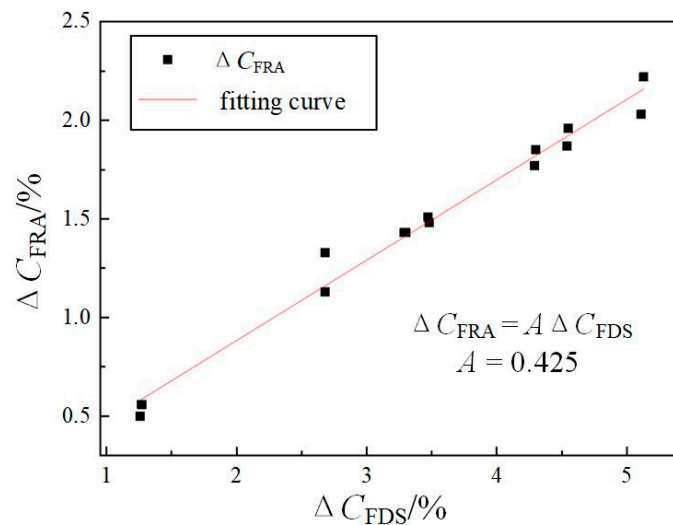


Figure 10. Relationship between the capacitance change rates based on FRA and FDS.

It can be seen from the above analysis that the average values of ΔC_{FRA} and ΔC_{FDS} satisfied an approximately linear relationship; that is, when ΔC_{FDS} changed by a given amount, ΔC_{FRA} also changed, within a particular range. If the change in ΔC_{FRA} exceeded a certain amount, it indicated that in addition to the state of the main insulation, the winding state had also changed. Therefore, in this section, the addition of an auxiliary criterion, based on the correlation coefficient R criterion, was considered to help curtail the influence of the state change of the insulation in diagnosing winding faults. When performing the transformer winding fault test, the following conditions should be met: (1) the value of the correlation coefficient R conforms to the assessment range corresponding to the winding deformation, (2) the auxiliary criterion is established, at which point it can be confirmed that the winding is indeed deformed. The auxiliary criterion is presented in Formula (7).

$$\Delta C_{FRA} > A \Delta C_{FDS} \quad (7)$$

Notably, when ΔC_{FRA} does not satisfy Formula (7), it does not mean that a winding deformation does not exist. The auxiliary criterion is proposed simply to reduce the likelihood of misdiagnosing winding deformations due to insulation aging or moisture.

5.2. Validity Verification of the Criterion Optimization Based on Capacitance Change Rate

In this section, using connection mode a as an example, the frequency response curves of high-voltage windings, with three DP for the insulation of 1078 with normal winding, 1078 with a local short circuit of high-voltage winding, and 857 with normal winding, were simulated and the results are shown in Figure 11. As seen, the amplitude-frequency response curve of the high-voltage winding, after the local short circuit, was clearly different than that of the normal winding. Additionally, this change was more pronounced in the high-frequency region, while there was no clear absence or increase of extreme points. Using the amplitude-frequency response curve of the insulation paperboard DP = 1078, with normal high-voltage winding as the reference curve, two types of capacitance change rates, ΔC_{FRA} and ΔC_{FDS} , when the high-voltage winding was locally short-circuited, were obtained when DP = 1078 and DP = 857, as shown in Table 6.

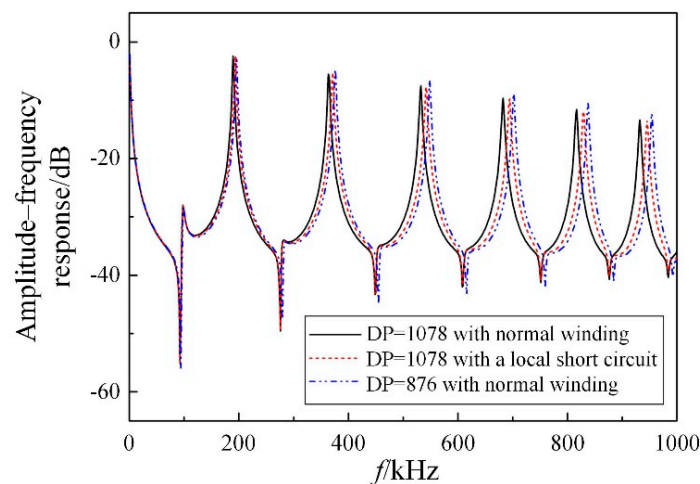


Figure 11. Relationship between the capacitance change rates based on FRA and FDS.

Table 6. Capacitance change rates under different insulation aging degrees and moisture contents.

Test Method	DP Value of Insulating Paperboard	Winding Condition	Average Value of $\Delta C/\%$
FRA	1078	locally short-circuited	1.28
	857	normal	1.89
FDS	1078	locally short-circuited	0
	857	normal	5.13

According to the data presented in Table 6, when the insulation paperboard DP = 1078 with the high voltage winding was locally short-circuited, $\Delta C_{FRA} = 1.28\%$ and $\Delta C_{FDS} = 0$, which satisfies the auxiliary criterion in Formula (7). When the insulation paperboard DP = 857 with the normal high-voltage winding, $\Delta C_{FRA} = 1.89\%$, indicating that the frequency response curve slightly deviated from the reference curve; however, $\Delta C_{FDS} = 5.13\%$, indicating that the main insulation capacitance changed significantly. At this time, $\Delta C_{FRA} = 0.368\Delta C_{FDS}$, which did not meet the auxiliary criterion in Formula (7). Therefore, according to the optimized criterion, the winding was not deformed, which is consistent with the actual situation. The above results verify that the criterion optimization method based on the comparison of the capacitance change rate can avoid misdiagnosing winding deformations due to insulation aging and moisture.

6. Conclusions

The aging of oil-paper insulation or changes in the moisture content can lead to errors when diagnosing the transformer winding faults. To address this issue, the frequency response of transformer windings with insulation aging and moisture was simulated and analyzed. According to the correlation coefficient R criterion, two criteria optimization methods based on the comparison of capacitance change rates were proposed, and the effectiveness of the methods was verified. The main conclusions of this study are as follows:

- The overall aging and moisture of the transformer's main insulation affects the winding frequency response, and errors may occur when diagnosing the winding deformations according to the correlation coefficient R criterion. The more significant the aging or moisture, the greater the possibility of misdiagnosis. The local moisture of the insulation has little effect on the frequency response of the winding as a whole.
- When the oil-paper insulation state changes, the average value of the capacitance change rate ΔC_{FRA} that is based on the transformer frequency response method is always smaller than the

average value of capacitance change rate ΔC_{FDS} that is based on the frequency domain dielectric spectrum of the transformer's main insulation. The average values of ΔC_{FRA} and ΔC_{FDS} satisfy a linear relationship, which is not significantly affected by the particular connection mode.

- (c) Based on the correlation coefficient R criterion, the auxiliary criterion $\Delta C_{FRA} > A\Delta C_{FDS}$ can be added to suppress the influence of the change of state of the insulation on the winding fault diagnosis results and achieve the optimization of the winding deformation criterion.

Notably, the proposed criterion optimization method is basically not affected by the particular connection mode, but the value of the coefficient A in the auxiliary criterion still depends on the transformer voltage grade and structure. In addition, when the auxiliary criterion is not satisfied, it does not mean that a winding deformation does not exist. The two methods proposed here aim to develop techniques to avoid misdiagnosing winding deformations due to insulation aging and moisture and provide a reference for the improvement and optimization of diagnostic standards for winding deformations.

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Appendix A. Main Parameters of a 10 kV Three-Phase Two-Winding Transformer

Table A1. Main parameters of a 10 kV three-phase two-winding transformer.

Transformer Parameter Name		Parameter Value
Rated power		50 kVA
High voltage winding	Rated voltage	10 kV
	Winding type	Continuous winding
	Total turns	490
Low voltage winding	Rated voltage	380 V
	Winding type	Spiral winding
	Total turns	18
Main insulation	Total thickness of paper tube	7 mm
	Total thickness of oil passage	36 mm
	Number of stay	8
Connection mode		Y, y_n0
Height		696 mm

Appendix B. Calculation Method of Lumped Parameters in the Finite Element Simulation Model of Transformer

In the equivalent circuit model of single-phase transformer shown in Figure 3, the parameters other than the winding inductance and resistance parameters, L_1 , R_1 , L_2 , R_2 and M , need to be calculated according to the dielectric parameters of the oil-paper insulation materials. The lumped parameters in Figure 3 are calculated according to the structural dimensions of the transformer in Table A1 and the dielectric parameters of oil-paper insulation materials. The specific methods are as follows:

1. Calculation of C_{10} , G_{10} , C_{20} , G_{20}

The multi-physical field analysis software COMSOL MultiphysicsTM is used to model the transformer structure to obtain the relevant parameters. Here, the transformer shell is considered as a

cuboid, and the finite element simulation model is constructed by taking the height of a unit on the radial plane of the winding, as shown in Figure A1. Using the model, the vacuum capacitance C_0 between the high voltage winding and the transformer wall can be determined, then C_{10} and G_{10} can be obtained using Formulas (A1) and (A2).

$$C_{10} = \varepsilon' C_0 \quad (\text{A1})$$

$$C_{10} = \omega \varepsilon'' C_0 \quad (\text{A2})$$

Because the insulation oil is mainly used between the high voltage winding and the transformer wall, both ε' and ε'' in these formulas take on the values from the data of insulating oil, and the results are presented in Section 3.2. C_{20} and G_{20} can be obtained by an analogous process.

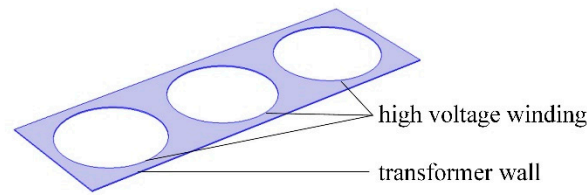


Figure A1. Finite element simulation model of a unit height part of a transformer.

2. Calculation of C_{12} , G_{12}

First, the vacuum capacitance between the high and low voltage windings is calculated, and then the relative complex dielectric constant of the main insulation is calculated. Accounting for the cylindrical structure of the high and low voltage windings, the vacuum capacitance C_0 between the high and low voltage windings can be expressed as in Formula (A3).

$$C_0 = \frac{2\pi\varepsilon_0 h_0}{\ln(r_1/r_2)} \quad (\text{A3})$$

where ε_0 is the vacuum dielectric constant, which is 8.85×10^{-12} F/m; h_0 is the height of a unit in the transformer simulation model/m; r_1 is the inner diameter of the high voltage winding/m; and r_2 is the outer diameter of the low voltage winding/m.

The relative complex dielectric constant of the main insulation section can be determined using the XY model expression in Formula (A4). The dielectric parameters of oil-immersed paperboard and the insulating oil are given as the test results in Section 3.

$$\varepsilon^* = \frac{Y}{\frac{1-X}{\varepsilon_{\text{spacer}}^*} + \frac{X}{\varepsilon_{\text{paper}}^*}} + \frac{1-Y}{\frac{1-X}{\varepsilon_{\text{oil}}^*} + \frac{X}{\varepsilon_{\text{spacer}}^*}} \quad (\text{A4})$$

Here, X is the ratio of the total thickness of paper tube to the main insulation thickness of the transformer; Y is the ratio of the total width of the stay to the average circumference of the main insulation of the transformer; $\varepsilon_{\text{oil}}^*$ is the relative complex dielectric constant of the insulating oil; $\varepsilon_{\text{paper}}^*$ is the relative complex dielectric constant of the paperboard; and $\varepsilon_{\text{spacer}}^*$ is the relative complex dielectric constant of the stay.

3. Calculation of C_{S1} , G_{S1} , C_{S2} , G_{S2}

The longitudinal capacitance of a continuous winding is composed of the interturn capacitance C_t and inter-cake capacitance C_d . The interturn capacitance C_t can be determined using Formula (A5).

$$C_t = \frac{2\pi\varepsilon_0\varepsilon_i r h_0}{d} \quad (\text{A5})$$

where ε_i is the relative dielectric constant of the winding varnish; r is the average radius of the high voltage winding/m; d is the distance between two adjacent high voltage windings/m.

The inter-cake capacitance C_d can be determined using Formula (A6).

$$C_d = \frac{\pi \varepsilon_0 \varepsilon'_{oil} (r_0^2 - r_1^2)}{\tau_{ks}} \quad (A6)$$

where ε'_{oil} is the real part of the relative complex dielectric constant of the insulating oil; r_0 is the outer diameter of the high voltage winding/m; τ_{ks} is the distance between two adjacent high voltage windings/m.

The relationship between the longitudinal capacitance C_{S1} and interturn capacitance C_t and inter-cake capacitance C_d can be expressed as in Formula (A7).

$$C_s = \frac{n}{6} C_d + \frac{n-2}{n^2} C_t \quad (A7)$$

where n is the number of turns in a cake of high voltage winding.

G_{S1} can be calculated according to the relationship between Formulas (A1) and (A2).

The spiral winding can be regarded as a continuous winding with 1 turn, C_{S2} and G_{S2} can be obtained by an analogous process.

4. Calculation of L_1, R_1, L_2, R_2

A single-cake high voltage winding can be regarded as a thin cylindrical coil whose coil width is much smaller than the inner diameter of the coil, and its self-inductance can be approximated by Formula (A8).

$$L_1 = \mu_0 n^2 r_1 \left[\ln \left(\frac{8}{h_0/r_1} \right) - \frac{1}{2} + 0.0182 \left(\frac{h_0}{r_1} \right)^{1.64} \right] \quad (A8)$$

where μ_0 is the vacuum permeability, which is $4\pi \times 10^{-7}$ H/m.

The equivalent resistance of a cake of high voltage winding at different frequencies can be expressed using Formula (A9).

$$R_1 = \alpha l \left(\frac{1}{\sigma w h} + \frac{1}{2(w+h)} \sqrt{\frac{\mu_0 \pi f}{\sigma}} \right) \quad (A9)$$

where α is the correction factor; l is the equivalent length of a single-cake high voltage winding/m; σ is the conductivity of the winding/S·m⁻¹; w and h are the width and height of the winding cross s/m; f is the frequency of applied excitation/Hz.

In Formula (A9), the first term is the DC resistance of the winding, the second term considers the high-frequency skin effect of the conductor, and α is the correction factor considering the proximity effect, where the value is generally greater than 1.

L_2 and R_2 can be obtained by an analogous process.

5. Calculation of M

The single-cake high voltage winding has mutual inductance with other high voltage windings, as well as with low voltage windings. Here, COMSOL Multiphysics™ is used to carry out two-dimensional axisymmetric modeling according to the actual position of the windings to calculate the mutual inductance between the windings. After the mutual inductance M is determined, the value of the inductance when establishing the equivalent circuit model of transformer is shown in Formula (A10).

$$L = L_s + M \quad (A10)$$

where L_s is the winding self-inductance/H, namely L_1 and L_2 in the above text.

Appendix C. Dielectric Parameter Test of Oil Paper Insulation Material

According to the IEC60641-2 test standards for oil-paper insulation materials, the samples of insulation paperboard with moisture content of 0.4%, 1.1%, 1.7% and 2.5% and polymerization degree of 1256, 1078, 957, 893 and 857 were prepared in this paper, and the dielectric parameters of the samples in the range of 1 kHz-1 MHz were measured by a concept40 broadband dielectric response tester. The results are shown in Figure A2.

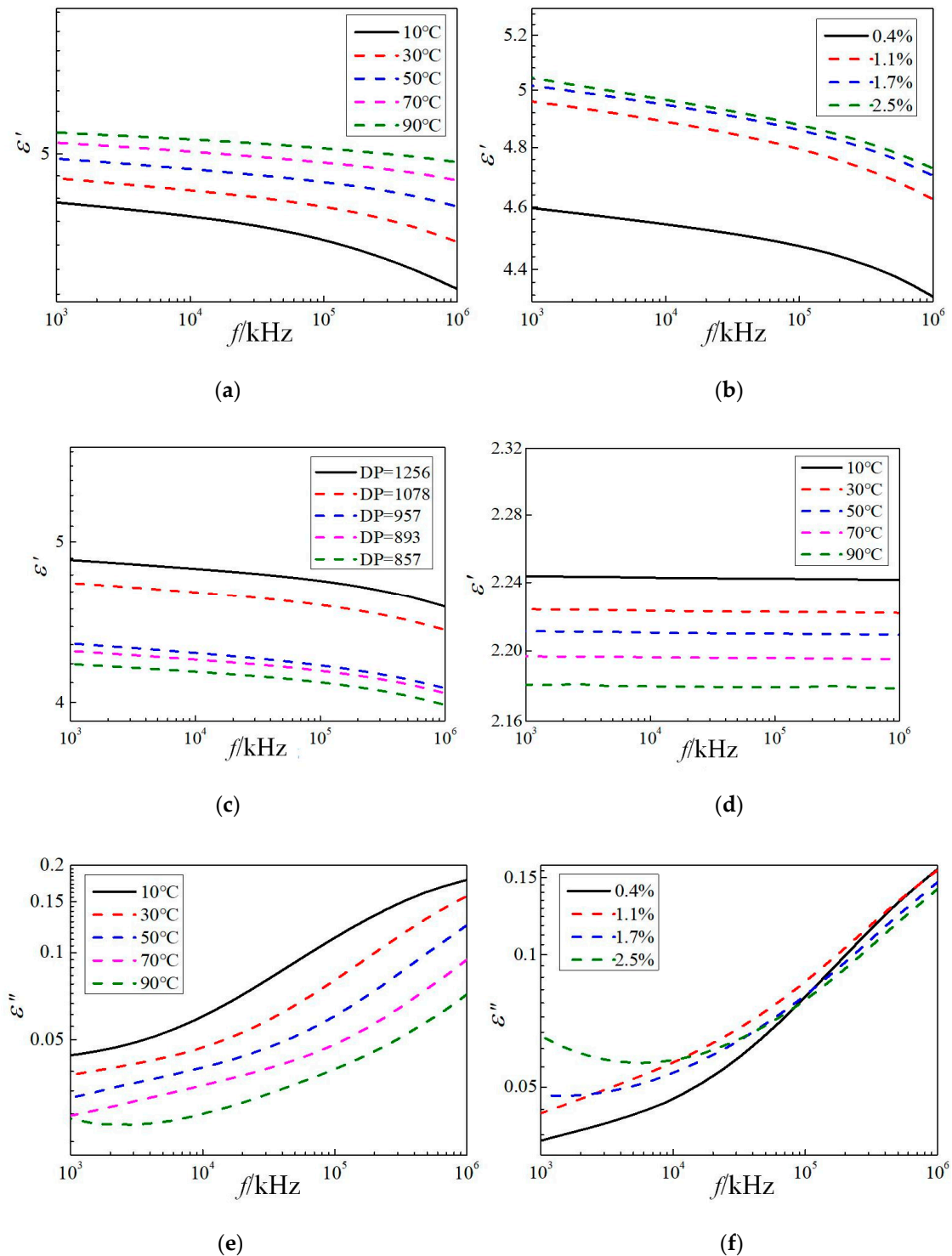


Figure A2. Cont.

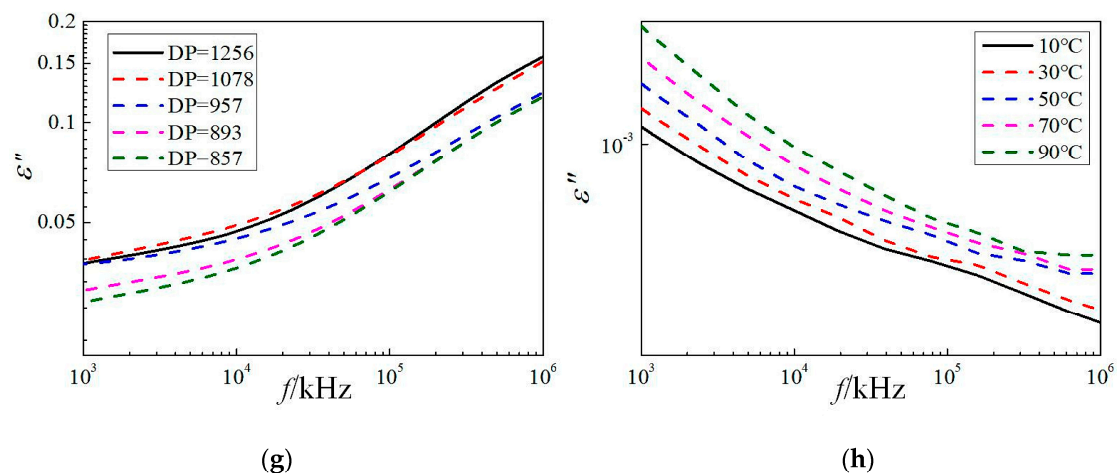


Figure A2. Dielectric properties results from oil-impregnated paperboard and insulating oil. (a) Real part of dielectric constant of oil-immersed paperboard at different temperatures; (b) real part of dielectric constant of oil-immersed paperboard with different moisture contents; (c) real part of dielectric constant of oil-immersed paperboard with different aging degrees; (d) real part of dielectric constant of insulating oil at different temperatures; (e) imaginary part of dielectric constant of oil-immersed paperboard at different temperatures; (f) imaginary part of dielectric constant of oil-immersed paperboard with different moisture contents; (g) imaginary part of dielectric constant of oil-immersed paperboard with different aging degrees; (h) imaginary part of dielectric constant of insulating oil at different temperatures.

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