

Article

Evaluation Method for Winding Performance of Distribution Transformer

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Abstract: In order to ensure the safe and stable operation of a power system, the performance evaluation of transformer windings after a short-circuit test can predict whether the windings are deformed in order to provide a useful reference for the operation and maintenance of the power sector. This paper proposes a method for evaluating the performance of transformer windings in order to improve the overall effectiveness of a winding evaluation. The index data obtained based on a short-circuit impedance method, frequency response method, and oscillation wave method are used in the algorithm proposed in this paper. First, the transformer winding performance evaluation index system is constructed. Second, the weight of each index is determined by analytic hierarchy process, and then the fuzzy comprehensive assessment method is introduced, and the fuzzy evaluation matrix is established, the evaluation results are calculated using the evaluation formula. Finally, the maximum membership principle is used to determine the performance level of the transformer winding on the evaluation results, and the evaluation results of the transformer winding state are obtained. The example shows that the evaluation level of the measured transformer winding performance can be obtained by this method as “good”. Compared with the traditional method, this method can simplify the evaluation while maintaining higher accuracy.

Keywords: short-circuit test; transformer winding; performance; evaluation; analytic hierarchy process; fuzzy evaluation method



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1. Introduction

A distribution transformer is one of the most core equipment in a distribution network; its main function is to transfer power and convert voltage [1] throughout the entire distribution network. Its performance affects the safe and stable operation of the distribution network [2,3]. According to the statistical data of the National Bureau of Statistics, the annual output of distribution transformers in China has maintained a growth rate of about 8% in the past five years; the number of distribution transformers is increasing. With the increase of distribution network scale and equipment capacity year by year, the operation problem of distribution transformers is increasingly prominent. The failure rate of the sampling distribution transformer short-circuit test in the South China Grid from 2012 to 2018 is 43.73%, which will not only cause significant economic losses, but also affect the stable operation of power. Therefore, it is urgent to develop several transformer condition monitoring systems and fault diagnosis techniques to identify the critical degree of transformer health and its remaining life [4].

At present, the transformer evaluation after short-circuit test needs a hanging inspection, and the hanging inspection will consume huge manpower and material resources [5]. There is no unified standard for a winding quality evaluation after transformer short-circuit test, according to the national standard GB1094.5-2008: Transformers can withstand external short-circuit thermal and dynamic stability without damage. However, no quantitative

standard threshold judgment is given for the definition of non-damage [6,7]. Therefore, evaluation of the integrity of the transformer windings after a short-circuit test has gradually attracted people's attention [8].

Domestic and foreign scholars have performed considerable research on transformer winding fault diagnosis. In 1966, Poles proposed the low voltage pulse method [9], by comparing the waveform of the input signal and the output signal, it can detect whether the transformer passes the short-circuit test. However, this method is vulnerable to interference and has weak repeatability; the short-circuit impedance method [10] is used to determine whether winding deformation occurs by measuring the short-circuit impedance value of the transformer. This method is simple and easy to operate and has been included in the standard. But the detection sensitivity is low, and it is difficult to detect the slight deformation of the winding. Canadian expert E. P. Dick proposed the frequency response method [11] to determine the winding deformation by measuring the response characteristics of the winding network. It has become an accurate and effective method through numerous significant works [12–17]. This method is sensitive to slight winding deformation but susceptible to uncertainties. Since then, many other scholars [18,19] have conducted extensive work in this field. The vibration analysis method [20,21] uses the vibration sensor attached to the tank to obtain vibration characteristics to determine whether the winding is deformed. However, for high-power transformers, Saponara et al. [22] used a distributed measurement node network of the system to diagnose mechanical stress based on vibration. Wu zhenyu, a Chinese scholar, proposed the oscillation wave method [23] to realize the performance evaluation of transformer winding without sling by establishing the corresponding relationship between the oscillation wave index and the internal parameters of the system [24–27]. This method has a strong anti-interference ability and good repeatability, but it is difficult to detect slight deformations.

Different methods have different response and sensitivity to winding faults, such as slight deformation, moderate deformation, heavy deformation, short-circuit, and broken circuit. Based on this, the winding evaluation methods are: short-circuit impedance method [10], frequency response method [11], and oscillation wave method [23]. In this paper, the short-circuit impedance method, frequency response method and oscillation wave method are used to evaluate transformer winding. To evaluate the performance of distribution transformer winding after a short-circuit test, and in-depth study of the mechanism of this methods and finding the appropriate indicators will be performed.

In summary, in order to more accurately, reliably and effectively evaluate the performance of transformer winding, ensure the quality of transformer products, and maintain the safe and stable operation of distribution network, research on the winding performance evaluation method of distribution transformer based on short-circuit test is of great significance.

2. Methods and Experiment

2.1. Theoretical Basis of Evaluation Method

2.1.1. Measurement Principle of Transfer Function Method

When the transformer passes the short-circuit test, the performance evaluation of the transformer winding must be conducted. At this time, the transfer function method plays an important role [28]. The degree and type of transformer winding faults can be classified by extracting the corresponding parameters in transfer function [29]. At high frequency, the magnetic resistance of transformer iron core is almost equal to that of air. At this moment, RLC of transformer winding itself constitutes a two-port network, and the transfer function $H(jw)$ is expressed as the transfer characteristics of the two-port network. When the transformer winding state changes, the RLC parameters in the transformer system are affected, and the transfer function is also changed. Thus, as long as the difference of transfer function before and after short-circuit test is compared, the internal situation of transformer can be understood, to realize the performance evaluation of transformer winding.

Two-port network means a network with a pair of input ports and a pair of output ports [30], as shown in Figure 1, satisfying:

$$I_1 = I'_1, I_2 = I'_2 \quad (1)$$

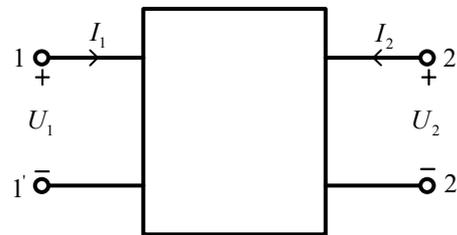


Figure 1. Current–voltage relationship of linear two-port.

I_1 and I'_1 are the currents at port 1 – 1', the same as I_2 .

If there is no power inside the network, and only RLC is included; the network is a passive linear two-port network.

When using a two-port network to analyze a circuit, after determining the parameters that characterize the two ports (such as voltage and current), these parameters can be used to compare the performance of different two ports in transmitting electrical energy and signals, to evaluate their quality.

2.1.2. Transformer Equivalent Circuit Model

When the transformer winding is excited by a high-frequency voltage signal with a frequency greater than 2 kHz, the permeability of the inner core of the transformer is almost the same as that of the air medium, and the role of the core can be ignored at this time. Therefore, the entire winding of the transformer can be seen as a distributed parameter network composed of resistance, inductance and capacitance [31,32]. Figure 2 shows the equivalent circuit diagram of the n -level distributed parameter network studied in this paper. In Figure 2, L_n and R_n represent winding inductance and resistance respectively, $n = 1, 2, 3 \dots$, C_{sn} and R_{sn} represent intercake or interturn capacitance and conductance, respectively, C_{gn} and R_{gn} represent earth capacitance and conductance of winding, respectively. The physical structure and insulation materials of the transformer determine the RLC parameters in the equivalent circuit. When the transformer winding is deformed or short-circuited, the value of RLC will change, such that the transfer function will also change.

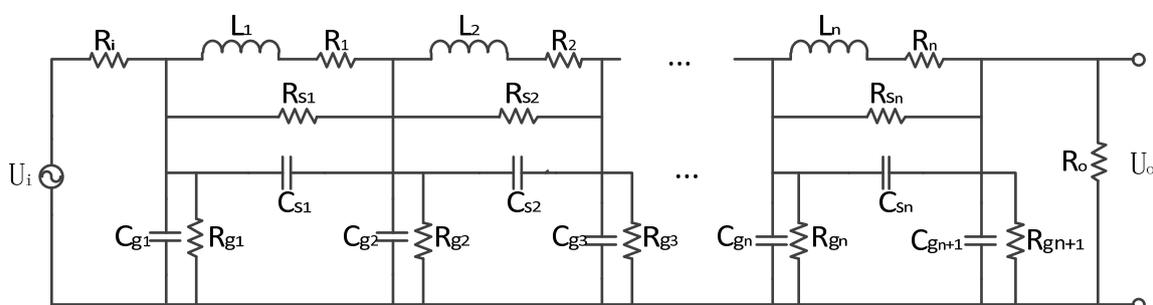


Figure 2. Simplified equivalent model of winding.

2.1.3. The Calculation of Circuit Parameters in the Model

The key to the model parameter calculation of a power transformer is the distribution parameter calculation at high frequency [33]. To analyze the specific calculation process of

the dielectric constant, distributed capacitance and distributed inductance parameters in the simplified equivalent model of transformer windings, we can use simulation software to build a distributed parameter network and perform circuit simulation on transformer windings. By changing the parameters of the equivalent circuit of the windings, we can simulate the transformer windings with different degrees of deformation and different types of faults, in order to evaluate the windings.

1. Calculation of dielectric constant.

The insulation medium of transformer capacitance between cakes is mainly the insulation of different potential parts of the same winding; thus, the equivalent dielectric constant calculation of capacitance between cakes:

$$\varepsilon_{de} = \frac{a_d}{\frac{a_0}{\varepsilon_{0e}} + \frac{a_p}{\varepsilon_p}} \quad (2)$$

In the form: a_d is the insulation thickness between cakes; a_0 is the width of the oil channel; a_p is the thickness of wire cake insulating paper; ε_{0e} is the equivalent dielectric constant; ε_p is the dielectric constant of insulating paper.

The equivalent dielectric constant ε_{we} of the main insulation gap between windings can be calculated according to the following formula:

$$\varepsilon_{we} = \frac{a_w}{d_w \left[\frac{a_p}{\varepsilon_p d_p} + \frac{a_0}{\varepsilon_{0e} d_0} + \frac{a_{pb}}{\varepsilon_{pb} d_{pb}} + \dots \right]} \quad (3)$$

In the form: a_w is the main insulation distance between windings; d_w is the average diameter of the main channel between windings; a_{pd} is the thickness of each panel between windings; d_p is the balanced diameter of the innermost layer of the outer winding and the outermost conductor turn insulation of the inner winding; ε_{pd} is the oil gap dielectric constant between two windings; d_0 is the average diameter of each oil gap between windings; d_{pd} is the average diameter of each panel between windings.

2. Calculation of distributed capacitance.

Because the winding and the iron core are similar to the arrangement of coaxial cylinder, the capacitance C_{gw} between the innermost winding and the iron core is [34]:

$$C_{gw} = \frac{\varepsilon_0 \pi D_m H}{\left(\frac{t_{oil}}{\varepsilon_{oil}} + \frac{t_{solid}}{\varepsilon_{solid}} \right)} \quad (4)$$

In the form: D_m is the average diameter between two windings; t_{oil} is the thickness of oil between two windings; t_{solid} is the thickness of solid insulation between two windings; H is the average height of winding.

The capacitance between cylindrical conductor and ground is:

$$C = \frac{2\pi\varepsilon H}{\cosh^{-1}\left(\frac{s}{R}\right)} \quad (5)$$

In the form: R is the radius of cylindrical conductor; s is the distance from the center of the cylindrical conductor to the ground plane.

Therefore, the capacitance between the outermost winding and the fuel tank is:

$$C_{gt} = \frac{2\pi\varepsilon_0 H}{\cosh^{-1}\left(\frac{s}{R}\right)} \times \frac{t_{oil} + t_{solid}}{\left(\frac{t_{oil}}{\varepsilon_{oil}}\right) + \left(\frac{t_{solid}}{\varepsilon_{solid}}\right)} \quad (6)$$

In the transformer, the distance between two turns and two cakes can be regarded as the calculation of parallel plate capacitor. Turn-to-turn capacitance is:

$$C_T = \frac{\varepsilon_0 \varepsilon_p \times \pi D_m (w + t_p)}{t_p} \quad (7)$$

In the form: ε_0 is the dielectric constant of vacuum; ε_p is the relative dielectric constant of paper insulation; D_m is the average diameter of winding; w is the axial bare width; t_p is the total thickness of paper insulation.

Similarly, only considering the structure, the total capacitance between the two axial continuous cakes is [35]:

$$C_{DA} = \frac{\varepsilon_0 k \pi D_m (R + t_s)}{\frac{t_p}{\varepsilon_p} + \frac{t_s}{\varepsilon_{oil}}} + \frac{\varepsilon_0 (1 - k) \pi D_m (R + t_s)}{\frac{t_p}{\varepsilon_p} + \frac{t_s}{\varepsilon_s}} \quad (8)$$

3. Calculation of distributed inductance.

When the frequency is high, the iron core of the transformer plays a smaller role, and the winding plays a larger role. Since the transformer winding can be regarded as a planar coil, the formula of the inductance is:

$$L_0 = \frac{\mu_0}{8\pi} d \Psi w^2 \quad (9)$$

In the form: d is the average diameter of the coil; w is the number of turns between two adjacent line cakes; μ_0 is the vacuum permeability; Ψ is the correlation function.

2.2. Analysis of Evaluation Methods

A transformer winding needs to be tested after short-circuit test to evaluate its quality. The evaluation results can divide the transformer quality into two levels: qualified and unqualified. The qualified degree is subdivided into excellent, good and medium, and the unqualified degree is subdivided into poor, worse and very bad, as shown in Table 1.

Table 1. Transformer quality and its definition.

Qualification of Transformer	Level	Definition
Qualification	excellent	Transformer after short-circuit test, using various methods for transfer function comparison, no change, no insulation damage, a variety of excellent performance.
	good	After the short-circuit test of the transformer, various methods are used to compare the transfer function, which basically does not change and has good performance.
	medium	After the short-circuit test of the transformer, the transfer function is compared by various methods. There is slight change and slight deformation of the winding, but it does not affect the performance of the transformer.
Disqualification	poor	Transformer insulation damage and winding deformation
	worse	Serious damage to insulation, winding damage, winding deformation.
	very bad	Winding breakup of transformer.

For the quality of the transformer, the relationship between the three methods and the quality of the transformer can be established to evaluate the performance of the transformer winding.

According to the capacitance formula:

$$C = \frac{\varepsilon S}{4\pi k d} \quad (10)$$

In the form: ε is the relative dielectric constant of the medium; S is the positive area of the bipolar plate; π is the circumference rate, k is the constant of electrostatic force, which is $8.9880 \times 10\text{Nm/C}$; d is the vertical distance between the two plates. According to Formula (10), due to the dielectric constant inside the transformer containing insulation paper, insulation pad and strut, insulation oil and other composite insulation dielectric constant, the dielectric constant is basically unchanged. When the winding deformation occurs, the internal effective area almost does not change; then, the equivalent capacitance is inversely proportional to the distance between the two plates.

The quality index of evaluating transformers can be divided into 6 grades: excellent, good, medium, poor, worse, very bad. When the deformation degree of the transformer winding is 0%, the transformer has no deformation and the quality index is excellent. When the degree of deformation of the winding is 2–5%, the deformation of the transformer is not obvious, and the quality index is medium. When the degree of deformation of the winding is 5–10%, the transformer is slightly deformed and the quality index is poor. When the degree of deformation of the winding is 10–30%, the transformer is deformed and the quality index is worse. When the degree of deformation of the winding is 30% and above, the transformer is severely deformed, and the quality index is very bad. As shown in Table 2:

Table 2. Percentage of winding displacement corresponding to changes of capacitance or inductance parameters and transformer quality.

Quality Index	Excellent	Good	Medium	Poor	Worse	Very Bad
Percentage of winding displacement	0	0–2%	2–5%	5–10%	10–30%	30% and above
Percentage of capacitance change	0	0–1.96%	1.96–4.76%	4.76–9.09%	9.09–23.08%	23.08% and above

2.2.1. Index Analysis of Short-Circuit Impedance Method

Transformers with short-circuit impedance method generally have tap-changer, and the fractional value z of short-circuit impedance is expressed as:

$$z = \frac{Z_k}{Z_{ref}} \times 100\% \quad (11)$$

In the form, Z_k is the short-circuit impedance; Z_{ref} is the reference impedance; the virtual part of X_k is Z_k , which is short-circuit reactance, where Z_{ref} is expressed as:

$$Z_{ref} = \frac{U^2}{S_r} \quad (12)$$

U represents the voltage of Z_k and Z_{ref} windings; S_r is the base value of rated capacity.

For the transformer winding, if one of the windings deforms, the inductance L_k of the phase will change; thus, the values of X_k , Z_k and z will also change. At this time, the deformation of the winding can be speculated by measuring the values of the three parameters.

As shown in Figure 3, the transformer is performing a short-circuit test. According to the short-circuit impedance data of distribution transformer before and after short-circuit test provided by multiple power supply companies, the relationship between impedance change and winding deformation can be obtained, and the test is qualified or not, in order to realize the performance evaluation of transformer winding, as shown in Table 3.



Figure 3. Short-circuit testing transformer.

Table 3. Comparative analysis of short-circuit impedance of distribution transformer before and after short-circuit test.

Rate of Change of Reactance (%)	Deformation Degree	Qualified Test
−8.4	Deformation	Poor
−5	Deformation	Poor
−6.3	Deformation	Poor
33	Serious deformation	Very bad
45	Serious deformation	Very bad
−2	No deformation	Medium
0	No deformation	Excellent
4.5	Slight deformation	Poor
0.42	No deformation	Good
44	Serious deformation	Very bad
71	Serious deformation	Very bad
45	Serious deformation	Very bad
17.7	Serious deformation	Very bad
−0.94	No deformation	Medium
0.92	No deformation	Medium
1.6	Slight deformation	Worse
1.5	Deformation	Worse
−1.1	Slight deformation	Worse
0.36	No deformation	Good
3.6	Slight deformation	Worse
0.36	No deformation	Good
0	No deformation	Excellent
0	No deformation	Excellent
2.3	Slight deformation	Worse
0	No deformation	Excellent
25	Serious deformation	Very bad
−1.1	Slight deformation	Worse

In view of the above deformation, the law between the change rate of transformer short-circuit impedance and the degree of deformation is obtained, as shown in Figure 4.

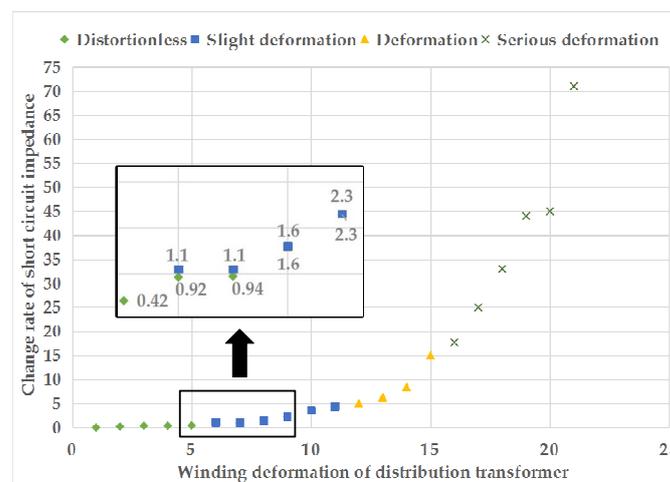


Figure 4. Relationship between short-circuit impedance change rate and deformation degree of transformer winding.

In the short-circuit impedance method, the change rate of short-circuit impedance reflects the winding deformation of distribution transformer. Therefore, the short-circuit impedance method can be used to evaluate the performance of transformer winding in most cases. However, due to the overlapping data of no deformation and slight deformation, it is difficult to determine whether deformation occurs for the overlapping part. According to the Chinese electric power industry standard DL/T1093-2018 and the horizontal comparison method of circuit impedance, this paper obtains the following conclusions, as shown in Table 4.

Table 4. Short-circuit impedance change rate threshold of distribution transformer winding quality.

—	Excellent	Good	Medium	Poor	Worse	Very Bad
Change rate of short-circuit impedance (%)	0	0–0.5	0.5–2.5	1–5	5–15	15 and above

2.2.2. Indicator Analysis of Frequency Response Method

Figure 2 shows the simplified transformer model. It is assumed that the distributed inductance, distributed capacitance and self-resistance of transformer winding are uniformly distributed, $L_1 = L_2 = \dots = L_n$, $R_{s1} = R_{s2} = \dots = R_{sn}$, $C_{s1} = C_{s2} = \dots = C_{sn}$, $C_{g1} = C_{g2} = \dots = C_{gn}$, $R_{g1} = R_{g2} = \dots = R_{gn}$. According to the frequency response method, when the equivalent model of the transformer is selected as N turns, the frequency response characteristics of the transformer winding will appear as $N - 1$ peaks and N valleys. In this paper, if $N = 7$, there will be 6 peaks, 7 valleys showing alternating phenomenon. The transfer function can be calculated by Formula (13):

$$H(f) = 20 \times \lg \left| \frac{V_2(f)}{V_1(f)} \right| \quad (13)$$

V_1 is the input signal and V_2 is the output signal.

When the transformer winding deformation and other abnormalities occur, the internal RLC parameter will change, which makes the peak and valley of the frequency response obtained by the frequency response method change. In *Multisim* simulation, by changing the distribution parameters in the simulation model, we observe the relationship between the parameters and the frequency response, and then compare the FRA results in

normal and fault conditions [36]. Therefore, the frequency variation percentage of the peak valley is used to evaluate the winding performance of the transformer. The formula is:

$$\Delta f = \frac{f_{n2} - f_{n1}}{f_{n1}} \times 100\% \quad (14)$$

Among them: Δf is the peak valley frequency change percentage; f_{n1} is the n resonant frequency of a winding without deformation; f_{n2} is the n resonant frequency of the deformed winding.

1. Influence of inductance parameter variation on frequency response results of transformer.

According to the simulation, the influence data of the frequency response of the transformer when the inductance is broken or short-circuit is extracted and processed, as shown in Figure 5.

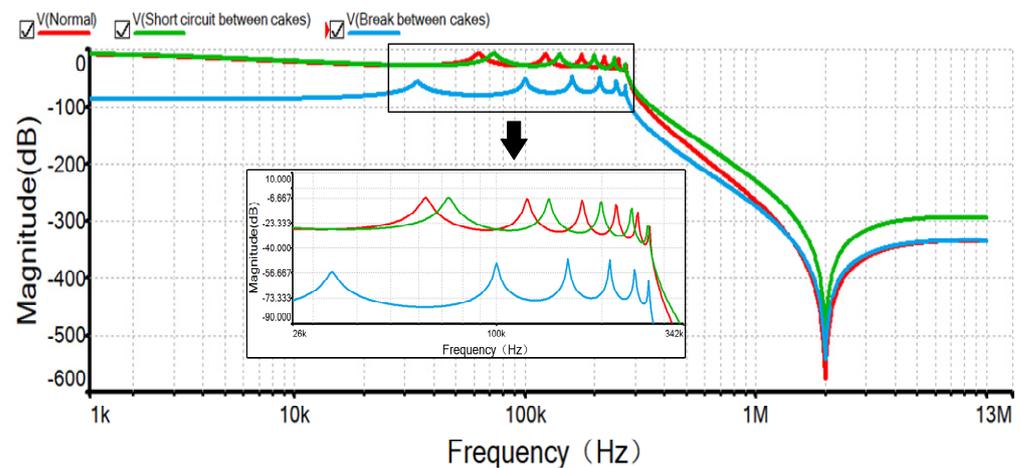


Figure 5. The frequency response of the transformer under the condition of inductance short-circuit breaking.

As shown in the Figure 5, it can be clearly seen that the frequency response in the middle and low frequency is different from that of the normal winding when the transformer is short-circuited and broken. When the first cake inductance is short-circuited in the middle and low frequency bands, the peaks and valleys of the winding are less than those of the normal peak and valley, and the frequency value of the peak is larger than the percentage of the frequency change under the normal frequency. When the first inductance is broken, the frequency relative to the normal value changes to decrease, and the peak value of the whole wave is shifted downward. Therefore, the frequency response method is easy to distinguish between the winding short-circuit and broken.

The influence data of the change of the first cake inductance of the transformer winding from -30% to 30% on the frequency response results of the transformer are extracted and processed, as shown in Figure 6.

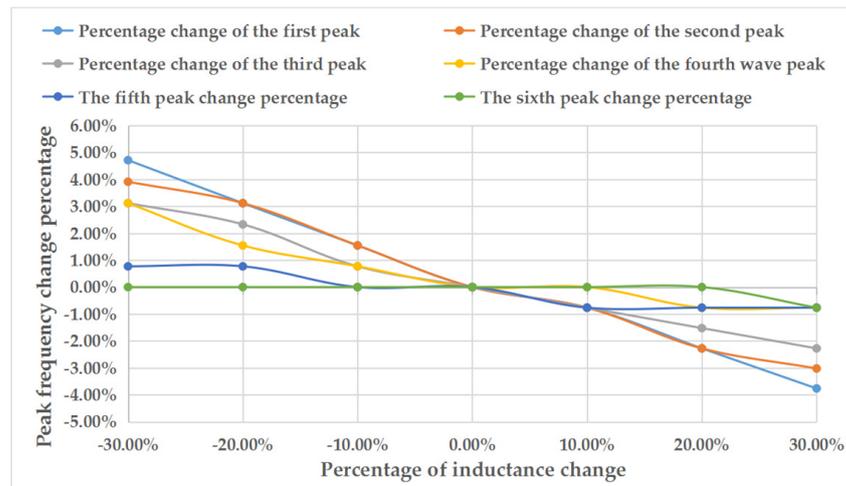


Figure 6. Breakline diagram of peak change of wave with inductance change.

With the increase of inductance parameters, the frequency response of the transformer shows that the frequency of the resonant point peak becomes smaller. Similarly, with the decrease of inductance parameters, the frequency response of the transformer shows that the frequency of the resonant point peak increases.

2. Influence of capacitance parameter variation on frequency response results of the transformer.

The ground capacitance values of the first to seventh turns are changed from -30% to 30% , and the influence of the ground capacitance changes on the transformer peak changes is obtained, as shown in Figure 7:

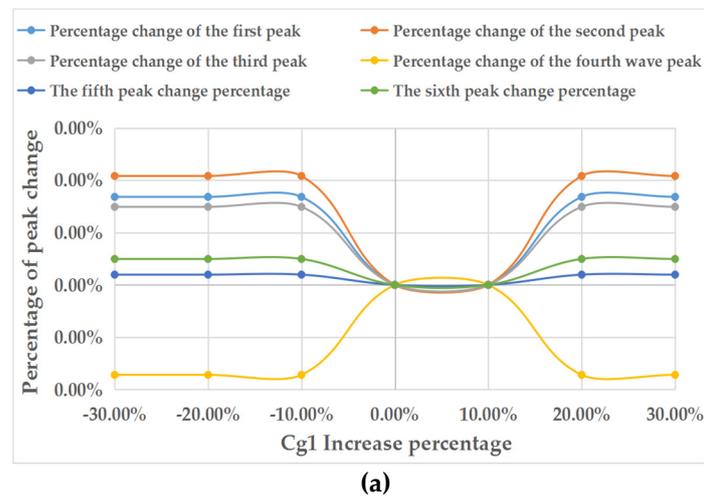
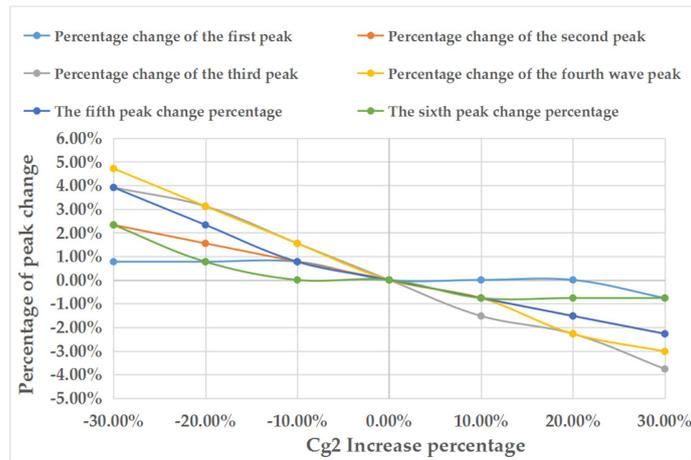
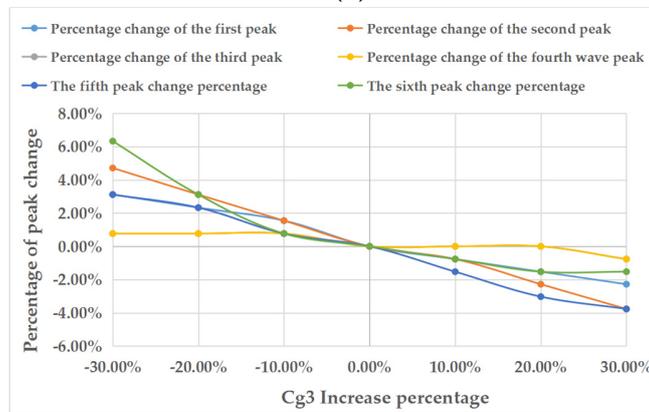


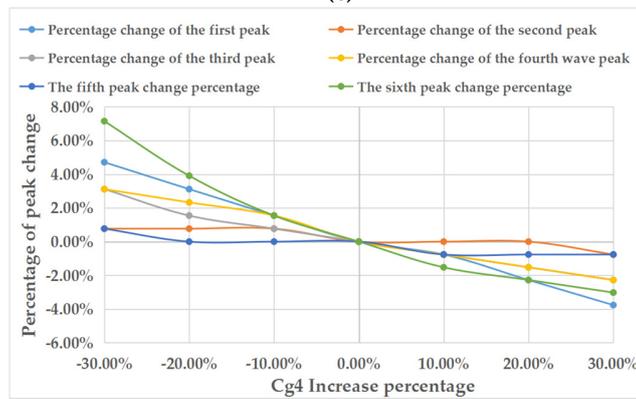
Figure 7. Cont.



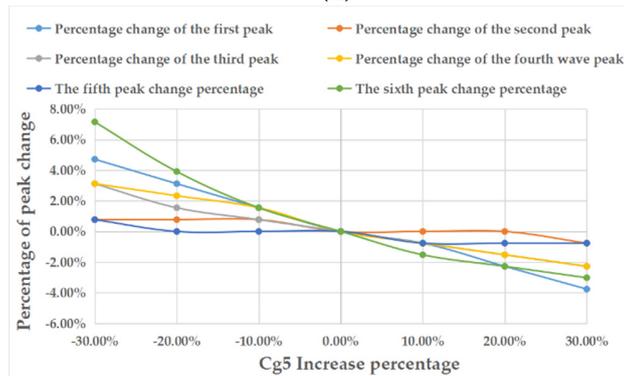
(b)



(c)



(d)



(e)

Figure 7. Cont.

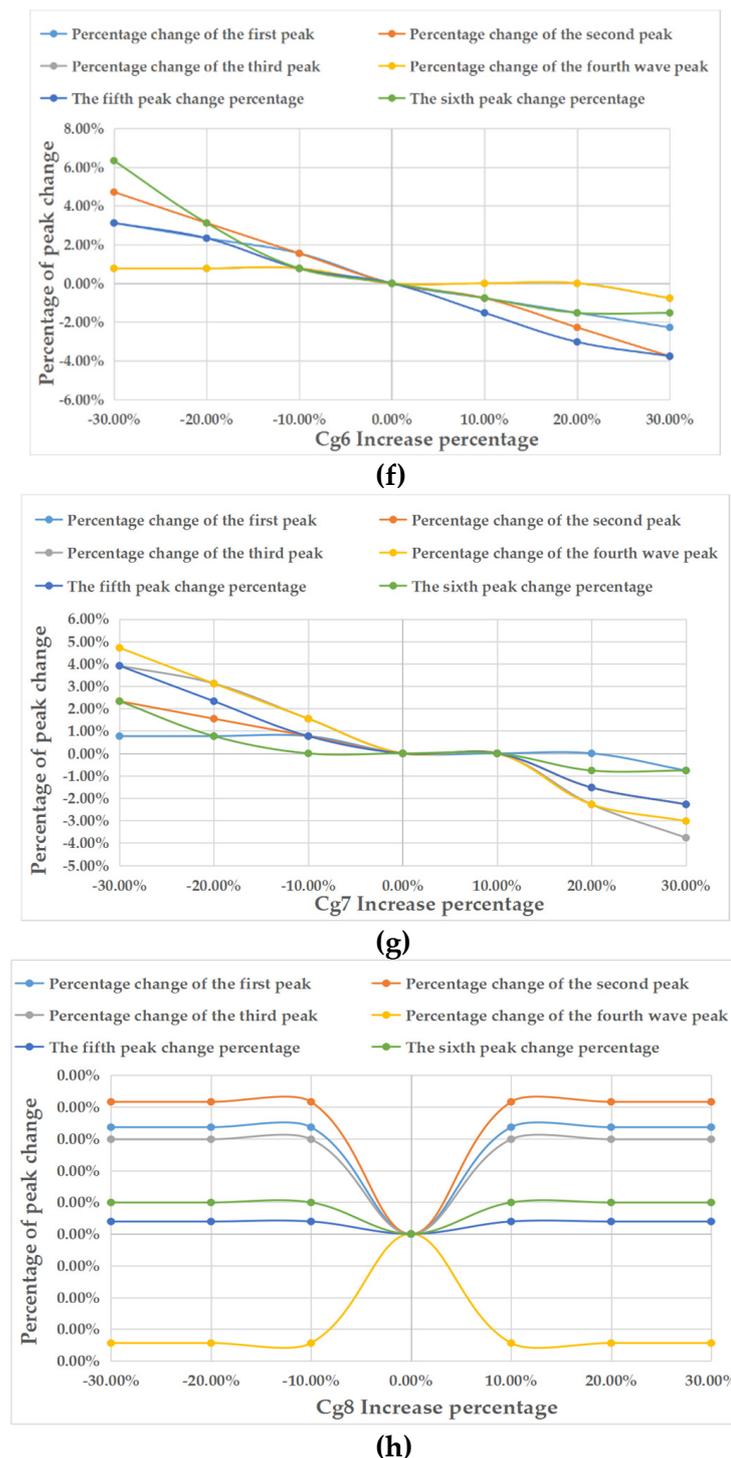


Figure 7. Influence of ground capacitance change on transformer peak frequency change: (a) The influence of Cg1 change on the change of wave peak frequency; (b) The influence of Cg2 change on the change of wave peak frequency; (c) The influence of Cg3 change on the change of wave peak frequency; (d) The influence of Cg4 change on the change of wave peak frequency; (e) The influence of Cg5 change on the change of wave peak frequency; (f) The influence of Cg6 change on the change of wave peak frequency; (g) The influence of Cg7 change on the change of wave peak frequency; (h) The influence of Cg8 change on the change of wave peak frequency.

It can be seen from the figure that when the ground capacitance parameter changes, the law of peak frequency change is a symmetrical relation between the end winding and

the head winding. For the winding wire cake at the head and tail ends, the increase of the ground capacitance is not obvious for the frequency change of the peak. For the middle line cake, when the ground capacitance changes, the change percentage of the peak frequency decreases linearly.

For the internal equivalent model of the transformer, when the parameters of the transformer simulation model change, the frequency response will also change. As shown in Table 5.

Table 5. Frequency response frequency change and test qualification analysis.

Percentage of Parameter Change	Frequency Change Percentage	Quality Index
0	0	Excellent
0–1.96%	0–0.27%	Good
1.96–4.76%	0.27–0.65%	Medium
4.76–9.09%	0.65–1.25%	Poor
9.09–23.08%	1.25–3.18%	Worse
23.08% and above	3.18%	Very bad

2.2.3. Indicator Analysis of Oscillation Wave Method

The performance evaluation of transformer winding is realized by the oscillation wave impact method. In the case of no impact on the system, a step or pulse signal is injected into the transformer to produce an impulse response or a step response [37]. In the case of no influence on the system, the step or pulse signal is injected into the transformer to produce the impact response or step response. The internal characteristics of the electrical equipment are identified by the various parameters of the system, and the relationship between the parameters of the oscillation wave and the deformation of the system is established in order to form a transformer winding performance evaluation system based on the oscillation wave.

The internal structure of the transformer at high frequency can be regarded as a series circuit composed of distributed parameters such as RLC [38,39]. As shown in Figure 8:

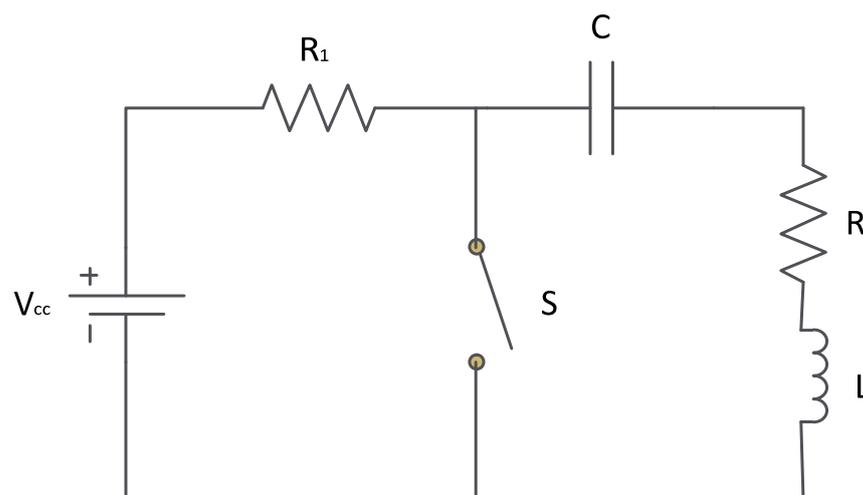


Figure 8. Series circuit.

When $t = 0$, the switch S is closed, applying the KVL and VCR theorem:

$$Ri + u_L + u_c = u_S(t) \quad (15)$$

Its characteristic root is:

$$p = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}} \quad (16)$$

When the circuit is under damped, it will oscillate:

$$R < 2\sqrt{\frac{L}{C}} \quad (17)$$

Then, u_C is:

$$u_C = Ae^{-\delta t} \sin(\omega t + \beta) \quad (18)$$

The performance of transformer winding is evaluated by oscillation wave method, as shown in Figure 9:

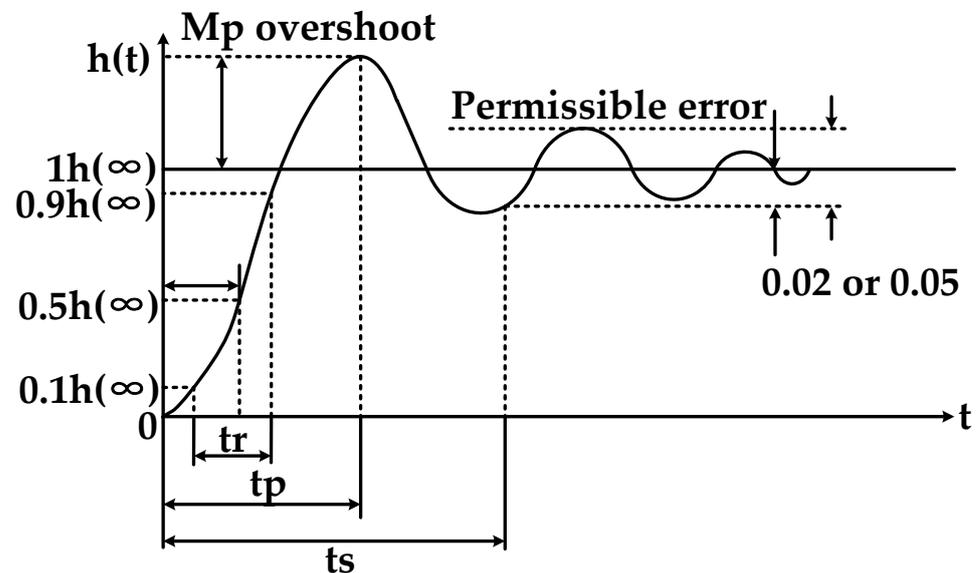


Figure 9. Oscillation wave curve of unit step response representing performance index.

In the form: f is the oscillation frequency of the response curve; t_d is the time required for the response curve to rise from zero to 50% of the steady-state value; t_r is the time required to increase the response curve from 10% to 90%; t_p is the time required for the response curve to rise to zero at the first peak; t_s is the shortest time to keep the response curve within the allowable error range. M_p is the difference between the maximum peak value of the response curve and the steady-state value.

1. Influence of inductance parameter variation on oscillation wave system index.

When the first inductance is short circuited or broken, it can be judged that the waveform indexes of the oscillation wave are different under normal conditions and short circuited or broken conditions, as shown in Figure 10:

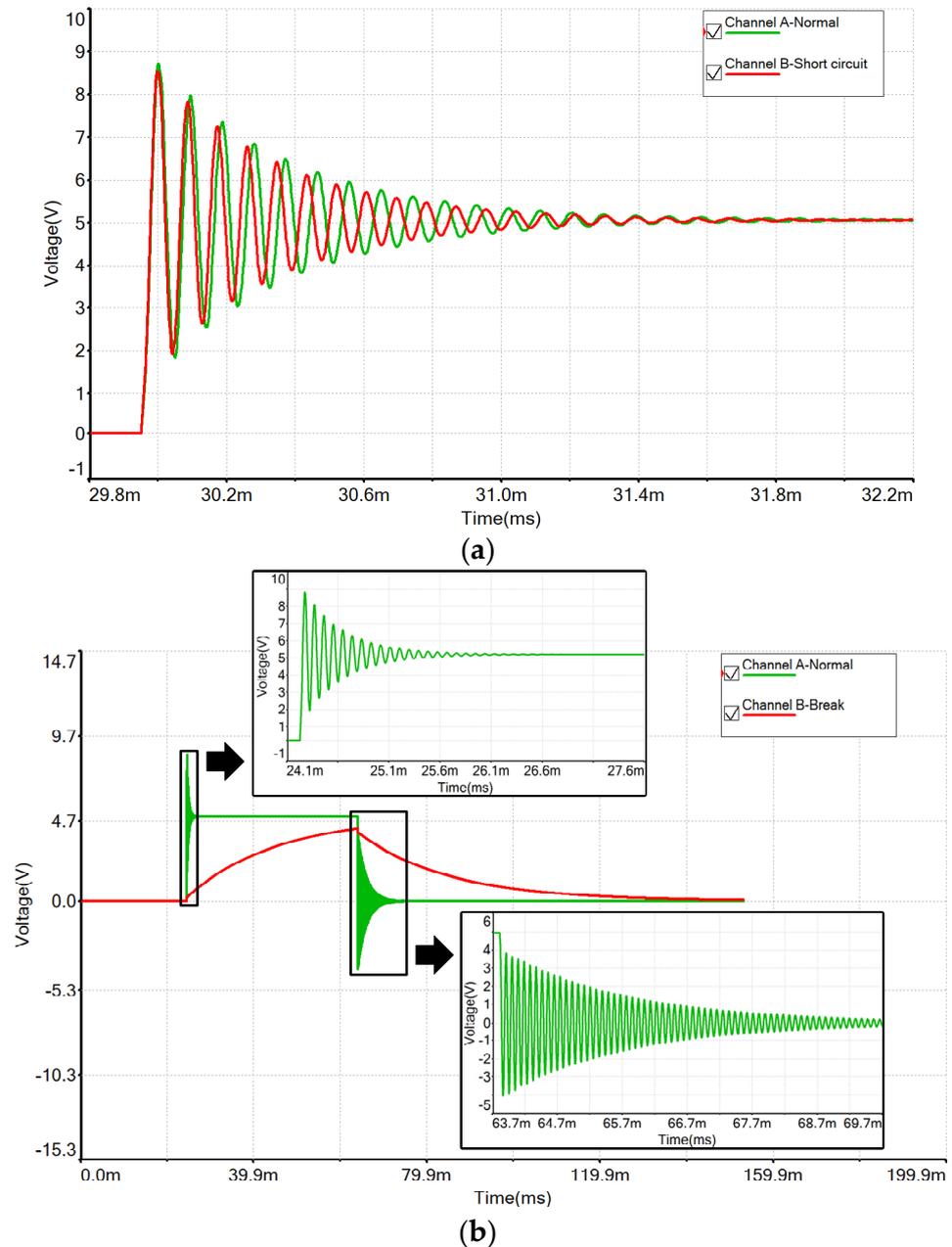


Figure 10. Waveforms of oscillation waves in normal and first cake short circuit and break: (a) short-circuit; (b) break.

When L short circuits, the frequency changes greatly, while t_d , t_r , t_p , t_s , M_p are decreased; when L is broken, the oscillation wave cannot start to vibrate, t_d becomes smaller, t_r , t_p , t_s and the M_p becomes larger.

The effect of changing the inductance of the first disc of the transformer winding from -30% to 30% on the index data of the oscillating wave system is shown in Figure 11.

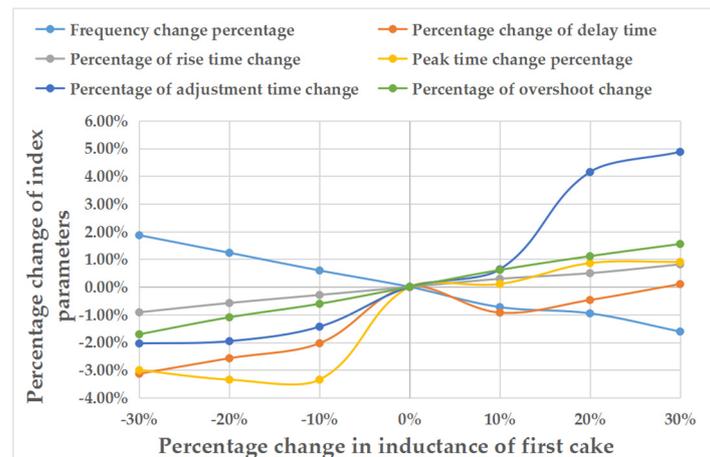


Figure 11. Influence of inductance variation of first cake on oscillation wave index parameters.

By changing the inductance parameters, the following conclusions are obtained, as shown by Table 6 shows.

Table 6. Threshold of inductance parameter variation on quality index.

Percentage Change of Transformer Equivalent Inductance Parameter	Frequency Change Percentage	Percentage of Rise Time Change	Quality Index
0	0	0	Excellent
0–1.96%	0–0.11%	0–0.06%	Good
1.96–4.76%	0.11–0.27%	0.06–0.13%	Medium
4.76–9.09%	0.27–0.52%	0.13–0.26%	Poor
9.09–23.08%	0.52–1.33%	0.26–0.65%	Worse
23.08% and above	1.33% and above	0.65% and above	Very bad

2. Influence of ground capacitance parameter variation on the index of oscillation wave system.

The equivalent parameters of each cake ground capacitance are increased by 10%, and the index data of the transformer oscillation wave system are extracted and processed, as shown in Figure 12.

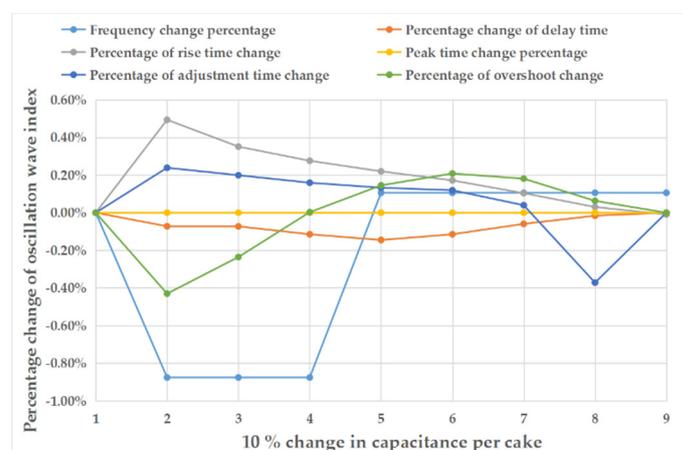


Figure 12. The broken line diagram of the influence of the increase of the ground capacitance of each cake winding of the transformer on the index of the oscillation wave system.

The equivalent parameters of the ground capacitance of the first cake increased from -100% to 200% . The index data of the transformer oscillation wave system are extracted and processed, as shown in Figure 13.

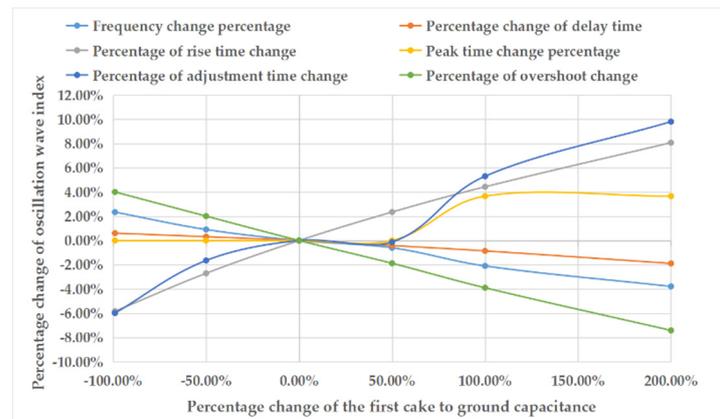


Figure 13. The variation law of oscillation wave parameter index with the first cake to ground capacitance.

By changing the capacitance parameters, the following conclusions are obtained, as shown by Table 7.

Table 7. The threshold value of transformer equivalent capacitance parameter variation on quality index.

Percentage Change of Transformer Equivalent Capacitance Parameters	Frequency Change Percentage	Percentage of Rise Time Change	Quality Index
0	0	0	Excellent
0–1.96%	0–0.04%	0–0.09%	Good
1.96–4.76%	0.04–0.09%	0.09–0.21%	Medium
4.76–9.09%	0.09–0.18%	0.21–0.41%	Poor
9.09–23.08%	0.18–0.45%	0.41–1.03%	Worse
23.08% and above	0.45% and above	1.03% and above	Very bad

For the degree of deformation of transformer winding to take the principle of large, considering the selection of the threshold of ground capacitance change, the frequency changes percentage and the rise time changes percentage value as the threshold of transformer quality index. The percentage of frequency change and the percentage of rise time are considered as the transformer quality index, as long as one index is set as a low quality gear. As shown in Table 8.

Table 8. Frequency change percentage or rise time percentage threshold.

Frequency Change Percentage	Percentage of Rise Time Change	Quality Index
0	0	Excellent
0–0.11%	0–0.09%	Good
0.11–0.27%	0.09–0.21%	Medium
0.27–0.52%	0.21–0.41%	Poor
0.52–1.33%	0.41–1.03%	Worse
1.33% and above	1.03% and above	Very bad

3. Discussion and Results

In this paper, the method of combining the analytic hierarchy process (AHP) and the fuzzy comprehensive assessment (FCA) is used to comprehensively evaluate the performance of the transformer winding [40]. AHP uses multiple criteria decision-making

methods; it uses the factors contained in the system and related situations to express a complex problem as an orderly hierarchical structure, determines the relative importance of each factor in the hierarchy through mutual comparison, and then integrates human judgments to determine the order of the relative importance of the factors [40]. Since the index corresponding to each method is unique, the standard for evaluating the winding performance score is also unique. Appropriate selection can significantly improve the efficiency of analysis [41]. The combination of the two methods is used to discuss the indicators obtained from the transformer windings in order to realize the comprehensive evaluation of the transformer winding performance.

3.1. Establish Hierarchical Structure of Comprehensive Evaluation Influencing Factors

When AHP is used to analyze the comprehensive evaluation factors, it is necessary to group them and form different levels to build a hierarchical model. As shown in Figure 14, the target layer is to evaluate the performance of transformer winding; the criteria layer is the three methods to realize the evaluation; index layer is to obtain the corresponding evaluation index through the test of three methods.

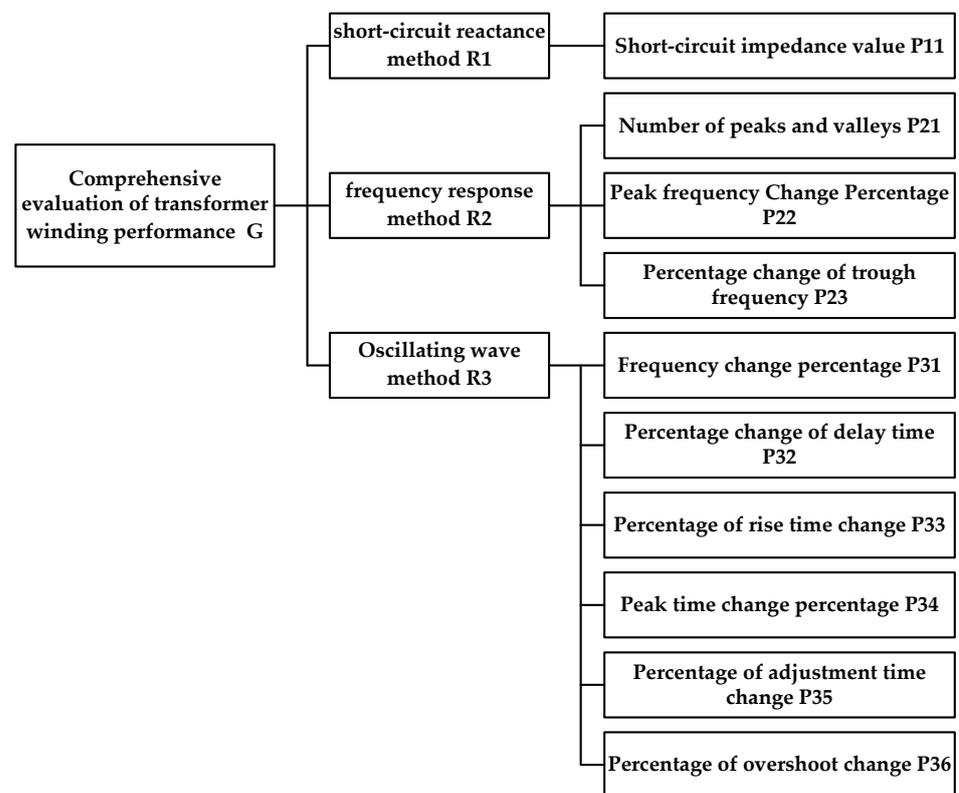


Figure 14. Analytic hierarchy process model for comprehensive evaluation of transformer winding performance.

3.2. Construct a Judgment Matrix and Calculate the Weights

By comparing the relative importance of each factor with respect to the factors of the previous layer, we used a scale of 1–9. We established a judgment matrix to obtain the maximum eigenvalue λ_{\max} , feature vector W , consistency index C_I and consistency ratio C_R of the judgment matrix. The meaning of the 1–9 scale is shown in Table 9.

Table 9. Scale meaning.

Scale a_{ij}	The Meaning of Index i to j
1	Two factors are equally important
3	The former factor is slightly more important than the latter
5	The former factor is obviously more important than the latter
7	The former factor is more important than the latter
9	The former factor is more important than the latter factor
2,4,6,8	Median value between adjacent factors
reciprocal	In the degree of importance, the ratio of i to j is a_{ij} , then the ratio of j to i is $a_{ji} = \frac{1}{a_{ij}}$

In R , a_{ij} is the ratio of the importance of i to j .

For the evaluation of transformer winding performance, the evaluation matrix of the criterion layer R to the target layer G is calculated. As shown in Table 10.

Table 10. Judgment matrix of R layer to G layer.

G	R_1	R_2	R_3
R_1	1	2	2
R_2	1/2	1	3
R_3	1/2	1/3	1

In the same way, the judgment matrix of the index layer P to the criterion layer R can be calculated, as shown in Tables 11–13.

Table 11. Judgment matrix of the index layer P to the criterion layer R_1 .

R_1	P_{11}
P_{11}	1

Table 12. Judgment matrix of the index layer P to the criterion layer R_2 .

R_2	P_{21}	P_{22}	P_{23}
P_{21}	1	3	3
P_{22}	1/3	1	2
P_{23}	1/3	1/2	1

Table 13. Judgment matrix of the index layer P to the criterion layer R_3 .

R_3	P_{31}	P_{32}	P_{33}	P_{34}	P_{35}	P_{36}
P_{31}	1	3	2	8	8	3
P_{32}	1/3	1	1/2	5	5	1
P_{33}	1/2	2	1	7	7	2
P_{34}	1/8	1/5	1/7	1	1	1/5
P_{35}	1/8	1/5	1/7	1	1	1/5
P_{36}	1/3	1	1/2	5	5	1

We calculated the relative weight of each factor under a certain criterion according to the judgment matrix. This paper uses the square root method to calculate the feature vectors W and maximum eigenvalue λ_{\max} of the judgment matrix.

First, calculate the square root:

$$v_i = \sqrt[n]{\prod_{j=1}^n a_{ij}} \tag{19}$$

Then, normalize it:

$$w_i = \frac{v_i}{\sum_{i=1}^n v_i} \quad (20)$$

Let the approximate feature vectors W be:

$$W = [w_1, w_2, \dots, w_n] \quad (21)$$

Calculate the maximum eigenvalue of the judgment matrix A :

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^n \frac{(A \cdot W)_i}{w_i} \quad (22)$$

Finally, use the Formula (23) to calculate the consistency target:

$$C_I = \frac{\lambda_{\max} - n}{n - 1} \quad (23)$$

The $\lambda_{G_{\max}}$ of the maximum eigenvalue of R to G is:

$$\lambda_{G_{\max}} = 3.0536 \quad (24)$$

Weights $(W_{R_1}^G, W_{R_2}^G, W_{R_3}^G) = (0.5278, 0.3325, 0.1396)$.

The $\lambda_{R_1_{\max}}$ of the maximum eigenvalue of P to R_1 is:

$$\lambda_{R_1_{\max}} = 1 \quad (25)$$

Weights $(W_{P_1}^{R_1}) = (1)$.

The $\lambda_{R_2_{\max}}$ of the maximum eigenvalue of P to R_2 is:

$$\lambda_{R_2_{\max}} = 3.0536 \quad (26)$$

Weights $(W_{P_1}^{R_2}, W_{P_2}^{R_2}, W_{P_3}^{R_2}) = (0.5936, 0.2493, 0.1571)$.

The $\lambda_{R_3_{\max}}$ of the maximum eigenvalue of P to R_3 is:

$$\lambda_{R_3_{\max}} = 6.0806 \quad (27)$$

Weights $(W_{P_1}^{R_3}, W_{P_2}^{R_3}, W_{P_3}^{R_3}, W_{P_4}^{R_3}, W_{P_5}^{R_3}, W_{P_6}^{R_3}) = (0.38, 0.1489, 0.252, 0.0351, 0.0351, 0.1489)$.

Finally, calculate the consistency ratio:

$$C_R = \frac{C_I}{C_R} \quad (28)$$

If $C_R < 0.1$, then the judgment matrix A reaches the consistency condition; if $C_R \geq 0.1$, then A is not reached the consistency condition. Calculate the positive and negative matrix 1000 times to obtain R_1 , as shown in the following Table. As shown in Table 14.

Table 14. Average stochastic index R_1 .

The Order of the Matrix	1	2	3	4	5	6	7	8	9	10
R_I	0	0	0.52	0.89	1.12	0.26	0.36	0.41	0.46	0.49

Calculation by the Formula (28):

Criterion layer R to target layer G , $C_I = 0.0268$, $C_R = 0.0515 < 0.1$; Index layer P to criteria layer R_1 , $C_I = 0$, $C_R = 0 < 0.1$; index layer P to criteria layer R_2 , $C_I = 0.0268$, $C_R = 0.0515 < 0.1$; Index layer P to criteria layer R_3 , $C_I = 0.0161$, $C_R = 0.062 < 0.1$.

The corresponding consistency ratio is:

$$C_R = \frac{\sum_{j=1}^3 W_{R_j}^G C_{Ij}}{\sum_{j=1}^3 W_{R_j}^G R_{Ij}} = 0.0179 < 0.1 \quad (29)$$

3.3. Construction of a Fuzzy Evaluation Matrix for Comment Sets

There are six comments in the comment set for transformer winding performance evaluation: {excellent, good, medium, poor, worse, very bad}. The corresponding score set is {6, 5, 4, 3, 2, 1}. Through the questionnaire or the expert group according to the above-mentioned principles, the score statistics of the test comprehensive evaluation indicators shown in Table 15 are obtained.

Table 15. Score statistics of each index of comprehensive testability evaluation.

Evaluation Index	Excellent	Good	Medium	Poor	Worse	Very Bad
P_{11}	5	84	8	2	1	0
P_{21}	7	71	10	9	0	1
P_{22}	1	48	21	13	14	3
P_{23}	5	63	7	20	3	2
P_{31}	2	65	12	11	10	0
P_{32}	0	75	10	9	3	3
P_{33}	5	74	6	14	0	1
P_{34}	3	70	9	10	8	0
P_{35}	3	78	5	8	4	1
P_{36}	4	89	4	0	2	0

Obtain the fuzzy evaluation matrix according to Table 15:

$$S_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1n} \\ r_{i21} & r_{i22} & \cdots & r_{i2n} \\ \vdots & \vdots & & \vdots \\ r_{im1} & r_{im2} & \cdots & r_{imn} \end{bmatrix}, \quad i = 1, 2, 3 \quad (30)$$

In the formula, m is the number of indicators in the indicator layer; n is the number of comment sets; i is the serial number of a single factor, which represents a certain stage of testability design.

Therefore:

$$S^T = \begin{bmatrix} S_1 \\ S_2 \\ \vdots \\ S_{10} \end{bmatrix}^T = \begin{bmatrix} 0.05 & 0.07 & 0.01 & 0.05 & 0.02 & 0 & 0.05 & 0.03 & 0.03 & 0.04 \\ 0.84 & 0.71 & 0.48 & 0.63 & 0.65 & 0.75 & 0.74 & 0.70 & 0.78 & 0.89 \\ 0.08 & 0.10 & 0.21 & 0.07 & 0.12 & 0.10 & 0.06 & 0.09 & 0.05 & 0.04 \\ 0.02 & 0.09 & 0.13 & 0.20 & 0.11 & 0.09 & 0.14 & 0.10 & 0.08 & 0 \\ 0.01 & 0 & 0.14 & 0.03 & 0.10 & 0.03 & 0 & 0.08 & 0.04 & 0.02 \\ 0 & 0.01 & 0 & 0.02 & 0 & 0.03 & 0.01 & 0 & 0.01 & 0 \end{bmatrix} \quad (31)$$

The comprehensive evaluation value B is obtained by calculating the comprehensive index of fuzzy evaluation:

$$B = W_p^G = [0.0476, 0.7581, 0.0951, 0.0631, 0.0254, 0.0065] \quad (32)$$

Calculate the score according to the principle of maximum membership:

$$U = \frac{0.0476 \times 6 + 0.7581 \times 5 + 0.0951 \times 4 + 0.0631 \times 3 + 0.0254 \times 2 + 0.0065 \times 1}{0.0476 + 0.7581 + 0.0951 + 0.0631 + 0.0254 + 0.0065} = 4.7031 \quad (33)$$

The U value is close to 5. According to the comment score set, the comprehensive evaluation of the quality of the transformer winding performance is close to the level “good”.

4. Conclusions

According to the performance of transformer windings after short-circuit test, this paper defines a set of reviews of transformer winding performance: {excellent, good, medium, poor, worse, very bad}; the corresponding score set is {6, 5, 4, 3, 2, 1}. Based on the short-circuit impedance method, frequency response method, and oscillating wave method, the quantitative relationship between the performance of the transformer and the respective indicators of the three methods is obtained, and the performance of the transformer winding is evaluated through AHP and FAC. The conclusions are as follows:

- (1) The short-circuit impedance method, frequency response method, and oscillating wave method are used to evaluate the performance of the distribution transformer windings that have undergone short-circuit tests. There is no need for hanging cover inspection, which solves the subjectivity of human observation and thus the objective, accurate, and quantitative description of the performance status of the transformer winding;
- (2) Transformer after short-circuit test and evaluation of transformer winding performance by short-circuit impedance method quantitatively obtain the short-circuit impedance change rate threshold of the transformer winding quality, and set the winding quality level for different thresholds. The frequency response method is used to evaluate the performance of transformer winding, and the percentage threshold of peak-valley frequency change is quantitatively obtained, setting the winding quality level for different thresholds. The oscillation wave method is used to evaluate the performance of transformer winding, and the threshold values of frequency change percentage and rise time change percentage are obtained quantitatively, setting the winding quality level for different thresholds. Thus, the problem of quantitative evaluation of transformer winding performance after short-circuit test is solved;
- (3) The evaluation language of transformer winding performance evaluation after short-circuit test is proposed, and the method of analytic hierarchy process and fuzzy evaluation method are combined to obtain the score of transformer winding performance evaluation quantitatively, and the evaluation language is given according to the score. Finally, the evaluation of transformer winding performance after short-circuit test is realized.

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