Research of Sweep Frequency Impedance to Determine Transformer Winding Deformation after Short-Circuit Impact

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Abstract: **The reliable running of the transformer is extremely important for the electric system. However, transformers will inevitably suffer various impacts, such as short-circuit current and mechanical vibration, which lead to permanent winding deformation, such as inner short circuit, distortion and bulge, lead and winding integral displacement. Failure to promptly identify the defects may result in their accumulation over time and ultimately result in transformer failure. This motivated the development of multiple methods for monitoring transformer winding condition, such as short circuit impedance (SCI) and frequency response analysis (FRA). However, these tests have certain limitations. For instance, SCI is insensitive to some little deformation while FRA has no quantitative criterion and is easily influenced by onsite condition. Sweep frequency impedance method is a new method to detect the winding deformation that combines the advantages of FRA and SCI. It can effectively detect winding deformation and reduce the rate of error detection while also having high signal-noise ratio, good reproducibility and strong anti-interference ability. This paper used sweep frequency impedance to detect the fault of an 110kV power transformer before and after impacts. Identify the deformation by short circuit impedance and correlation coefficient. The test results show that short circuit faults lead to changes in both the 50Hz impedance and the correlation coefficient of the sweep frequency impedance curve. The magnitude of these changes increases with the severity of the short circuit.**

Keywords—Sweep Frequency Impedance; Winding Deformation; Identification criterion; short-circuit

I. INTRODUCTION

The transformer is one of the most important pieces of equipment in the power system with its stable operation playing a critical role in the safe operation of the power system; however, transformers inevitably suffer the impact of short-circuit current and mechanical vibration during operation. Such events will lead to permanent deformation of windings, including warping, shifting and bulge of the windings. If not detected in time, the deformations may accumulate over a long period and ultimately lead to transformer failures [1-3].

To monitor the condition of transformer windings, people developed a large amount of methods to diagnose the winding deformations. Among these methods, short circuit impedance (SCI) and frequency response analysis (FRA) had been used widely due to their good performance. However, some defects shown up according to many experiences of test: SCI is insensitive to some little deformation, and FRA has no quantitative criterion and is easily influenced by onsite condition. Therefore, sweep frequency impedance method is a new method to detect the winding deformation. It combines the advantages of frequency response method and the short circuit impedance method. Sweep frequency impedance method, can effectively detected the winding deformation, reduce the rate of error detection, it also has high signal-noise ratio, good reproducibility and strong anti-interference ability. That make it to be a good replacement of SCI and FRA [4]

II. SYSTEM INTRODUCTION

A. Instrument Overview

The structure of the sweep frequency impedance instrument is shown as Fig. 1. It is including broad frequency signal generator; power amplifier; high-speed acquisition [5].

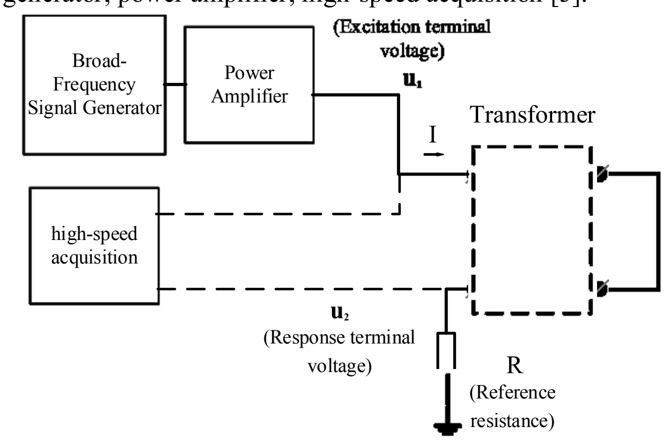


Fig. 1 Structure of the system

During testing, the broadband signal generator generates sinusoidal signal from 10Hz to 1000 kHz. The power amplifier will magnify the sinusoidal signal for 10 times, then load the signal to the head terminal of the winding (excitation terminal). Meanwhile collect the amplitude u_1 u_2 and phase φ_1 φ_2 of the excitation signal $\overrightarrow{u_1}$ and response signal $\overrightarrow{u_2}$ on both ends of the winding by the high-speed acquisition. According the formula:

$$Z = R + jX = \frac{\overrightarrow{u_1} - \overrightarrow{u_2}}{i_1}; \quad i_1 = \frac{\overrightarrow{u_2}}{R} \tag{1}$$

Obtained:

$$|Z| = R \cdot \sqrt{\left|\frac{u_1}{u_2}\right|^2 - 2 \cdot \left|\frac{u_1}{u_2}\right| \cdot cos(\varphi_1 - \varphi_2) + 1} \tag{2}$$

The impedance under different frequency of the winding is obtained. The 50Hz short circuit impedance and correlation coefficient was used to determine the situation of transformer winding deformation in sweep frequency impedance method.

B. Judgment standard

50Hz short-circuit reactance identification criterion is shown as TABLE I [6]

TABLE I 50HZ SHORT-CIRCUIT REACTANCE IDENTIFICATION CRITERION

R_{50HZ} variations	<1.0%	1%-2%	>2%
Fault degree	No fault	Warning range	Existed fault

High frequency section (1 kHz-1000 kHz) of the sweep frequency impedance curve contains multiple resonant peaks, according to different winding fault condition, the location and amplitude of the resonance peaks might change. Which reflects abundant information.

The correspondence between frequencies and the fault types are shown as TABLE II

TABLE II CORRESPONDENCE BETWEEN FREQUENCIES AND THE FAULT TYPES

Frequency /kHz	Fault types
1-100	Interturn short circuit
100-600	Distortion and bulge, etc. Local deformation
>600	Lead and winding integral displacement

In case of no fault in the winding, the amplitude and location of the resonant peaks should be consistent. Watch the curve between 1 kHz to 1000 kHz, if doubt exists deformation, the curve should be analyzed by correlation coefficient method. According the formula. The ranges of the low-, medium-, and high-frequency bands for R_{xy} and the deformation levels related to the R_{xy} value have been defined in the Chinese standard [7] and by some other workers [8], as shown in TABLE III.

$$R = \sum_{i=1}^{n} x_i \cdot y_i \sqrt{\sum_{i=1}^{n} {x_i}^2 \cdot \sum_{i=1}^{n} {y_i}^2} \qquad (3)$$

X $\{x_1,x_2,x_3,\cdots,x_n\}$ and Y $\{y_1,y_2,y_3,\cdots,y_n\}$ are the sweep frequency impedance sequence of two tests.

TABLE III RELATIONSHIP BETWEEN CORRELATION COEFFICIENT AND DEFORMATION DEGREE OF THE TRANSFORMER WINDING

Fault degree	correlation coefficient		
	R_{Lf}	R_{Mf}	R_{Hf}
None deformation	>2.0	>1.0	>0.6
Slight deformation	<2.0	<1.0	<0.6
Obvious deformation	<1.0	<0.6	
Severe deformation	<0.6		

C. The Testing Transformer

In this paper, the research is based on an 110Kv three-phase three-winding power transformer. Voltage grade is 110/35/10kV, connection group is YNynd11. The transformer is shown in Fig. 2

Fig. 2 The testing transformer

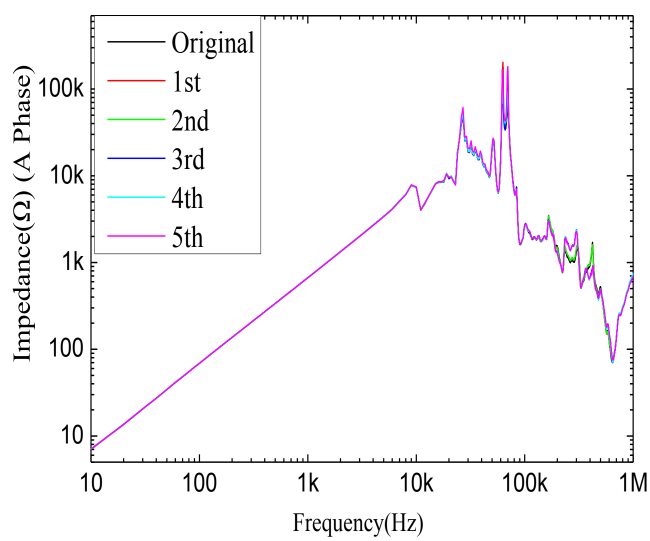
III. TEST RESULTS AND ANALYSIS

The transformer has been loaded short circuit voltage for many times to verify the effect of sudden short circuit in the transformer winding.

Short out the medium voltage winding of the transformer, load short-circuit current at the high voltage side. Test the sweep frequency impedance curve of the high-voltage winding after every short circuit.

A. The SFI curve of Normal Winding

We loaded each phase of the high-voltage windings with short-circuit current for five times. Current is 70% of the rated current. After each impact, test the sweep frequency impedance of the winding. The sweep frequency impedance curve of each phase are shown as Fig. 3.



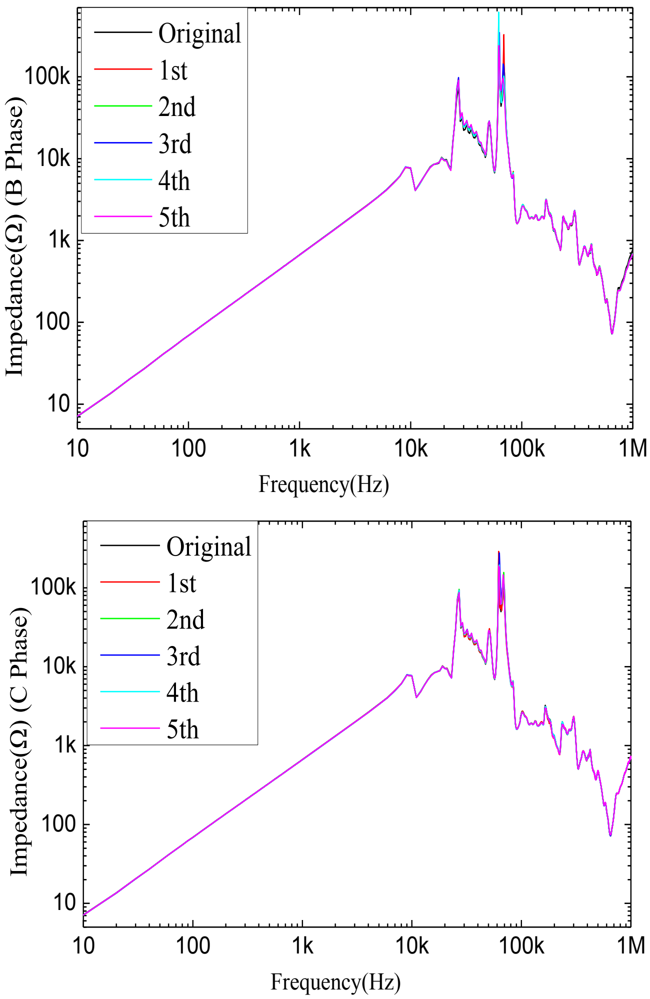


Fig. 3 The SFI curve of normal winding

According to Fig. 3, the sweep frequency impedance curve of each phase did not change appreciably after five times of short-circuit impact. Using the 50 Hz value of the sweep frequency impedance curve gives the short-circuit impedance before and after the impact, as shown in TABLE IV.

TABLE IV SHORT-CIRCUIT IMPEDANCE OF EACH IMPACT

IMPEDANCE (Ω)	A PHASE	B PHASE	C PHASE
0	34.305	34.305	34.305
1^{ST}	34.303	34.268	34.341
2^{ND}	34.278	34.267	34.310
3^{RD}	34.292	34.193	34.317
4^{TH}	34.326	34.226	34.240
5^{TH}	34.308	34.167	34.258

Table IV shows that the 50Hz short-circuit impedance of each tests changed little with all values falling within 1% of each other. This indicates that no obvious deformation occurred in the transformer windings; however, the impedance of the B phase exhibits a downward trend, as shown in Fig. 4, suggesting that the winding may become weaker after repeated impact.

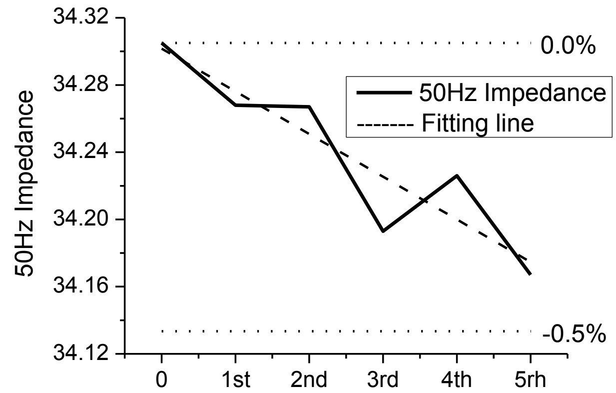


Fig. 4 The 50Hz impedance of B-phase

B. *The SFI curve of faulted winding*

We next applied 84% of the rated current on the B-phase five times and measured the sweep frequency impedance curve after each impact with the results shown in Fig. 5. Fig. 5 shows that the sweep frequency impedance curve after the first five impacts agree well with the original curve. The original curve above 600 kHz was not matched well with the others, because testing lead placement of the original is different from the others. More importantly, the high frequency part of the sixth curve is obviously different from others. Specifically, the curve above 30kHz is strikingly different from previous ones with extra peak appearing at 60kHz.

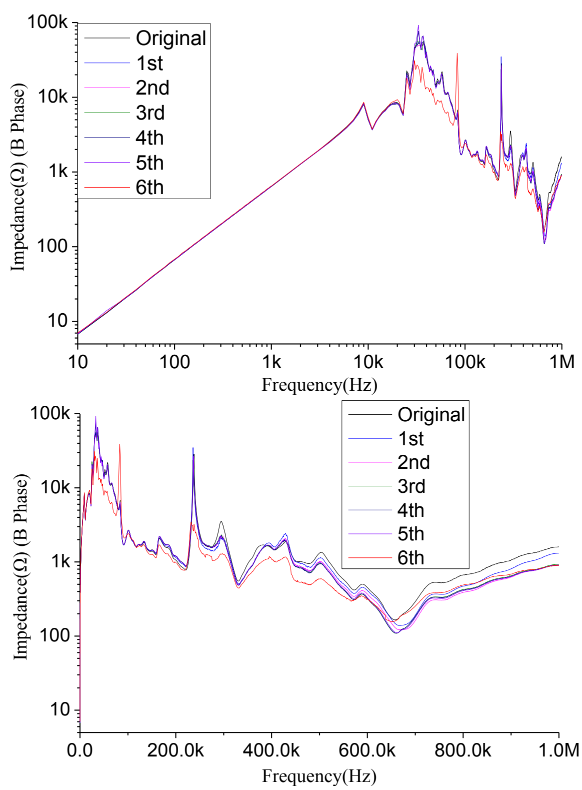


Fig. 5 The SFI curve of faulted winding

Use the 50Hz value of sweep frequency impedance, get the short-circuit impedance of winding before and after each impact. As shown in Table V

TABLE V SHORT-CIRCUIT IMPEDANCE OF EACH IMPACT

N0.	IMDANCE (Ω)	ERROR (%)
0	33.066	0.00
1st	33.126	0.18
2nd	33.080	0.04
3rd	33.066	0.00
4th	32.993	-0.22
5th	33.063	-0.01
6th	33.560	1.49

According to Table V, the value of short-circuit impedance had little change and the winding deformation is not obvious under 5 times short-circuit current impact. However, after the sixth impact, the value of impedance increased 1.49% which entered the alarm zone. It needs to use correlation coefficient method for further identification. [9].

The correlation coefficient between the original curve and the curve after each short circuit impact is shown in Table VI.

TABLE VI CORRELATION COEFFICIENT BETWEEN THE ORIGINAL AND TESTS 1ST-6TH

N0.	1st	2nd	3rd	4th	5th	6th
R_{Lf}	3.14	3.37	2.77	2.29	1.91	**0.60**
R_{Mf}	1.08	1.46	1.69	1.25	1.51	**0.48**
R_{Hf}	2.25	2.30	2.83	2.79	2.79	2.07

Table VI shows that the correlation coefficients are within the normal range following one to four impacts, indicating no winding deformation. After the fifth short circuit, the low frequency correlation coefficient R_{Lf} dropped to 1.91, indicating slight deformation. After the sixth short circuit, the low frequency and middle frequency correlation coefficients, R_{Lf} and R_{Mf}, dropped to 0.60 and 0.48, suggesting serious deformation.

Fig. 6 The deformation of the B-phase wingding

After the sixth time of short circuit impact, do the pendant-core examination for the transformer. We found many turns of the middle part of the B-phase high-voltage winding had been inward sunken [10], as shown in Fig. 6. The winding deformation is very serious.

IV. CONCLUSION

This paper describe a short circuit impact test on a 110 kV power transformer, and do sweep frequency impedance test after every impact. Based on the test result, on the condition of deformation caused by short-circuit impact, the location and amplitude of the resonance peaks on the sweep frequency impedance curve might change. The 50Hz impedance will also change. When the winding occurred distortion and local deformation, the low frequency and middle frequency correlation coefficient will decrease.

In addition, the research show that, under short-circuit impact on the winding, if its 50 Hz impedance values had a trend of continuous change, its ability of resist short circuit may be decreased. This assumption still needs a further verification.

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