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Study on Winding Looseness of Power Transformer Based on Vibration

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Abstract. The vibration of transformer is closely related to windings, so researching on vibration signal of power transformer has potential to realize online detection of winding looseness. In this paper, a series of tests have been made to obtain vibration signal by setting winding looseness on a 10/0.4kV three-phase transformer. A linear fitting equation has been obtained by fitting the amplitude of the 100Hz component of the vibration signal under different short-circuit currents. The results show that the slope of the fitting equation will increase when the winding becomes loose. The research results show the potential of this method in condition monitoring of power transformer.

1. Introduction

The power transformer as the key equipment in the power system which undertake voltage conversion, power distribution and transmission, which provide guarantee for the safe operation of the power system. Since the transformer has been shipped from the factory, factors such as transportation, installation, and short-circuit current impact will reduce the pre-tightening force [1]. The primary effect on the transformer is to make the winding looseness. Winding looseness will reduce the ability of the winding to withstand short-circuit current surges, posing a safety hazard to the grid [2]. Therefore, the diagnosis method of winding looseness defects is of great significance for timely finding winding faults and ensuring grid safety.

The traditional method of transformer fault monitoring required open the transformer, which cost a lot of manpower, material and financial resources. Therefore, scholars are constantly exploring new detection methods, such as low voltage pulse method LVI [3] and frequency response method FRA [4], which are gradually accepted by the industry. However, these methods can only be carried out under off-line conditions. If you want to monitor the mechanical state of the transformer in time, these methods are obviously constrained. In the 2000s, researchers have proposed a method to monitor the state of transformer using vibration signals [5, 6]. Transformer vibration is a complex and comprehensive performance. Many signal processing methods have been applied to transformer fault diagnosis. The paper [7] proposes a transformer vibration monitoring method based on load current. The paper [8] proposes a diagnostic model based on the variation of different frequency components at different positions in the vibration signal and the combination of energy between them, introducing multiple frequency components and giving Empirical formula.



Based on the previous research, this paper through the transformer winding looseness test to compare the change of the characteristic value of the vibration signal before and after the winding looseness, and obtain the judgment basis for the loosening of the transformer winding. The vibration signal analysis method to monitor the winding looseness, which is a powerful supplement and perfection for the online monitoring and fault diagnosis system of the power transformer.

2. Theory of transformer vibration

2.1 Winding vibrations

The transformer winding can be simply regarded as a mechanical structure in which the insulating spacers and the wire cake are alternately stacked, and the upper and lower ends are closely connected by the pressing plate. The insulation block is regarded as an elastic element, the rigidity coefficient is k , and the coil is regarded as a mass concentration module, and the mass is m . Suppose the primary current is $i = I \sin(\omega t + \theta)$, where I is the current amplitude, ω is the power frequency, and θ is the current lead voltage phase angle, then the electric power acting on the winding coil is $F = bI^2(\cos(2\omega t + 2\theta)/2 - 1/2)$, where b is a constant related to the position of the winding, which reflects the electromagnetic force received at different positions of the winding. When the transformer is running, the wire cake is subjected to the alternating electromagnetic force and is in a dynamic process. Therefore, the winding can be regarded as a multi-degree of freedom spring mass system which subjected to electromagnetic force, gravity and oil damping [9], and the axial direction winding can be obtained by the spring system. The dynamic equation of displacement is shown as follows:

$$m\ddot{x} + c\dot{x} + kx = F + mg \quad (1)$$

Where c , x are friction coefficient of the transformer oil, displacement of winding.

Calculate vibration acceleration (a_w) by simplified winding equivalent model [10]:

$$a_w = A_w \sin(2\omega t + 2\theta + \varphi) \quad (2)$$

$$A_w = \left| \frac{4\omega^2 b}{\sqrt{(k - 4m\omega^2)^2 + 4c\omega^2}} \right| I^2 = k_y I^2 \quad (3)$$

Where A_w is the vibration amplitude of the winding, φ is the constant related to the winding parameters. k_y reflects the relationship between the amplitude of the fundamental frequency of the winding and the square of the current.

According to the relevant theory, the axial pre-loading of the winding is mainly changed the rigidity coefficient of the insulation block to affect the vibration of the winding, the relationship among the stress σ of the insulation block, the strain ε and the transformer winding pressing force T can be expressed as:

$$\sigma = a\varepsilon + t\varepsilon^2 \quad (4)$$

$$\sigma = \frac{T}{S} \quad (5)$$

Where a and t are constant coefficients and S is the total area of each pad.

After the winding pressing force T changes, the rigidity coefficient k must change:

$$k = \frac{dT}{dl} = \frac{d\sigma S}{d\varepsilon l} = \frac{S}{l}(a + 3t\varepsilon^2) \quad (6)$$

Where l is a layer of insulation block thickness. It can be seen from equation (4), (5), (6), it can see that, when $k < 4m\omega^2$, the rigidity coefficient k increases with the T , and the winding amplitude A_w is decreases; when $k < 4m\omega^2$, the winding amplitude A_w is decreased after T increase. it is worth noting that when $k < 4m\omega^2$, the winding will resonate.

Transformer core vibration is mainly due to the magnetostrictive properties of silicon steel sheets in an alternating magnetic field. Assuming that the primary side voltage is $u = U \sin \omega t$, the core

vibration acceleration (a_c) is expressed as follows, and the amplitude of a_c is represented by A_c [11]:

$$a_c = A_c \cos 2\omega t \quad (7)$$

$$A_c = \frac{4Kl}{(NS')^2} U^2 = k_c U^2 \quad (8)$$

Where K is the magnetostriction proportional coefficient, l is the original size of the silicon steel sheet, N is the number of primary sides, and S' is the cross-sectional area of the core.

The above analysis shows that the vibration frequency of the transformer winding and the core is theoretically 2ω , which is called the fundamental frequency component. The fundamental amplitude of the winding vibration is proportional to the square of the current. The amplitude of the core vibration is proportional to the square of the voltage.

2.2 Fault diagnosis of transformer winding looseness

For the closed tank, the transmission path of the vibration signal from inside to outside is as shown in the Figure 1. Figure 1 shows the vibration signals generated by the windings and cores after being excited by current and voltage are not directly transmitted to the surface of the tank, but the vibration signals of the windings and the core are mechanically coupled, and then transmitted to the surface of the tank through the transformer oil. The vibration signal loss comes from the mechanical coupling loss generated when the winding is coupled to the core vibration, and the transmission loss generated when vibration cross oil.

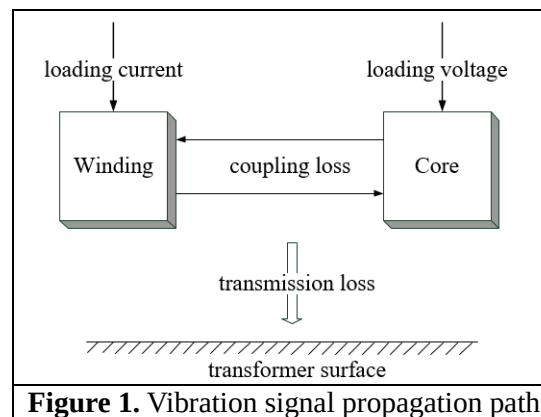


Figure 1. Vibration signal propagation path

Combined with the previous analysis, the fundamental frequency amplitude of the vibration signal of the tank surface can be expressed as a linear superposition of the vibration of the winding and the vibration of the core. Therefore, the fundamental frequency amplitude of the vibration signal of the tank can be expressed as:

$$A = c_1 A_c + c_2 A_w \quad (9)$$

Where: A is the base frequency amplitude of the vibration signal of the tank; c_1 and c_2 are the proportional coefficients, which are related to the transmission characteristics of the vibration signal.

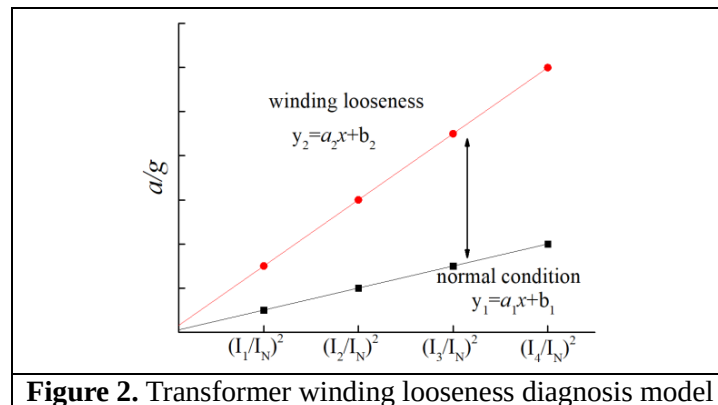
According to the relationship between the winding and the core, current and voltage, the above formula is rewritten as:

$$A = c_1' (I^2 / I_N^2) + c_2' (U^2 / U_N^2) \quad (10)$$

Since the primary voltage is kept at a small level, the equation (10) can be regarded as a linear function of A with respect to I is written as follows:

$$y = ax + b \quad (11)$$

Therefore, through a change of the slope of the first equation, it can be judged whether the winding is loosened or not. The loosening diagnosis model is shown in Figure 2.

**Figure 2.** Transformer winding looseness diagnosis model

The condition for the establishment of the diagnosis model is that the slope is related to the pre-tightening force, that is, when the pre-tightening force is the same, the amplitude is proportional to the square of the current, and the slope is the same, but when the pre-tightening force is different, the slope is different. Obviously the condition is valid.

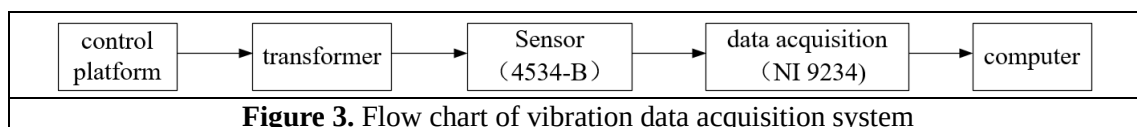
3 The test platform

3.1 test facilities and the location of measuring points

Test facilities include vibration sensor, transmission cable, data acquisition instrument, oscilloscope recorder and control platform, in which the selection of sensor and installation position have a greater impact on the test. In this test, the 4534-B type uniaxial acceleration sensor of B&K company is used. The sensor has the characteristics of high sensitivity and wide response range. It meets the test requirement and the main parameters are shown in the Table 1. Flow chart of vibration data acquisition system is showed in Figure 3.

Table 1. Main parameters of acceleration sensor

Frequency range /Hz	Sensitivity /mV/ms ⁻²	Temperature /°C	Weight /gram
0.2-12800	98	-55-125	8.6

**Figure 3.** Flow chart of vibration data acquisition system

The test object is a distribution transformer with a rated voltage of 10kV. According to the direction of the force of the winding of the transformer winding and the principle of vibration propagation, the radial vibration of the winding can only propagate in the form of longitudinal waves in the transformer oil, due to the vibration of the radial direction. The transmission path in the middle of the tank is the shortest, and the measurement points are arranged in the middle of the side of the tank; the axial vibration of the winding can be transmitted to the tank in the form of longitudinal waves and transverse waves by solid structural members or in the form of longitudinal waves by transformer oil. At the top, measurement points are placed at the top of the tank to monitor the vibration of the windings. Considering the principle of measuring points and the surface structure of the transformer tank, a total of 6 points on the top and side of the tank were selected for vibration measurement. The specific distribution of the measuring points is shown in the Figure 4: the top three points are located above the three-phase windings of A, B and C; the three points on the side are located in the middle of

the side of the tank facing the three-phase windings of A, B and C respectively. The vibration acceleration sensor is magnetized on the surface of the transformer tank by a magnet.

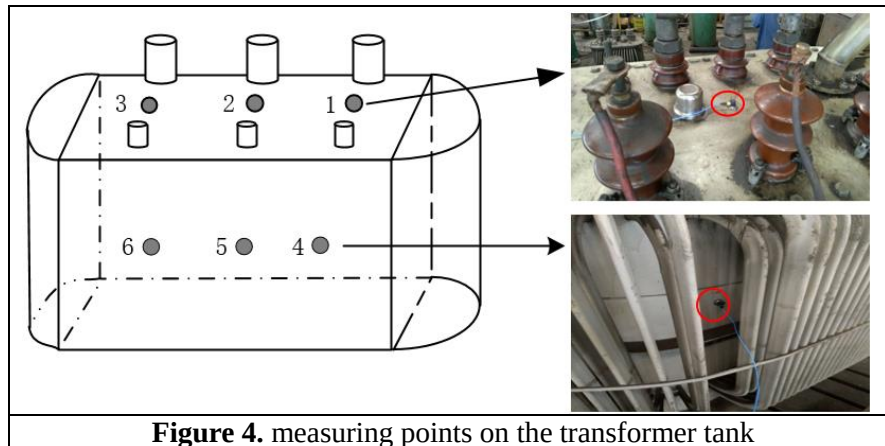


Figure 4. measuring points on the transformer tank

3.2 Vibration dates acquisition

In order to study the relationship between winding vibration and current. To make short-circuit of the test transformer, through the voltage regulator adjust voltage, so that the short-circuit currents change within the rated range, and measure the vibration of the transformer tank surface. In the short-circuit test, the voltage is very low which is $(4.0 \sim 10.5)\% U_{1N}$. Therefore, the main magnetic flux in the iron core is small, the core vibration can be neglected, so the vibration of the transformer is mainly caused by the winding. Then, when the winding is normal (not loose), measuring the vibration signal of the transformer tank when the current of the transformer is gradually increased from $0.1I_{1N}$ to $1.1I_{1N}$. Finally, artificially set the transformer winding loose fault: open the transformer top cover, and lift the iron core and winding to adjust the compression nut between the winding coils to make the winding loose. Adjusting voltage to make the transformer with loose windings test under the same conditions as normal, measuring the surface of the transformer tank vibration. Figure 5 shows the setting of the transformer winding loosening experiment. In the Figure 6, the vibration signal before and after the winding looseness is showed of the measuring point 4.

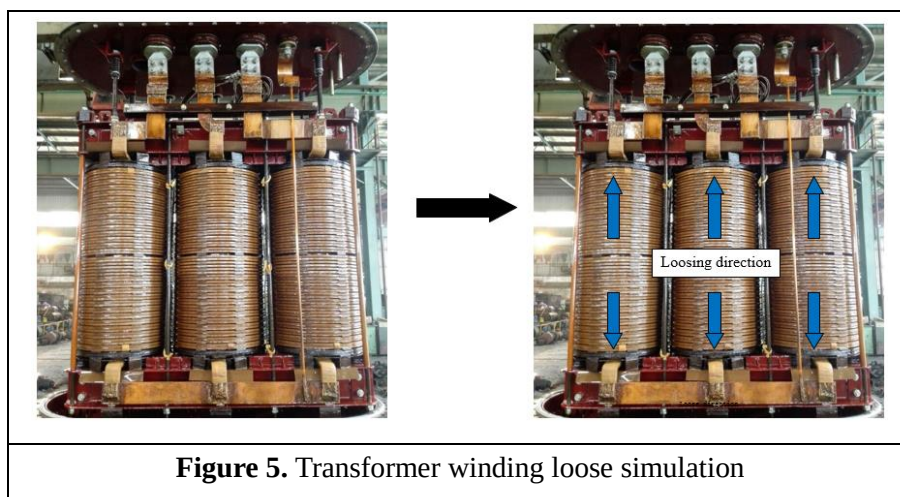
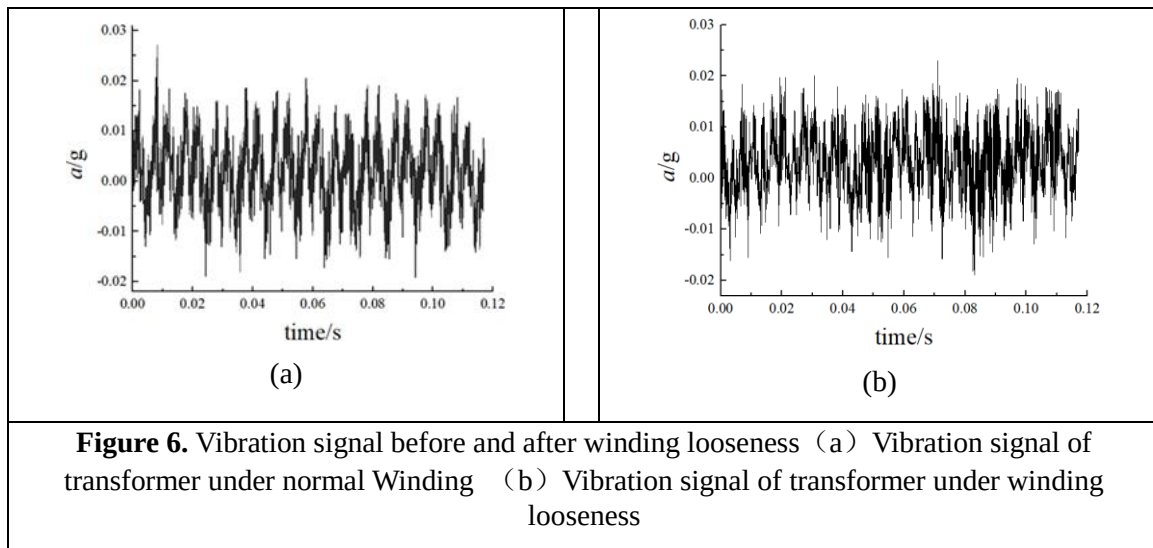


Figure 5. Transformer winding loose simulation



4 Experimental results analysis

Since frequency of the current is 50 Hz, the fundamental frequency of the transformer vibration signal is 100 Hz. In order to compare variation of amplitude of the 100Hz component with square of load current under before and after of the winding looseness, the results shown in Figure 5. The dotted line is the curve of the 100 Hz component with the current after the winding is loose, and the broken line is the curve of the 100 Hz component with the current under normal condition of the winding.

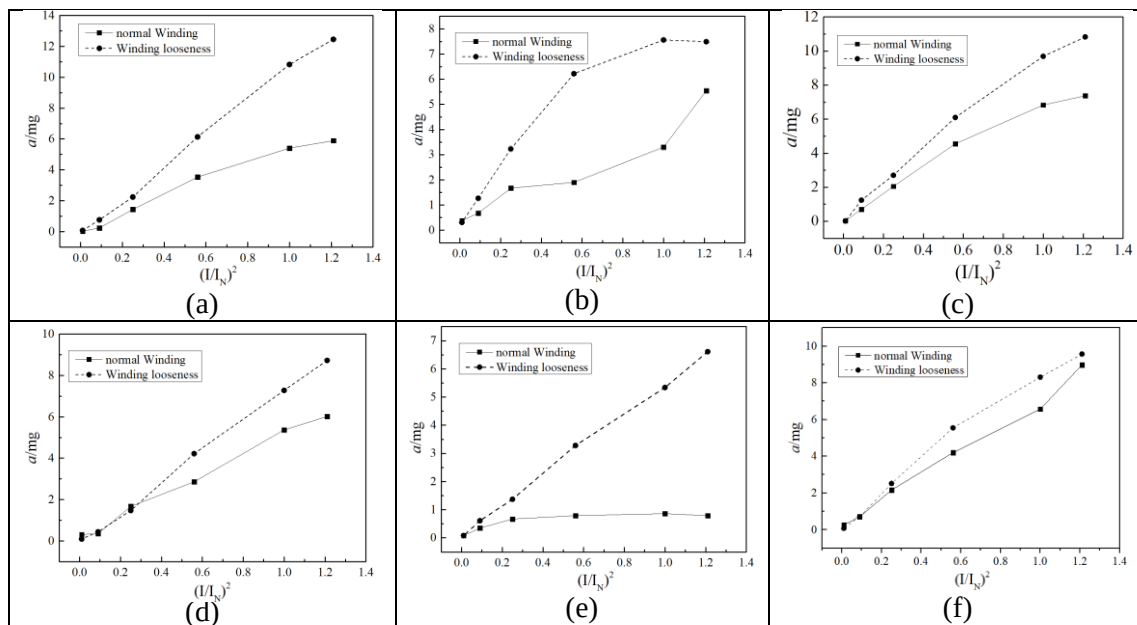


Figure 7 shows that, except for measuring point 5, the amplitude of the vibration 100Hz component is proportional to the square of the current, which is basically consistent with the theory. The amplitude of the vibration 100Hz component after the winding of the measuring points of No.1 and No.2 is obviously larger than that of normal; the amplitude of the fundamental frequency of measuring points 3, 4, 6, which is larger than the normal state of the winding, but the difference is not obvious.

Table 2. Comparison of fundamental frequency amplitude and current square fitting equation " $y=ax+b$ " at each measuring point before and after winding looseness

measuring points	normal winding		winding looseness	
	a	b	a	b
NO.1	5.14	0.17	10.66	0.13
NO.2	3.71	0.31	6.11	1.17
NO.3	6.26	0.32	9.05	0.39
NO.4	4.96	0.18	7.38	0.12
NO.5	0.50	0.33	5.37	0.09
NO.6	6.93	0.33	7.98	0.31

Table 2 shows that the slope of characteristic equation of No. 1 and No. 2 point after winding looseness almost 2 times than normal, which means that it is probably to diagnose the winding is looseness by the change of slope of fitting equation. Except for NO.2 point, the b value fluctuates in the range of 0.1-0.4, which indicates that the amplitude of the core vibration signal obtained by short circuit experiment is small, and the transformer vibration is mainly caused by windings.

5 Conclusion

This paper through designing the winding loosening experiment and obtaining the vibration signal of the transformer tank, a method of diagnose the transformer winding looseness based on vibration is proposed. The method first need to obtain the transformer vibration signal under different short-circuit currents, and then, fit the amplitude of the 100Hz component of winding vibration with square of load currents to obtain a linear fitting equation. The slope of the equation can be used to diagnose the winding is looseness.

Acknowledgments

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