Research on transformer condition evaluation technology based on vibration signal analysis

Ma Hao, Yao Chuang, Duan Minghui, Wei Jufang, Zhang Xin, Zhao Cong

Department of Condition Evaluation for Power Equipment, Electric Power Research Institute of Tianjin Electric Power Corporation, Tianjin 300384, China
hao.ma1@tj.sgcc.com.cn

Abstract. In order to analyze and judge the looseness defects of transformer core and winding, the causes and characteristics of core and winding vibration were analyzed theoretically. It could be seen that the resonance frequency and frequency spectrum distribution of vibration signals at different measuring points were not the same. The vibration signals of different measuring points of the transformer shell under the conditions of normal core and winding looseness and different degrees of looseness were tested experimentally. Then the method for judging the looseness defect of core and winding based on the content of fundamental frequency signal was proposed, which had advantage in effectiveness and convenience. Finally, the further research direction was pointed out to promote actual using.

1. Introduction

As one of the key equipment of power system, the stable operation of transformer is very important to the safety and reliability of transmission and distribution network. At the same time, the internal loss also affects the operation economy of substation and distribution station. Although the progress of manufacturing technology and performance of transformer reduces the probability of internal fault, the cases of equipment damage and performance loss caused by external faults and the aging of equipment in operation are emerging. According to statistics, in the past five years, the transformer failure caused by external short circuit accounts for more than 30%[1].

When the transformer winding passes through the external short-circuit current, it can bear dozens or even hundreds of times of the rated operating conditions. When the performance of the winding fastening measures is reduced and the short-circuit resistance is insufficient, the winding deformation will be caused, and even the internal short-circuit will occur; when the fixed bolt or tension band of the core is loose, the vibration amplitude of the silicon steel sheet will increase, resulting in the increase of no-load loss and the increase of internal temperature rise Add, accelerate equipment aging. Therefore, it is of great significance to master the state of transformer winding and core in time to formulate the maintenance strategy of transformer, which is conducive to prolonging the service life of equipment[2,3].

In recent years, the researchers have proposed the transformer core and winding state detection technology based on the transformer vibration signal, and summed up certain rules. This paper combined theoretical analysis and model experiments to prove the effectiveness of detecting transformer’s condition using vibration signal analysis.
2. Theoretical analysis of influence factors of transformer vibration

2.1. Core vibration mechanism

The vibration of the core is mainly caused by the magnetostriction of the silicon steel sheet and the magnetic leakage at the joints and between the sheets. Due to the application of step joint and weft free adhesive tape in iron core binding, the vibration of transformer core mainly depends on the magnetostriction of silicon steel sheet.

The supply voltage $U_1$ is shown in formula (1). According to the principle of electromagnetic induction, the magnetic induction intensity generated in the core can be expressed as formula (2).

$$U_1 = U_s \cos \omega t$$

$$B = \frac{\phi}{S} = \frac{U_s}{\omega N S} \cos \omega t = B_0 \cos \omega t$$

where $\phi$ is the core magnetic flux; $B_0 = U_S / \omega NS$; $S$ is the cross-sectional area of the core; $N$ is the winding turns.

Because of the linear relationship between the magnetic flux density and the magnetic field intensity, the magnetic field intensity in the iron core is shown in formula (3).

$$H = \frac{B}{\mu} = \frac{BH}{B_s} = \frac{B_0}{B_s} \cos \omega t$$

where $B_s$ is the saturation magnetic induction of the core and $H_C$ is the coercivity.

Under the action of external magnetic field, the micro deformation of silicon steel sheet caused by magnetostriction satisfies the following relationship:

$$\varepsilon = \frac{\Delta L}{L}$$

$$\frac{\Delta L}{L} \frac{1}{dH} = \left| H \right| \frac{2 \varepsilon_s}{H_c}$$

where $\varepsilon$ is the axial magnetostriction rate of silicon steel sheet; $\Delta L$ is the maximum axial expansion amount of silicon steel sheet; $L$ is the original axial size of silicon steel sheet; and $\varepsilon_s$ is the saturated magnetostriction rate of silicon steel sheet.

Based on the above relations, it can be concluded that the maximum axial expansion caused by magnetostriction is shown in formula (5).

$$\Delta L = L \int_0^H \left| H \right| \frac{2 \varepsilon_s}{H_c^2} dH = L \frac{\varepsilon_s}{H_c^2} H^2 = L \frac{\varepsilon_s}{B_s^2} \frac{B_0^2}{(\omega N_{core} S B_s)} \cos^2 \omega t$$

Therefore, when the transformer is unloaded, the vibration acceleration of the core caused by the magnetostriction of the silicon steel sheet is shown in formula (6).

$$a_c = \frac{d^2 \Delta L}{dt^2} = -\frac{2 L \varepsilon_s U_s^2}{(\omega N_{core} S B_s)} \cos 2 \omega t$$

It can be seen from formula (6) that the vibration acceleration is proportional to the square of voltage under the condition of constant core material and working temperature.

Due to the nonlinearity of transformer core material, the actual waveform of core flux density is not a standard sine wave, so the core vibration signal contains a large number of high-order harmonic components in addition to the fundamental frequency component. For the transformer core working in the power system with the frequency of 50 Hz, the components of 200, 300 and 400 Hz are more obvious in addition to the 100 Hz component of the fundamental frequency. The no-load vibration spectrum of typical oil immersed power transformer caused by the nonlinear magnetostriction of core silicon steel sheet is shown in figure 1.
2.2. Winding vibration mechanism
When the load current flows through the winding, the dynamic electromagnetic force will be generated between windings and turns, which will cause the vibration of the winding. Assuming that the current flowing through the winding is shown in formula (7), then the electric force acting on the winding coil can be obtained.

\[ I = I_m \sin(\omega t + \theta_0) \]  
(7)

\[ F = pI_m^2 \left(1 - \frac{1}{2} \cos(2\omega t + 2\theta_0) \right) \]  
(8)

where \( I_m \) is the amplitude of the load current, \( \theta_0 \) is the initial phase of the load current and \( p \) is the electrodynamic coefficient.

In the operation, the dynamic process of the winding with pie structure can be regarded as a mechanical system composed of elastic entities. That means the stiffness of the core is infinite, the pressing plates of the winding are rigid, the coil is a concentrated mass module, the insulation pad and the end coil are elastic elements. In that way, the winding is equivalent to a spring mass system, and the winding position is obtained according to the dynamic theorem.

\[ M \frac{d^2z}{dt^2} + C \frac{dz}{dt} + Kz = F + Mg \]  
(9)

where \( M \) is the mass matrix of winding coil cake, \( C \) is the damping coefficient matrix, \( K \) is the elastic coefficient matrix.

By solving the equations, the winding acceleration can be obtained.

\[ a_w = -\omega_a^2 Ae^{-2\lambda t} \sin(\omega t + \alpha) - pI_m^2 D \sin(2\alpha t + 2\phi_0 + \beta) \]  
(10)

where \( \omega_a = (K/M)^{1/2}, A \) and \( \alpha \) are obtained from initial conditions, \( D \) and \( \beta \) are constants related to inducting parameters under fixed conditions.

According to the theoretical analysis, the vibration of the transformer winding is composed of a steady component and a gradually decaying component. Therefore, the vibration acceleration signal of the transformer winding running stably in the ideal state is also twice of the power frequency.

Therefore, under ideal conditions, there is only 100Hz component in the vibration acceleration signal of the winding. In fact, due to the nonlinear characteristics of insulation pad material, the vibration signal of winding may also have harmonic. And in the long-term operation with load, the winding will deform due to loose fasteners and short-circuit impact, and the high-order harmonics in the vibration spectrum will gradually increase.

3. Mechanical performance evaluation of transformer

3.1. Evaluation on fastening state of iron core

3.1.1. Test process
Hammering method is usually used in core vibration test[4]. The impact hammer is used to excite the oil tank, and the vibration signal and input force signal collected by the piezoelectric acceleration sensor are analyzed to judge the mechanical state of the iron core. The test object is S9-M-100/10 three-phase oil immersed power transformer. During the test, the power supply is as regular working state, and three detection points are set in the middle of the top of the transformer, as shown in figure 2.

![Figure 2. Test object](image)

As reference, loosen the fastening screw of clamp near phase A to increase the distance between clamps by about 3mm, so as to increase the gap between silicon steel sheets.

3.1.2. Test results

The ratio of 100Hz signal collected from three measuring points at standard and loose state is shown table 1.

| Standard state | Loose state |
|---------------|-------------|
| 100Hz (mV)    | 1kHz (mV)  |
| 100Hz (mV)    | 1kHz (mV)  |
| ratio         |         |
| Point 1 0.003541 | 0.014237 | 24.87% | 0.005075 | 0.017038 | 29.79% |
| Point 2 0.003041 | 0.013177 | 23.08% | 0.004191 | 0.016562 | 25.30% |
| Point 3 0.002852 | 0.012285 | 23.22% | 0.004032 | 0.015995 | 25.21% |

As we can see in phase A(point 1), under standard conditions, the maximum ratio of 100Hz vibration acceleration signal component to the component within 1kHz is near 25%. While the minimum value of 100Hz vibration acceleration signal component within 1kHz component is up to 29% after the iron core is loosened. Therefore, it is easy to judge whether the iron core is loose or not by checking the ratio of 100Hz vibration acceleration signal component to the component within 1kHz.

3.2. Evaluation on fastening state of iwinding

3.2.1. Test process

The winding looseness defect is simulated by changing the preload because the winding is pressed by the preload screw. Therefore, the pre tightening force of the winding can be realized by measuring the deformation of the strain gauge pasted on the pre tightening screw. The strain gauge with temperature self compensation is selected to avoid the influence of temperature on the deformation of strain gauge. When the strain gauge does not deform, the output voltage of the test circuit is 0. And when the fastening screw is loosened, the tightening force of winding decreases, thus the strain gauge deforms. The larger the deformation is, the higher the output voltage is. When the preload is less than 50% of the standard preload, it is considered that the winding is loose, and the short-circuit current impact resistance of the winding will be greatly affected.

During the test, the low-voltage side winding of the transformer is short-circuit, and the current is set to the rated current. At this time, the voltage at the high-voltage side is about 2% of the rated voltage, and the influence of core vibration can be ignored.
3.2.2. Test results
The vibration signals under different preload conditions are measured, and the results are shown in the table below.

| Point  | Standard state | 50% Loose state | 80% Loose state |
|--------|----------------|-----------------|-----------------|
| 1      | 0.003614       | 0.002746        | 0.002136        |
| 2      | 0.003247       | 0.002939        | 0.0028972       |
| 3      | 0.003146       | 0.002921        | 0.0028705       |

It can be seen from the table that the vibration signal of point 1 has a monotonic decreasing relationship with the preload. Therefore, it can be judged that the winding corresponding to the measuring point has loose defects according to the value.

4. Conclusion
In this paper, the vibration mechanism of transformer core and winding is analyzed theoretically, and the characteristics of vibration signal on the surface of transformer oil tank under different loosen state are measured by experiments. The judgment of core and winding looseness based on the content of fundamental frequency component in vibration signal is proposed. In the next step, the vibration signal analysis of large power transformer will be carried out, the establishment of accurate vibration model of iron core and winding and the separation technology of environmental vibration signal will be studied, so as to optimize the analysis algorithm and improve the detection accuracy.

Acknowledgments
This work was supported by State Grid Corporation Science and Technology Projects (Research on comprehensive evaluation technology of short circuit resistance of transformer in operation under hot state, NO. 5500-202055092A-0-0-00).

References
[1] Liu Hongliang. (2019) Evaluation and treatment of short circuit resistance of power transformer[M]. Electric Power Press, Beijing.
[2] Hao Zhen, Long Kaihua, Zhao Yankun, et al. (2014) Abnormal vibration diagnostic methods of transformers caused by two defects[J]. Electric Power, 47(6): 55–60, 65.
[3] Liu Jun, Zhang Anhong. (2012) Simulation and evaluation of short circuit dynamic stability of windings in power transformer[J]. Transformer, 49(6): 14-25.
[4] Meng Yongpeng, Zhong Bo, Jia Shenli. (2020) Application and development of the vibration analysis in the condition monitoring of electrical equipment[J]. High Voltage Apparatus, 41(6): 461-465.