Study on Vibration Noise Signal Characteristics of 10kv Distribution Transformer under Different Load Conditions

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Abstract. In order to study the effect of load on the transformer vibration noise. In this paper, a S13-M-200/10 distribution transformer is taken as the experimental subject and an experimental platform was built to collect the vibration noise signals of the transformer under no-load, short-circuit, resistive load, inductive load and different load rate. These signals are used to study the vibration characteristics of transformers under different load rate and load characteristics. The results show that the amplitude of the 100Hz fundamental frequency increases with the increase of the load rate, and the amplitude of other frequency basically has no change. The inductive load will cause the increase of the amplitude of 150Hz and 250Hz components, and the amplitude increases with the increase of the inductive load. The research results of this paper provide a theoretical basis for the condition monitoring of transformers based on vibration noise signal.

1. Introduction
As the city's electricity consumption increases year by year, the number of distribution transformers in urban areas is increasing, and the noise caused by their operation is becoming more and more prominent. Therefore, how to effectively reduce noise has been a hot research topic. At the same time, the transformer fault diagnosis technology based on the vibration noise signal has the advantages of no electrical connection with the transformer under test, safety and convenience, etc., and the study on the vibration noise of the transformer is favored by scholars. The vibration noise of transformer is affected by many factors. In order to effectively reduce the noise of the distribution transformer or use the vibration noise to monitor the state of the transformer, it is necessary to understand the influence of load, structure and other factors on its vibration and noise.

The There is a certain basis for the research on transformer vibration noise at home and abroad. For the magnetostriction problem of iron core, a three-dimensional magneto-mechanical coupling calculation model is established to analyze the sound field distribution near the core in reference [1]. In reference [2], vibration noise of an amorphous alloy core dry distribution transformer is tested and mechanical modeling is analyzed to identify the sound source of the transformer, and corresponding noise reduction measures are proposed. Literature [3] studied the influence of load current on the magnetic flux density and noise of the core of the autotransformer, and the study showed that the magnetic flux density and noise of the core would increase when the autotransformer was loaded with...
capacitive load. Literature [4-6] studies the vibration force and stability of transformer windings under short-circuit fault state. To sum up, previous studies mainly focus on the variation of vibration noise and noise reduction, while there are relatively few studies on the influence of load size and load type on the vibration noise characteristics of transformers. It is very important for transformer optimization design and noise reduction to analyze the vibration noise signal characteristics of transformer with comprehensive consideration of load types.

In this paper, the generation mechanism of transformer vibration noise is analyzed, and the influence of load type on vibration noise is studied. Then, the three-phase oil-immersed distribution transformer s13-m-200/10 is taken as the research object to build the experimental platform, design the vibration and noise signal test scheme, collect the vibration and noise signals under different sizes and types of loads of the transformer, and analyze the frequency characteristics of the noise signal.

2. The mechanism of vibration noise of transformer

2.1 Mechanism of vibration and noise

The vibration noise of transformer mainly comes from the vibration of iron core and winding.

When the transformer is running without load, the winding current is very small, about 2% of the rated current. At this time, the winding vibration can be ignored, and it is considered that the noise in the no-load state comes from the core vibration. The core vibration mainly comes from magnetostriction of silicon steel sheet under alternating magnetic field [7-9]. Assuming that the thickness, width and length of the silicon steel sheet are b, w and L, then,

$$U_0 \sin \omega t = -N_w \frac{d\phi}{dt} = -N_w A_c \frac{dB}{dt}$$  \hspace{1cm} (1)

Where, $U_0$ is the power supply voltage, $N_w$ is the number of turns of the windings, $B$ is the magnetic induction intensity, and $A_c$ is the cross-sectional area of the single-layer iron-core silicon steel sheet. Therefore, magnetic induction $B$ can be expressed as,

$$B = -\frac{U_0}{N_w A_c} \int \omega t \sin \omega t dt = -\frac{U_0}{N_w A_c \omega} \cos \omega t = B_0 \cos \omega t$$  \hspace{1cm} (2)

Where $B_0$ is the maximum magnetic induction intensity.

$$B_0 = \frac{U_0}{N_w A_c \omega} \leq B_s$$  \hspace{1cm} (3)

$B_s$ is the magnetic induction intensity at saturation. According to the relationship between magnetic induction intensity $B$ and magnetic field intensity $H$,

$$B = \frac{B_s}{H} \Rightarrow H = \frac{B_s}{B} B_0 \cos \omega t$$  \hspace{1cm} (4)

Thus, the electromagnetic force that causes the core to produce magnetostriction due to the change of magnetic field can be expressed as follows,

$$F = \frac{dL}{L} = \frac{\lambda_s}{H_s^2} \int H dH = \frac{\lambda_s}{H_s^2} \frac{H_s^2}{B_s^2} B_0^2 \cos^2 \omega t = \frac{\lambda_s U_0^2}{B_s^2 N_w^2 A_c^2 \omega^2} \cos^2 \omega t$$  \hspace{1cm} (5)

Where $\lambda_s$ is the maximum magnetostrictive ratio of the silicon steel plate; therefore, it can be obtained that the acceleration $a_c$ of the core vibration is,

$$a_c = \frac{d^2F}{dt^2} = -\frac{2\lambda_s U_0^2}{B_s^2 N_w^2 A_c^2} \cos 2\omega t$$  \hspace{1cm} (6)

According to equation (6), the vibration acceleration frequency of the transformer core is twice that of the power supply, namely 100Hz. At the same time, due to the nonlinearity of core materials, core magnetic flux is not a standard sine wave. Therefore, the actual core vibration and noise signal spectrum is composed of 100Hz fundamental frequency and its higher harmonics, and the amplitude of higher harmonics is often greater than 100Hz.

When the load current flows through the transformer winding coil, due to the existence of magnetic
leakage field, dynamic electromagnetic force is generated between the windings, between the wire cakes and between the wire turns, causing the winding vibration. It is assumed that the current flowing through the windings of a transformer power transformer is [10-11],

\[ I = I_m \sin(\omega t + \phi_0) \]  

(7)

The \( I_m \) is the value of the load current \( \Phi_0 \) is the initial phase load current, the effect on the windings of electric power is,

\[ F = pI_m^2 \left( \frac{1}{2} \cos(2\omega t + 2\phi_0) - \frac{1}{2} \right) \]  

(8)

Where, \( p \) is the electrodynamic coefficient. When studying the dynamic process of the winding coil of a transformer, it can be regarded as a mechanical system composed of elastically connected entities. According to the mechanical structure of the transformer windings, it is assumed that the stiffness of the core is infinite, the upper and lower platen of the windings are rigid, the line cake is the concentrated mass module, the insulating pad and the end ring are the elastic elements, the transformer windings are equivalent to the spring mass system, and the differential equation of the winding displacement is obtained according to the dynamic theorem,

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

(9)

Where, \( M \) is winding line cake mass matrix; \( C \) is the damping coefficient matrix; \( K \) is the elastic coefficient matrix. To solve the equations, winding acceleration can be obtained,

\[ a_w = -\omega_n^2 A e^{2\omega_n t} \sin(\omega_0 + \alpha) - pI_m^2 \sin(\omega_0 + 2\phi_0 + \beta) \]  

(10)

In the equation, \( \omega_n = (K/M)^{1/2} \); \( \alpha \) and \( \alpha \) are given from the initial conditions; \( D \) and \( \beta \) are constants related to winding parameters under fixed conditions. It can be concluded from the theoretical analysis that the vibration of the transformer winding is composed of a steady state component and a gradually decaying component. Therefore, the vibration acceleration signal of the transformer winding that operates stably under the ideal state is also twice of the power supply frequency, namely 100Hz. According to literature [11], the vibration noise signal collected in the air is the superposition signal of the vibration of the iron core and winding, and the superposition signal is expressed as,

\[ a = \sqrt{a_c^2 + a_\alpha^2 + 2a_c a_\alpha \cos \varphi} \]  

(11)

In the formula (11), \( a_c \) is the vibration amplitude of the winding, \( a_\alpha \) is the vibration amplitude of the core, and \( \varphi \) is the phase difference of the vibration signal generated by the core and the winding. From this, it can be known that the vibration noise signal has both base frequency 100Hz component and high frequency component.

2. 2 Theoretical analysis of the influence of load type on vibration noise

In the actual operation of transformer, its load type is not only resistive load, but also inductive load with resistive load, that is, power factor is generally not equal to 1, there is phase difference between current and voltage, and the phase difference between the vibration signal generated by transformer core and winding is,

\[ \varphi = 2\phi_0 + \beta - \frac{\pi}{2} \]  

(12)

In the equation, \( \phi_0 \) is the initial phase of load current, and \( \beta \) is the constant related to winding parameters under fixed conditions. According to equation (10), the phase difference between voltage and current is zero when the load is of pure resistance, and the vibration noise signal of transformer is generated by linear superposition of winding and core vibration signal. However, the phase difference between voltage and current is different under different inductive load, which leads to different vector synthesis modes of vibration between the core and winding, and then the amplitude of noise signal generated by vibration is also different. Therefore, this paper analyzes the variation of the amplitude and frequency spectrum with the load type by collecting vibration and noise signals of the...
3 Experiment setup

3.1 Test systems

In this paper, an experimental platform is set up to test the vibration and noise signals of transformers according to the electrical wiring mode shown in Figure 1. The experimental platform consists of voltage regulator, experimental transformer and load cabinet. The rated capacity of the voltage regulator is 800 kVA, and the system voltage can be continuously adjustable from 0 to 10 kV. The load cabinet is composed of resistance cabinet and inductance cabinet, which can provide resistive load and inductive load for the system respectively. During the test, the required voltage is output by the voltage regulator and applied to the transformer under test. Through the load cabinet can adjust the load size, type. The platform can be tested under different no-load voltage, different short-circuit current and different load conditions. The experimental transformer is three-phase oil-immersed distribution transformer, model is S13-M-200/10, and the main parameters are shown in Table 1.

| Parameter          | Value       |
|--------------------|-------------|
| Rated capacity     | 200 kVA     |
| Rated voltage      | 10/0.4 kV   |
| Rated current      | 11.5/288.7 A|
| Connection symbol  | Dyn11       |

Figure 1. Schematic diagram of electrical wiring of the experimental platform

3.2 Test project

In this paper, the transformer no-load test, short-circuit test and load operation state are respectively set up. In the short-circuit test, vibration signals with short-circuit current of 0.3I_N, 0.6I_N, 0.85I_N and I_N were tested. At the same time, vibration and noise signals under resistive load with current of 0.3I_N, 0.6I_N, 0.85I_N and I_N were tested. In the experiment, the load rate of the transformer was set as 29.2%, 58.04%, 86.74%, 100% and 115.13% (resistive load) respectively, and the corresponding vibration and noise signals were collected. The load in actual operation of distribution transformer is mostly resistive load and resistive inductance load, so this paper mainly studies the influence of resistive load and resistive inductance load on vibration and noise signal. In the experiment, transformer belts were set with different types of loads as shown in Table 2. In the four cases, the total capacity was basically the same, and all of them were rated capacity.
Table 2. Different load types

| load type          | resistive load | resistance-inductance load |
|--------------------|----------------|----------------------------|
| per phase P(kW)    | 66             | 63                         |
| Q(kVar)            | 0              | 20                         |
| total capacity(kVA)| 198            | 198                        |

4 Results and discussion

4.1 Transformer winding and core vibration noise characteristics

Figure 2 shows the frequency spectrum of the vibration noise signal of rated short-circuit and rated no-load voltage. It can be seen from the second section that the winding vibration is the main one in short circuit and the core vibration is the main one in no-load. According to Figure 2, the 100Hz component is the main frequency in the frequency spectrum of the winding vibration noise, and the high harmonic component is less, which is consistent with the theoretical analysis (other short-circuit load noise signal spectrum are similar to the rated short circuit current, 100 Hz component are just different amplitude, here no longer list):

![Figure 2. Spectrum of vibration noise signals under short-circuit load and no-load](image)

Under the no-load experiment, due to the non-linearity of the core material and other reasons, in the frequency spectrum of vibration and noise signal under no-load, the content of high-order harmonic is large, the 200Hz component is the main frequency, and the amplitude of 100Hz is small. Figure 3 shows the linear superposition of vibration and noise signals at different short-circuit currents and rated no-load conditions:

![Figure 3. Spectrum of superimposed noise signal](image)

![Figure 4. Spectrum of vibration noise signals under different load current conditions](image)
voltage. Figure 4 shows the frequency spectrum of vibration noise under different loads. By comparing Figure 3 and 4, it can be seen that the distribution of the superimposed signal’s frequency spectrum is consistent with the noise signal at different load, but the amplitude of each frequency is different. The amplitude of each frequency of superimposed signal and load signal satisfies formula (11). That is, in the normal operation of transformer with load, the core and winding vibration noise are nonlinear superposition, and the amplitude of each frequency after superposition is less than the linear superposition of the core and winding vibration noise signal.

4.2 Effect of load rate on vibration noise of transformer

The frequency spectrum distribution under different load rates is shown in Figure 5. According to Figure 5, the noise signal frequency is mainly concentrated in the range of 100~300Hz. When the load rate is small, that is, when the transformer is under light load, the noise spectrum distribution is similar to the distribution rule under no load state of the transformer. The main frequency is 200Hz. With the increase of load rate, the main frequency becomes 100Hz, because the winding vibration amplitude increases with the increase of load current, while the harmonic component in the winding vibration is small and the amplitude is small, mainly 100Hz amplitude increases, so the main frequency of noise signal is 100Hz.

The variation curves of amplitude of 100~500Hz frequency component with load rate were drawn, and the results were shown in Figure 6. Figure 6 shows that the amplitude of 100Hz of the base frequency increases approximately in a square relation with the increase of the load rate. This is because the larger the load rate is, the greater the load current in the windings will be. At this time, the vibration noise of the transformer mainly comes from the vibration of the windings. It can be seen that the influence of load rate change on the vibration noise signal of transformer is mainly reflected in the fundamental frequency component.

4.3 Effects of different loads on vibration and noise signals

The frequency spectrum of the four types of load vibration noise signals in Table 2 is shown in Figure 7. According to the Figure 7, with the increase of the inductive load, the amplitude of each frequency of the noise signal increases, and odd frequency multiplication components such as 150Hz and 250Hz appear. The curve of amplitude of each frequency varying with the inductive load is shown in Figure 8. According to Figure 8, when the transformer is loaded with resistive inductance, the fundamental frequency component of the vibration noise signal spectrum is smaller than that of resistive load, and smaller and smaller with the increase of the inductive load in the load; The odd frequency multiplication components of 150Hz and 250Hz appear, and increase with the increase of the inductive load. When the inductive load is greater than 40kVar, the saturation phenomenon occurs. According to formula (10) in this paper, when the inductive load is loaded, the phase difference between the voltage and the current increases with the increase of the inductive load, so that the phase difference between the core and the
winding vibration signal increases, while the cosφ decreases accordingly. The amplitude of the superposition signal between the winding and the core vibration decreases correspondingly, so that the amplitude of the vibration noise signal of each frequency decreases.

$$a_c = \frac{2L_0\omega^2 B_1^2}{B_j^2} \cos(2\omega t) + \sum 2k^2 L_0 \omega^2 \frac{B_j^2}{B_1^2} \cos(2k\omega t) \quad (k = 3, 5, ... \quad (13)$$

It can be seen that the amplitude of high-order harmonic components in winding vibration will increase with the increase of harmonic current, thus causing the amplitude of 200 and 300Hz to increase.

5 Conclusion
In this paper, under no-load, short-circuit, resistive loads with different values, different load characteristics, the vibration noise signal of S13-M-200/10 distribution transformers are collected and analyzed by spectrum. The following conclusions are obtained:
1. Under resistive load condition, the vibration noise signal spectrum is a nonlinear superposition of the vibration noise spectrum at no load and rated short circuit, and the vibration noise signal frequency distribution is the same as the superimposed signal, and the amplitude of each frequency is different.
2. The amplitude of the vibration noise signal 100Hz increases with the increase of the load of the transformer. The amplitude and ratio of other frequencies rarely change with the change of the load rate. Therefore, the change of the load rate mainly affects the fundamental frequency component of the spectrum, and has almost no effect on the frequency component of the spectrum.
3. The increase of the resistance load of the transformer will cause the increase of 150Hz and 250Hz components obviously and the decrease of fundamental frequency component.

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