The Influence of Load on the Vibration and Noise Characteristics of Transformer

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Abstract. In order to further understand and grasp the impact of load on the vibration and noise characteristics of the transformer, this article analyzes the impact of load factors, power factor, harmonic current, three-phase unbalance and other load factors on transformer vibration and noise from the perspective of transformer vibration mechanism. A 10kV/200kVA three-phase oil-immersed distribution transformer was used as the object. Experiments were conducted to study the changes in the spectrum distribution, noise intensity and A-weighted sound pressure level of the transformer vibration and noise under the influence of different load factors. The results show that: when the frequency increases, the amplitude of the 100Hz fundamental frequency in the vibration noise signal increases, and the noise level increases accordingly; when the power factor increases, the amplitude of the odd frequency components in the vibration noise signal gradually decreases with the increase of the power factor. There is no obvious fluctuation in amplitude except 100Hz. When the harmonic current and the three-phase are unbalanced, the spectral components become complicated and accompanied by a large number of odd-order frequency multiplication components. With the increase of harmonic content, the amplitude of vibration noise signal and A-weighted sound pressure level increase significantly; the degree of unbalance and the occurrence of unbalance have a greater impact on the amplitude of vibration noise signal and A-weighted sound pressure level. The research in this paper provides a reference for the noise suppression of power equipment and the fault diagnosis technology based on vibration and noise signals.

1. Introduction
As the last stage of the power system, the number of distribution transformers is huge, widely distributed in all corners of cities and villages. Due to the harsh working environment and complex conditions, three-phase unbalance, load fluctuations and other phenomena often occur. The access of many non-linear loads such as power electronic devices makes the current harmonic problem more serious. Once the transformer fails or is damaged, it will bring huge property losses to the society and threaten personal safety; at the same time, the noise generated by its vibration will also have a greater impact on nearby residents. Therefore, it is of great significance to grasp the operating status of the transformer in time and control its vibration and noise level.

In recent years, some scholars have proposed a state monitoring technology based on transformer noise signals. The principle is to realize the evaluation of the transformer state by collecting vibration and noise signals. This method has the characteristics of online monitoring and no electrical contact with the tested transformer [1, 2]. Therefore, studying the vibration and noise characteristics of
different operating conditions and the influence of different factors on the vibration and noise characteristics is conducive to the early realization of the transformer condition monitoring technology based on vibration and noise signals.

There have been many achievements in the research on transformer vibration and noise at home and abroad. Literature [3,4] studied the relationship between the fundamental frequency component of transformer vibration signal with voltage, current, and oil temperature; Literature [5,6,7] studied the influence of insulating materials in transformers on winding vibration characteristics; Literature [8,9,10] By studying the compression force, the relationship between the natural frequency of the winding and the temperature is obtained; the literature [11,12] studied the transformer box wall and found that the vibration amplitude of the box wall surface increases with the increase of temperature. The amplitude of some areas has decreased. For example, literature [13] only studied the relationship between the load current change and the amplitude and frequency distribution of the fuel tank vibration signal; literature [14,15] established a model considering current and voltage, and studied the vibration and noise signal changes under different currents. The impact of changes in load types is not considered.

On the whole, the literature on the influence of load factors on the characteristics of vibration and noise signals is mostly focused on the study of current and voltage [16,17], but the load factors also include load factor, power factor, three-phase unbalance, current Harmonics, etc. Therefore, studying the influence of the load on the vibration and noise characteristics of the transformer is helpful to improve the transformer fault diagnosis technology, and it is also of great significance to control the noise of power equipment.

This article first theoretically analyzes the influence of load factors such as load factor, power factor, current harmonics, and three-phase unbalance on the vibration and noise characteristics of the transformer. Based on this, the influence of these load factors on the noise characteristics is studied based on experiments, and the relationship between the change in load factor and the change in noise characteristics.

2. Theoretical Analysis of the Impact of Load on Transformer Vibration and Noise

2.1. The Mechanism of Transformer Noise

The noise during transformer operation is mainly produced by the vibration of the iron core and winding.

The magnetic hysteresis effect of the silicon steel sheet itself and the electromagnetic force between the gaskets caused by magnetic flux leakage make the iron core vibrate. As the manufacturing process matures, the amplitude of electromagnetic force vibration can be ignored. The current literature draws the conclusion that the core vibration frequency is 100 Hz through simple mathematical derivation. However, in actual measurement, it is found that in addition to the fundamental frequency of 100Hz, it also contains components such as 200Hz and 300Hz with larger amplitude. For this reason, this article derives from the perspective of energy conservation to explain this phenomenon. The expression of Gibbs free energy (G) in thermodynamics is:

\[ G = U - TS + PV \]  

(1)

T is temperature; S is entropy; PV volume work; U is internal energy.

When the transformer is working normally, the magnetic permeability is high, and the magnetization curve is close to linear. Combining the analysis method in literature [9], apply it to ferromagnetic materials, namely:

\[ G(\sigma, M, T) = U - TS - \sigma E \]  

(2)

\( \sigma \) is the core preload; \( \varepsilon \) is the core strain; M is the magnetization; T is the temperature. For core materials, the energy per unit volume is:

\[ dU = -\sigma d\varepsilon + \mu_0 H dM + T dS \]  

(3)
Then the total differential of $G(\sigma,M,T)$ is:
\[ dG = dU - SdT - TdS - \varepsilon d\sigma - \sigma d\varepsilon = -\varepsilon d\sigma + \mu_0 H dM + S dT \]  
(4)

Will expand at $(0,0)$, at this time $G(0,0) = 0$. Get the relationship between free energy and parameters:
\[ G(\sigma,M) = \frac{\partial^2 G}{2\partial \sigma^2} \sigma^2 + \frac{\partial^3 G}{6\partial \sigma^3} \sigma^3 + \cdots + \frac{\partial^2 G}{2\partial \sigma \partial M} \sigma M^2 + \frac{\partial^2 G}{6\partial \sigma^2} \sigma^2 M^2 + \cdots + \frac{\partial^3 G}{2\partial M^3} M^3 \]  
(5)

The formula (5) is divided into three categories: only related to $\sigma$; related to $\sigma, M$; and related only to $M$. Core strain $\varepsilon$ consists of elastic strain and magnetostrictive strain, and magnetostriction is the main factor of core strain. Then it can be expressed by a polynomial with $M$ in (M is an odd function, removing terms with odd powers) can be written as:
\[ \varepsilon = x_1 M^2 + x_2 M^4 + x_3 M^6 + \cdots \]  
(6)

$x$ is the function expression after merging the like.

The magnetization can be approximately regarded as proportional to the excitation current $i$, that is, $M = bi$, $b$ is a constant, and into equation (6):
\[ \varepsilon = x_2 b_2 i_2^2 \sin^2 \omega t + x_4 b_4 i_4^4 \sin^4 \omega t + x_6 b_6 i_6^6 \sin^6 \omega t + \cdots \]  
(7)

It can be seen that the vibration and noise signals of the iron core are mainly 100Hz, 200Hz, and 300Hz.

The reason for winding vibration is the electromagnetic attraction caused by alternating current flowing between the windings. The current directions between the high and low voltage windings are opposite and mutually repel each other; the current directions of the turns in the windings are the same and attract each other. Make the winding produce axial and radial vibration, and the axial vibration is dominant. Let us set the transformer current as:
\[ I = I_m \sin (\omega t + \phi) \]  
(8)

$\phi$ is the phase difference between current and voltage, the winding electromagnetic force is:
\[ F(t) = \frac{p I_m^2}{2} \left[ \cos(2\omega t + 2\phi) - 1 \right] \]  
(9)

$p$ is the electrodynamic coefficient and $I_m$ is the current amplitude.

It can be seen from equation (9) that the vibration frequency of the electromagnetic force of the winding is twice the current, that is, 100 Hz. In practice, due to the non-linearity of the insulating pad and other factors, there are harmonic components in the vibration acceleration.

2.2. The Influence of Load Factors on Transformer Vibration and Noise

It is generally believed that there is no mutual interference between the vibration of the iron core and the winding, and vector superposition can be performed during calculation. The influence of load factors on the vibration and noise of the transformer essentially affects the vibration of the winding and the iron core, and changes the amplitude and phase of the vibration acceleration. Load factors generally include load factor, power factor, current harmonics, and three-phase unbalance.

When the load factor changes, the voltage remains basically unchanged, and its change has a greater impact on the amplitude of the winding vibration acceleration, but has little effect on the combined phase angle and the core vibration acceleration amplitude.

When the power factor changes, the combined acceleration amplitude and phase change.
When there are harmonics in the current, it can be expressed as:

$$F(t) = \frac{pI_0^2}{2} \left[ \cos (2\omega t + 2\phi) - 1 \right]$$  \hspace{1cm} (10)

$I_1$ is the fundamental wave current, and $I_k$ is the harmonic current. When the current has harmonics, the winding electromagnetic force is:

$$F(t) \propto \left[ I_1 \cos (\omega t + \phi) \right]^2 + \sum_{k=2}^{n} 2I_k \cos (\omega t + \phi) \cdot I_k \cos (\omega t + \phi) + \left\{ \sum_{i=1}^{n} I_i \cos (\omega_i t + \phi) \right\}^2$$ \hspace{1cm} (11)

Equation (12) consists of three parts. The first part is the square of the fundamental current, which represents the electromagnetic force when the fundamental current component acts alone, with a frequency of 100 Hz; the second part is the product of the fundamental current and the harmonic current, which represents the fundamental The effect of wave current and harmonic current, The frequency of this part is $f_i \pm 50$ Hz; the third part is the accumulation of the product of the $k_i$ time harmonic and the $k_j$ time harmonic, where $k_i,k_j=3,5,7,9,\ldots$. When $k_i=k_j$, it is similar to the electromagnetic force of the first part of the fundamental current, and the component frequency in the vibration acceleration is $2f_i$ Hz; when $k_i\neq k_j$, it is the interaction between different orders of harmonics, and the frequency at this time is $f_i \pm f_k$ Hz. The presence of harmonics enlarges the frequency spectrum of the vibration signal, even with components above 1000 Hz; at the same time, the amplitude of high-frequency components becomes larger. These harmonic frequencies may be close to the natural frequency of the transformer, causing the transformer to resonate, accelerating the aging of the mechanical state of the transformer and causing failure.

Different from load factor, power factor, and harmonics, the impact of three-phase unbalance on transformer vibration is more complicated. When three-phase unbalance occurs, the excitation component of the primary side has not changed, so the iron core vibration is little affected; the winding current of each phase changes, so the winding vibration changes. Because the vibration and noise signal is generated by the superposition of the three-phase winding and the iron core vibration, as shown in Figure 1 (the iron core is not shown).

![Figure 1. Three-phase winding vibration superposition and propagation](image)

Taking any point $M$ on the box wall as an example, the vibration amplitude of the three-phase winding at point $M$ is also different due to the increase in distance. At the same time, when the vibration wave is transmitted to the boundary between the oil and the tank, the normal velocities of the two media are equal, as shown in equation (12).

$$v_{1n} = v_{2n}$$  \hspace{1cm} (12)
when the vibration wave is transmitted to the box wall, only the component perpendicular to the surface of the box wall causes the box wall to vibrate and sound.

Combining these two processes, because the incident angle of the vibration wave of each phase at the same point on the box wall is not the same and the distance from each phase is not completely equal, even under the same degree of unbalance, there will be three-phase unbalanced winding positions. The difference makes the vibration and noise signal at the measuring point have different changes.

3. Transformer Vibration and Noise Signal Acquisition Platform
In this experiment, B&K’s model 4189 sound sensor was used for collection. The test object was a 10kV three-phase oil-immersed distribution transformer model S11-M-10/10. The specific wiring diagram is shown in Figure 2.

In Figure 2 the voltage regulator can be used for continuous adjustment of 0~10kV; the sound sensor is distributed around the transformer to collect the vibration and noise signal and stored in the data acquisition device through the data cable; the load cabinet can be adjusted for reactive and active loads, harmonious The wave load is provided by the full bridge rectifier circuit. The main content of this experiment is to study the influence of load factors on the noise characteristics of the transformer by changing the load factor, current harmonics, power factor and setting three-phase unbalance and other different load factors.

The collection position is selected to be one-half of the height of the transformer cabinet and 30 cm from the cabinet surface. This collection is selected Four measuring points 1, 2, 3, 4 are shown in Figure 3 for the specific positions.

4. The Influence of Load on Transformer Vibration and Noise Signal

4.1. A-weighted Sound Pressure Level
Noise in transformer operation is one of the important influencing factors in power grid construction. As a key parameter to measure the noise level of transformers, the calculation steps of A-weighted sound pressure level are as follows:

1) The sound pressure level of the noise signal \( L_{P_i} \).

\[
L_{P_i} = 10 \log \frac{P_i^2}{P_0^2}
\]  

\( P \) is the time domain amplitude of the noise signal, \( P_i \) is the center frequency of the i time frequency band, and \( P_0 \) is the reference sound pressure, which is \( 20 \times 10^{-6} \) Pa.

2) A-weighted sound pressure level calculation \( L_{PA} \).

\[
L_{PA} = 10 \log \left[ \sum 10^{(L_{PAj} + \Delta A_j) / 10} \right]
\]  

\( \Delta A_j \) Indicates the A-weighted value in the j-th frequency band.
4.2. The Influence of Load Factor on Transformer Vibration and Noise Signal

The load factor is one of the important factors that affect the noise characteristics of the transformer, and load factor fluctuations often occur during transformer operation. Keep the transformer voltage at the rated voltage. Take 1 measuring point as an example. The main components of the vibration and noise signal under different load rates change with load rate as shown in Figure 4.

When the load factor changes, the frequency spectrum components of the vibration and noise signal do not change, and the 100Hz, 200Hz, and 300Hz components are the main components, accompanied by a small amount of 400Hz, 500Hz, and 600Hz components. At the same time, as the load rate increases, the amplitude of the fundamental frequency component of 100Hz increases rapidly, and the main frequency of the vibration and noise signal gradually becomes 100Hz, and its amplitude rises from the initial 0.58mPa to the final 7.2mPa, an increase of 11 times. The amplitude of 200Hz and 300Hz components does not fluctuate much with the increase of load rate; the high frequency components show a slight upward trend.

When the load rate is adjusted, the load voltage is almost unchanged, the iron core vibration is not affected, and the load current is changed. Compared with the iron core vibration noise signal, the frequency spectrum composition of the winding vibration noise signal is relatively simple.

Table 1 shows the A-weighted sound pressure level of the average vibration and noise signal at the four measurement points under different load rates. On the whole, as the load factor increases, the A-weighted sound pressure value of the transformer vibration and noise signal gradually increases, and the noise level gradually increases.

| Load factor(%) | A-weighted value /dB | Load factor(%) | A-weighted value /dB |
|---------------|----------------------|---------------|----------------------|
| 27            | 32.89                | 100           | 34.39                |
| 42            | 32.74                | 114           | 34.42                |
| 57            | 33.57                | 142           | 35.59                |
| 84            | 34.19                | 200           | 36.56                |

4.3. The Influence of Power Factor on Transformer Vibration and Noise Signal

The power factor of the transformer in actual operation is often less than 1. Ensure that the transformer load remains unchanged while adjusting the size of the inductive load. The amplitude changes of the main components of the vibration and noise signal under different power factors at 1 measuring point are shown in Figure 5.

Table 1. The average A-weighted sound pressure level of the vibration and noise signals of the four measurement points when the load rate changes

Figure 4. Main components of vibration and noise signals under different load rates

Figure 5. The amplitude of the main component changes when the power factor changes
It can be seen that the addition of the inductive load makes the signal appear more 50Hz odd frequency components such as 150Hz, 250Hz, and the amplitude of the 50Hz odd frequency components gradually decreases as the power factor tends to 1. Taking the 150Hz component as an example, when the power factor is 100%, the amplitude is 0.07mPa, which is about 90% lower than when the power factor is 81.4%. The 100Hz fundamental frequency amplitude gradually increases as the power factor tends to 1, the 200Hz and 300Hz components are affected by the power factor, and the amplitude of the high-frequency components of 400Hz and above shows an increasing trend as the power factor increases. Therefore, when detecting the fault of the transformer through vibration and noise, the influence of power factor changes cannot be ignored.

Table 2 shows the A-weighted sound pressure level of the average vibration and noise signal at the four measuring points under different load rates. On the whole, as the load factor approaches 1, the A-weighted sound pressure value of the transformer vibration and noise signal first increases and then decreases, but the overall noise level tends to increase.

Table 2. Average A sound level of vibration and noise signals at four measurement points under different power factors

| Power factor (%) | A-weighted value /dB | Power factor (%) | A-weighted value /dB |
|------------------|----------------------|------------------|----------------------|
| 0.814            | 36.11                | 0.957            | 35.67                |
| 0.942            | 34.31                | 1.000            | 34.42                |

4.4. The Influence of Current Harmonics on Transformer Vibration and Noise Signals

This experiment is carried out under rated load and 60% rated load. The effect of harmonics on the noise characteristics of transformers is studied by adding 3, 5, and 7 harmonics to the current respectively and adding 3, 5, and 7 harmonics at the same time. When adding different harmonics under rated load, the frequency spectrum distribution of the noise signal at 1 measuring point is shown in Figure 6. After adding harmonics, the amplitudes of the main components of the vibration and noise signal are shown in Figure 7.

It can be seen that after the addition of harmonics, the noise spectrum distribution range becomes wider and the components become complicated. There are many high-frequency components such as 700Hz and 900Hz in the frequency spectrum, and even components above 1000Hz; at the same time, there are a lot of 50Hz odd frequency components such as 150Hz and 250Hz. Larger amplitude components appear near 450 Hz and 950 Hz. It is presumed that the part of the vibration and noise signal is close to the natural frequency of the transformer, and the maximum value caused by resonance.
component harmonics reduce the 100Hz fundamental frequency component more. When the different harmonics are injected, the sound pressure value of the vibration and noise signal A-weighted at 1 measuring point is shown in Table 3.

| Harmonic order in current | A-weighted value /dB | harmonic order in current | A-weighted value /dB |
|--------------------------|----------------------|--------------------------|----------------------|
| 1                        | 34.42                | 1.7                      | 44.96                |
| 1.3                      | 44.86                | 1.3, 5, 7                | 46.96                |
| 1.5                      | 45.11                | -                       | -                    |

It can be seen that the noise level of the transformer is significantly increased when the harmonics are present, and the sound pressure level A increases by more than 10db compared to the fundamental current; compared to a single harmonic, the noise level increases even more when the multiple harmonics exist.

The main frequency components of the vibration noise signal within 1000 Hz under different harmonic content under rated load are shown in Figure 8, and the A-weighted sound pressure value of transformer vibration and noise is shown in Table 4. It can be seen that as the harmonic content increases, the amplitude of each frequency component shows an increasing trend. For example, when 35% harmonic content is relative to 0% content, the 100Hz fundamental frequency amplitude doubles, and the 200Hz amplitude increases 6 times. At the same time, as the harmonic content increases, the transformer vibration noise level A increases, and when the harmonic content is 35%, the noise level A increases by about 60%.

To sum up, the existence of harmonics will make the frequency spectrum distribution of vibration noise signals wider and the components more complex, and the sound level of vibration noise A will increase significantly. With the increase of harmonic content, the amplitude of each component of transformer vibration noise signal will increase. The sound level increases accordingly. The difference in the order of the harmonics has a smaller effect on the vibration and noise signal, and has a greater impact on the vibration and noise than a single harmonic and multi-component harmonic.

| Harmonic content | A-weighted value /dB | Harmonic content | A-weighted value /dB |
|------------------|----------------------|------------------|----------------------|
| 0                | 32.78                | 35%              | 50.51                |
| 17.5%            | 43.97                | -                | -                    |

4.5. Formatting Author Names
In the actual operation of distribution transformers, three-phase unbalance often occurs, and one-phase or two-phase unbalance and other more extreme situations may occur. Here, we choose 0%, 50%, and 100% to study the influence of three-phase unbalance on the vibration and noise characteristics of the transformer under five different working conditions (see Table 5).

| Working condition | A phase load | B phase load | C phase load | Unbalance |
|-------------------|--------------|--------------|--------------|-----------|
| 1                 | 66kW         | 0kW          | 0kW          | 100%      |
| 2                 | 0kW          | 66kW         | 0kW          | 100%      |
| 3                 | 66kW         | 66kW         | 0kW          | 50%       |
| 4                 | 66kW         | 0kW          | 66kW         | 50%       |
| 5                 | 66kW         | 66kW         | 66kW         | 0%        |
The amplitude of the main components under each working condition at the measuring point is shown in Figure 14, and the sound level of transformer vibration noise A is shown in Table 6. When the three-phase is unbalanced, the noise signal spectrum is distributed on 100~600Hz, and the main components are 100Hz, 200Hz, 300Hz, but there are a lot of 50Hz odd-order frequency components. Compared with the balanced load, the fundamental frequency of 100Hz and 200Hz when the three-phase unbalance occurs has a huge difference compared with the balanced load. Taking 100Hz as an example, the fundamental frequency of 100Hz under balanced load condition 5 is about 2.6mPa, while the amplitude of 100Hz fundamental frequency under condition 2 and 4 is only about 1mPa, which is 60% lower than condition 5, condition 1, 3 Compared with working condition 5, it is reduced by about 90%. The amplitude of the high-frequency components of 300 Hz and above is less affected by the three-phase imbalance. Taking the 300 Hz component as an example, the amplitude difference between working condition 4 and working condition 5 is the largest but only 22.6%. Compared with the transformer vibration noise under rated load, the sound level A is generally higher, so three-phase unbalance should be avoided; at the same time, the vibration and noise signal changes caused by three-phase unbalance should be considered when fault diagnosis based on vibration and noise signals.

| Working condition | 1 | 2 | 3 | 4 | 5 |
|-------------------|---|---|---|---|---|
| A-weighted value /dB | 34.51 | 34.26 | 35.02 | 35.46 | 33.22 |

![Figure 8. Main frequency amplitude at different harmonic content](image1)

![Figure 9. Amplitude of main components of noise under different working conditions](image2)

5. Conclusion
This paper studies the influence of load factors such as load factor, power factor, current harmonics, and three-phase unbalance on transformer vibration and noise from both theoretical and experimental aspects, and the following conclusions are obtained:

When the load rate increases, the noise level of the transformer gradually increases, and the amplitude of the 100Hz fundamental frequency in the noise signal increases and the amplitude of other components changes little. As the power factor gradually approaches 1, the amplitude of the 100Hz fundamental frequency in the vibration and noise signal fluctuates greatly, the amplitude of the 50Hz odd frequency multiplication gradually decreases, and the amplitude of the high-frequency component above 400Hz gradually increases; Harmonic load will significantly increase the level of vibration and noise, which will broaden the noise signal spectrum and complicate the components. As the harmonic content increases, the level of transformer vibration and noise gradually increases, and the amplitude of each component continues to increase. The number of harmonics has less impact on noise signals, and composite harmonics have greater impact on vibration and noise; When the noise level in each...
working condition is higher than the rated load when the three-phase is unbalanced, the position of the unbalanced phase will have a greater impact on the measured vibration and noise signal.

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