Vibration characteristics and vibration isolation design of oil-immersed power transformer

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Abstract: Transformer vibration and noise has become a prominent problem in power grid construction and operation. Firstly, on the basis of expounding the vibration mechanism of iron core and winding, the transmission path of vibration and noise of transformer is analyzed. Secondly, it is pointed out that it is not cost-effective to control transformer vibration and noise only from the selection of core and winding materials, manufacturing process and structural optimization. It is necessary to start from the transmission path of transformer sound and vibration, and adopt auxiliary vibration reduction and noise reduction measures such as vibration isolation of the body to reduce the transmission of vibration of the body to the oil tank wall, foundation and adjacent structures. Then, the design method of oil immersed power transformer body vibration isolation is discussed, and the relevant parameters such as frequency ratio, damping ratio and the arrangement of vibration isolation support are proposed. The reasonable vibration isolation design of transformer body can achieve remarkable vibration isolation effect and the vibration isolation efficiency can reach more than 96%. Finally, the vertical design stiffness of 81 kinds of oil immersed power transformer vibration isolation layers with 4 voltage levels of 10 kV, 35 kV, 110 kV and 220 kV are calculated. Taking a typical 110 kV transformer as an example, the corresponding vibration isolation design scheme is proposed. The research provides a good reference for the vibration isolation design of transformer body in the future.

1. Introduction
With the rapid advancement of urbanization and the rapid development of power grid construction in China, the vibration and noise caused by transformers, reactors and other equipment have become prominent problems in power grid construction and operation[1]. Transformer noise is caused by the vibration of iron core and winding under the action of voltage and current, which propagates outward through tank structure. Among them, the reason why the winding vibrates is that after the load is applied by the equipment, the electromagnetic force generated by the current interacts at different parts of the annular coil, so that the coil itself produces periodic expansion and contraction; The vibration of
iron core is mainly caused by magnetostriction of silicon steel sheet in magnetic field. Because both electromagnetic force and magnetostriction effect are closely related to the periodic change of electromagnetic field, the vibration and noise characteristics of transformer equipment are directly related to the frequency of applied alternating current \[2\].

In order to reduce the vibration and noise of transformers, many feasible methods have been put forward abroad\[^{3-4}\]. For example, by improving the core structure, reducing the magnetostriction of silicon steel sheets and reducing the rated working magnetic density of the core, good vibration and noise reduction effects have been achieved. In addition, European and American countries have adopted noise reduction measures such as sound insulation, sound absorption and noise elimination, which have also achieved remarkable results. China has also achieved remarkable results in substation noise control. Transformer manufacturers, power grid companies, relevant universities and scientific research units have carried out a large number of research and application of transformer vibration and noise control technologies, which are not much different from those of foreign countries in terms of theoretical research on vibration and acoustics and formulation of relevant standards. Especially, many remarkable scientific and technological achievements, practical technical measures and schemes have been achieved in the aspects of acoustic vibration analysis, sound insulation, noise elimination and plane layout optimization of substation sound source equipment and comprehensive noise reduction technology of the whole station. Based on the noise control standards for power transmission and transformation projects promulgated by IEC and other international organizations, and referring to the noise level control indexes of foreign developed countries, GB/T22075-2008 audible noise control standards for HVDC converter stations were compiled, forming reasonable equipment manufacturing standards and noise test detection methods.

Vibration and noise reduction of transformer body is the shortest and most effective way to control transformer vibration and noise. To reduce the body noise of transformer, firstly, optimize the structure and manufacturing process of transformer Iron cores and windings and oil tank, and select high-quality silicon steel sheet with high magnetic permeability; Second, we should start with the propagation path of noise and vibration, cut off the propagation path, consume or block the energy of vibration and noise. On the basis of analyzing the vibration mechanism and propagation path of transformer core and winding, this paper discusses the vibration isolation design method of transformer Iron cores and windings, calculates the vertical design stiffness of vibration isolation layer of 81 oil-immersed power transformers with different voltage grades, and takes a typical 110kV transformer as an example to carry out the vibration isolation design of transformer Iron cores and windings. The research in this paper has a good reference for the design and application of vibration isolation of transformer Iron cores and windings.

2. Vibration mechanism and propagation path of transformer body.

2.1. Vibration mechanism of Transformer body.
Transformer body refers to the iron core and winding assembled into a whole by clamps inside the oil tank. The iron core is formed by stacking thousands of ultra-thin silicon steel sheets, and the winding is a coil wound around the iron core. Iron core is generally composed of central column, side column and yoke. The main column, side column and yoke of iron core can be simplified as an integral structure when modeling and analyzing, so as to keep the outline of the outer edge of iron core consistent with the actual structure. Each phase winding has three coils: high-voltage, medium-voltage and low-voltage. When modeling, the winding can be simplified into a cylinder, keeping the inner and outer radius, and the cylinder height is consistent with the actual size. Figure 1 is a body model of a 220kV three-phase integrated transformer.
Fig.1 Core and winding model of typical transformer.

The iron core and winding produce electromagnetic vibration on silicon steel sheet and coil under no-load and load conditions, which leads to noise. Under normal circumstances, when the transformer is unloaded, the noise signal caused by winding vibration is very small, and the noise of the transformer is mainly caused by magnetostriction of the core; Under load, because the magnetic flux in the core is very small, the vibration of the core can be ignored, and the noise of the transformer is mainly caused by the winding vibration under the action of magnetic field force. In normal operation of transformer, the vibration of transformer body is composed of core vibration caused by magnetostriction of silicon steel sheet and winding vibration caused by magnetic field force. The silicon steel sheet undergoes magnetostriction under the action of alternating magnetic field, which makes the iron core vibrate periodically with the change of excitation frequency. Because the change period of magnetostriction is 1/2 of the power frequency voltage, the core noise caused by magnetostriction is based on 2 times of the power frequency voltage. Due to the strong nonlinear characteristics of core magnetostriction and the different magnetic flux path lengths along the inner and outer frames of the core, the vibration and noise of the core include not only the fundamental frequency, but also the even multiples of the power frequency voltage frequency and other higher resonant frequencies\[^5\].

The current in the transformer body coil interacts with the leakage magnetic field, causing electromagnetic force on the winding wire. The leakage field and the current in the windings cause the windings to generate axial and radial electromotive forces. Research has shown that the windings of large-capacity power transformers can generate 1kN~20kN axial electromotive force under the action of the leakage magnetic field. The vibration causes the transformer oil to vibrate, which is transmitted to the iron core clip through contact, causing metal impact and making the iron core as a whole vibration. Since the leakage flux is alternating, according to the electromagnetic theory, an alternating electromagnetic-3 attraction will be generated between the magnetically conductive steel parts with an air gap. If the connection of these parts is unreliable, metal impact will occur, resulting in noise\[^6-7\].

2.2. Sound and vibration propagation path of transformer body

As the electromagnetic force received by the transformer core and winding is mainly transferred to the clamps of the restrained core and winding through the insulating board, the vibration of the body and clamps is transmitted to the tank through the insulating oil medium and the bottom or top fixing device, which causes the vibration of the tank wall. It can be seen from the vibration propagation path of transformer body and oil tank body in figure 2 that there are mainly two propagation paths for the vibration of transformer body to the tank wall. The first propagation path is that the vibration of the body propagates to the insulating oil of the transformer through solid-liquid coupling, which causes the vibration of the insulating oil medium. When the vibration energy wave is transmitted to the tank wall, it is transmitted to the tank wall through liquid-solid coupling, which causes the vibration of the tank wall. The second propagation path is that the vibration of the body is transmitted directly to the tank bottom and the top cover plate through the connecting device between the clamps and the bottom or top of the tank, and then to the wall plate through the bottom plate and the cover plate.
2.3. Frequency spectrum characteristics of transformer vibration (noise)

Since the vibration signals on the transformer body and clamps are difficult to be collected, the vibration signals on the oil tank surface can represent the vibration spectrum characteristics of the transformer body according to the vibration propagation characteristics of the transformer body. Figure 3 shows the response spectrum of the fuel tank surface acceleration measured during the field operation of a 500kV transformer. In addition, the research shows that the vibration signal on the surface of the transformer oil tank is strongly correlated with noise, and the vibration signal on the surface of the transformer oil tank is basically consistent with the spectrum signal of near-field noise. Therefore, the spectrum of near-field noise can also be used to evaluate the vibration spectrum of the transformer body.

As can be seen from figure 3, the linear spectrum characteristics of the vibration spectrum on the transformer surface are very obvious, that is, the vibration energy is concentrated at several frequency points. As can be seen from the figure, frequency points of the transformer vibration energy concentration are 100Hz and a series of harmonic frequencies (integer multiples of 50Hz). Among them, the energy of 50Hz even times (i.e. 100Hz and its harmonic frequency) is significantly higher than that of odd times, and the energy of low frequency band is higher than that of high frequency band. 100Hz and its harmonic frequency points (within 1000Hz) account for the majority of the total vibration energy.
In order to further analyze the characteristics of vibration spectrum of iron core and winding, the characteristics of vibration spectrum can be analyzed by measuring the near-field noise of transformer under no-load and short-circuit test conditions. Six transformers with different voltage levels and capacities from different manufacturers are selected for in-plant measurement. The measured near-field noise spectra of the six transformers under short-circuit test conditions have good consistency, which shows that the noise is prominent at 100Hz, while the noise at other frequency points is small, almost to a negligible degree. Figure 4 shows the noise spectrum of 220kV transformer (capacity is 24000kW) produced by a domestic factory, which is the largest at 100Hz, about 90dB, and other places are basically background noise. According to the vibration mechanism of iron core and winding, the noise of transformer in short-circuit state mainly comes from the vibration caused by electromagnetic force of winding coil when it is energized, and the electromagnetic force of coil is proportional to the square of current, and the frequency is twice the power frequency of 50Hz of short-circuit current, that is, 100Hz.

![Figure 4 Frequency spectrum curve of transformer noise under short circuit condition.](image)

When the transformer is in no-load state, the vibration spectrum of the transformer core is complex. As shown in figure 5, there are more resonance frequencies at even multiples of the power frequency voltage, which is consistent with the previous analysis. The test research also shows that the no-load noise of transformer varies greatly with voltage, and the noise at 97% rated voltage is about 3dB(A) lower than that at 93% voltage, and it is about 6dB(A) lower than that at 93% voltage, which shows that the vibration of transformer core is very sensitive to voltage variation. The frequency spectrum characteristics of vibration and noise in actual load operation of transformer are basically the same as those in no-load operation, and the amplitude can be linearly superimposed on the amplitude of 100Hz frequency point under short-circuit current condition.

![Figure 5 Resonance frequencies in no-load state](image)

(a) vibration acceleration spectrum of the tank wall when the transformer (220kV) in the station is unloaded
Near-field noise spectrum of transformer (500kV) under no-load test

Fig. 5 Frequency spectrum of vibration and noise of transformer under no-load condition.

3. Vibration and noise reduction technology of transformer body

Iron core and winding, as the most core components in the transformer, have a complex structure, and their vibration and noise are greatly influenced by factors such as production, manufacturing process and installation mode. Therefore, in order to reduce the vibration and noise of the transformer, the hysteresis expansion and winding vibration of the iron core must be suppressed at the source first.

Although reducing the vibration and noise of transformer body from the aspects of transformer core and winding can suppress the acoustic vibration source of transformer, these measures and methods are relatively mature, and are often restricted by economic cost and difficult to further improve. Under the premise of the existing structure technology, the transformer body noise can be reduced only by using silicon steel sheet with excellent performance and reducing magnetic flux, which will lead to the decrease of the cost performance of the transformer. In addition, it is very difficult to reduce the noise by improving the materials, process and structure of the core and winding itself, and the relative technical requirements are higher, and the input cost will be very high. Therefore, it is necessary to combine transformer propagation path and characteristics of vibration and noise, vibration isolation, vibration absorbing, take body damping mode, the methods, such as energy consumption, high efficiency to reduce vibration to the tank wall, base, adjacent structure, add dissipative damping vibration absorber which is used to tank wall vibration, thus reducing box wall vibration amplitude and noise level of radiation [8].

First, the vibration of the tank wall is suppressed by strengthening the structure of the tank wall and adding the mass damper of the tank wall. Increase the strength and stiffness of the transformer oil tank wall, such as appropriate dense reinforcement in the middle of the tank wall, fill iron sand, river sand or asbestos plate in the tank wall reinforcement, and adopt double-layer sandwich or hollow oil tank to effectively reduce the amplitude of the tank wall. In addition, according to the thin-wall vibration control theory and the vibration characteristics of the tank wall, the rational arrangement and scientific design of dynamic vibration absorber parameters on the tank wall can theoretically reduce the vibration amplitude and radiation noise of the tank wall effectively.

Second, by setting high damping elastic elements at the bottom of the body and the bottom of the tank, the vibration of the body and the tank wall is effectively isolated and propagated outward. A high damping elastic element is set between the clamp and the tank bottom plate to make the rigid connection become an elastic connection. By isolating and dissipating the vibration caused by electromagnetic force between the iron core and the winding, the vibration of the tank body can be effectively reduced to spread to the tank bottom plate and the around walls. A high damping elastic element is set between the bottom of the oil tank and the foundation to suppress the transmission of the oil tank vibration to the foundation and adjacent structures. In addition, the connection between the tank body and the tank wall should be minimized, and the cantilever on the tank wall and uneven connection parts of the tank connection should be reduced. If there is a connection, soft or elastic damping connection should be used as far as possible.
4. Vibration isolation design of transformer body

4.1. Principle of transformer body vibration isolation technology

The vibration isolation layer of the transformer body is composed of different types of vibration isolation devices between the bottom beam of the transformer body support and the bottom plate of the oil tank. The vibration isolation mechanical model of the transformer body can be simplified into the single point model as shown in figure 6[9]. Assumes that the transformer body comprehensive vibration force $F$, as stated earlier, because the body and winding vibration force can be simplified as a composed of 100 Hz and a series of resonant frequency superposition of harmonic load, namely for the transformer body, load excitation $F(t)$ can be written as the following form:

$$ F(t) = F_1 \times \sin(\omega_1 t + \phi_1) + F_2 \times \sin(\omega_2 t + \phi_2) + L + F_n \times \sin(\omega_n t + \phi_n) = \sum_{i=1}^{m} (F_i \cos \omega_i t) $$

(1)

According to D’Alembert principle, the motion equation of the single-degree-of-freedom vibration isolation system of the transformer body, as shown in figure 6, can be written:

$$ M \ddot{X}(t) + C_{eq} \dot{X}(t) + K_{eq} X(t) = F(t) $$

(2)

Where, $M$ is the total mass of the body and clamps, kg. $K_{eq}$ and $C_{eq}$ are the equivalent stiffness and equivalent damping of the vibration isolation layer respectively.

The transformer body is mainly composed of 100Hz, 200Hz, ..., several vibration spectrum curves with obvious line spectrum characteristics in the running state, the design of the vibration isolation layer can take 2-3 low-order frequencies as the target to design the vibration isolation layer and the vibration isolation device, and connect the elastic elements with different stiffness in series to form the vibration isolation device. The equivalent stiffness $K_{eq}$ and equivalent damping $C_{eq}$ of series spring system composed of several different types of vibration isolation elements are respectively [9]:

$$ K_{eq} = \left( \sum_{j=1}^{n} \frac{1}{k_j} \right)^{-1} $$

(3)

$$ C_{eq} = \sum_{j=1}^{n} c_j $$

(4)

The force transmitted to the bottom plate of the oil tank is $F_d$, and the relationship between $F_d$ and $F$ can be obtained by solving the equation of motion (1):
\[
T = \frac{F_d}{F} = \frac{1}{\sqrt{[1 - \lambda^2]^2 + (2\xi\lambda)^2}}
\]

(5)

Where: \( T \) is the amplification factor or transmissibility of response power; \( R \) is the corresponding vibration isolation efficiency; \( \omega_i \) for a particular frequency vibration force; \( \omega_{eq} \) is the equivalent natural frequency for machine body vibration isolation layer; \( \lambda \) for incentive frequency vibration isolation layer and the body than; \( \xi \) for vibration isolation layer of equivalent damping ratio. By solving equation (5), between available transmissibility \( T \) and damping ratio \( \lambda \) and frequency ratio relation curve \( \lambda \) as shown in figure 7 [10].

It can be seen from figure 7 that in order to obtain good vibration isolation effect, the frequency ratio must be greater than \( \sqrt{2} \); In the vibration isolation area, the larger the frequency ratio, the better the vibration isolation effect, so it is necessary to make the vibration isolation layer have a lower natural frequency \( \omega_{eq} \). In order to ensure the vibration isolation effect, the vibration isolation frequency ratio of transformer body should be \( \lambda \geq 6 \). Near the resonance frequency, the damping ratio has significant shock absorption effect, which doubles the damping ratio and nearly doubles the dynamic amplification coefficient Far away from the resonance frequency, the damping of the structure system still has a certain damping effect, but it is not as obvious as the damping effect near the resonance frequency, so the damping of the vibration isolation layer is not as big as possible, and it is more appropriate to take 10-20% [11-12].

Fig. 7 The curve of transmission rate with damping and frequency ratio.

4.2. Design of vibration isolation layer stiffness of transformer body

According to the single mass point vibration isolation theoretical model of the transformer body shown
in figure 6, on the premise that the target transmission rate \( T \) and damping ratio \( \xi \) are known, the frequency ratio of the target control excitation frequency \( \omega_i \) to the vibration isolation layer can be obtained by formula (5), and the design stiffness \( k_i \) of the vibration isolation layer can be obtained from the mass of transformer body \( M \), that is:

\[
k_i = 4\pi^2 \times \left( \frac{\omega_i}{\lambda} \right)^2 \times M \quad (6)
\]

It can be seen from formula (6) that when the target control excitation frequency \( \omega_i \) and \( \lambda \) are known, the vertical stiffness \( k_i \) of the vibration isolation layer is proportional to the body mass \( M \); the stiffness \( k_i \) of the vibration isolation layer is proportional to the target control excitation frequency \( \omega_i \). It is proportional to the square, so when the transformer body is designed for vibration isolation, 100 Hz can be used as the control frequency of the vibration isolation layer. The designed vibration isolation layer stiffness has better vibration isolation efficiency for other higher-order resonance frequencies. In addition, the vertical stiffness \( k_i \) of the vibration isolation layer is inversely proportional to the square of the frequency ratio \( \lambda \). Therefore, theoretically, the larger the frequency ratio \( \lambda \), the smaller the vertical design stiffness of the vibration isolation layer is required. However, considering the body weight and long-term operation safety, vibration isolation The layer frequency ratio \( \lambda \) is appropriate to be 6-8. Figure 8 shows that the vibration excitation frequency of the body is 100Hz, which is the vibration control frequency. The damping ratio \( \xi \) is set to 0.1 and \( \lambda \) is set to 8. A total of 81 oil-immersed power transformer vibration isolation layers are obtained for 4 voltage levels such as 10kV, 35kV, 110kV and 220kV. The vertical design stiffness and design vibration isolation efficiency exceed 96%, and the vibration isolation effect is significant.
After the vertical design stiffness of the vibration isolation layer of the transformer body is obtained, the position and number of vibration isolation bearings can be determined according to the mass of the transformer body and the connection mode between the transformer body clamp and the bottom of the transformer body.
lower oil tank. According to the bearing capacity of the vibration isolation device, the design principle of the number of vibration isolators can be controlled according to the surface pressure $P_A$ of the effective bearing area $A$ of the vibration isolators, and $P_A \leq 8\text{MPa}$ is generally suitable.

Fig. 9 110kV power transformer body vibration isolation layer layout scheme.

5. conclusion

(1) The test has obtained the vibration and noise spectrum characteristics of the core and winding of the oil-immersed power transformer. The core vibration is more complicated in the no-load state, and the magnetostrictive line spectrum energy is mainly at the voltage power frequency resonance frequency point within 1000Hz. In the case of short circuit, the coil winding is mainly single-frequency vibration of 100Hz. Under load, the vibration of the transformer body can basically be linearly superimposed by the two working conditions of no-load and short-circuit.

(2) Only from the improvement of core, winding itself of the material, technology, structure to reduce the vibration and noise of the body is limited, need higher technical requirements, the cost of investment will be very large. It is necessary to combine transformer propagation path and characteristics of vibration and noise, take body vibration isolation, vibration absorbing and damping energy dissipation ways, methods, such as lowering body vibration to the tank wall and base, adjacent structure, add dissipative damping vibration absorber which is used to tank wall vibration, thus reducing box wall vibration amplitude and noise level.

(3) The vibration isolation design method of oil-immersed power transformer body is discussed, and the vertical design stiffness of 81 kinds of vibration isolation layers of oil-immersed power transformer with four voltage levels of 10, 35, 110 and 220kV is calculated, which can be used as reference for the vibration isolation design of transformer body in the future. The design vibration isolation efficiency is over 96%, and the vibration isolation effect is remarkable.

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