Force Characteristics Test of 10kV Oil-Immersed Transformer for Noise Control

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Abstract. Noise complaint of distribution transformers is a significant problem in the electrical industry's environmental protection. Much research has been done on the noise source characteristics and noise propagation characteristics of the distribution transformer, but few investigations on the magnitude and frequency spectrum variation of vibration source force. In this paper, a 10kV oil-immersed transformer's force characteristics under various operating conditions are tested based on a semi-anechoic room. Specifically, the force's amplitudes and frequency spectrums on the transformer's base structure under the rated voltage, the rated current, and rated load are obtained. The force's amplitude under the three conditions is 223.8N, 22.2N and 218.1N, respectively. These results are of great significance to understanding the distribution transformer's vibration source characteristics and could be used on its noise controlling.

1. Introduction
Distribution transformer is the end link of the electric power system, which undertakes to transmit electric energy to users [1]. With the continuous development of social development and the increase of electric power load, the number of distribution transformers increases gradually. Besides, it is close to the users compared with the higher voltage grade transformer. As a result, complaints and disputes of its noise problems are increasing significantly.

Up to now, lots of research has been done on the transformer noise generation mechanism and characteristics of transformer noise [2-5]. There are standards for transformer sound level measurement, while no standard for transformer vibration source characteristics [6]. For most distribution transformer in buildings, structural is the primary way of transformer noise transmission [7-9]. The transformer's vibration is transmitted through the foundation to the adjacent building structure, and then along the building structure to the distance until it is transmitted to the room. The acceleration sensor is installed near the transformer installation base to indirectly measure the ground vibration to obtain the transformer's vibration characteristics. This method is not precise enough because the base's mechanical impedance is hard to know. So, the transformer vibration source characteristics are still not accurately obtained.

In this paper, the force characteristics of a 10kV oil-immersed transformer under various operating conditions are tested based on a semi-anechoic chamber by relying on the structure characteristic of an anechoic room. Specifically, the force's amplitude and frequency spectrum on the base structure of the transformer under no-load rated voltage, short-circuit rated current and rated load are obtained by
measuring the acceleration value of the ground. The force's amplitude under the three conditions is 223.8N, 22.2N and 218.1N, respectively. This paper's results are of great significance to understanding the distribution transformer's vibration source characteristics and could be used on its noise controlling.

2. Transformer vibration and noise characteristics

The transformer's noise is generated by the transformer core and coils. The silicon steel sheet's magnetic striation causes the periodic vibration of the core, and the electromagnetic attraction between the joint and lamination of the silicon steel sheet due to magnetic flux leakage causes the core vibration too. The galvanized winding in the magnetic field causes axial and radial vibration generated by the electromagnetic force.

The magnetostriction period is half of the cycle of power supply, so the fundamental frequency of vibration of the transformer core caused by magnetostriction is 100Hz. However, because the core's magnetostriction is not always linear and some other issues, there are integer harmonic component frequencies except fundamental frequency, such as 150Hz, 200Hz, etc.

The electromagnetic force between the laminates comes from the magnetic flux leakage at the core joint and the side between the silicon steel sheets due to the uneven distribution of the main flux.

With the improvement of the silicon steel sheet's stacking process, the vibration caused by the electromagnetic force generated by leakage flux is small. Therefore, it can be considered that the magnetostriction mainly causes the vibration of the core.

3. Test method of transformer force measuring

3.1. Test platform

The experiments are carried out on a 10kV transformer noise and vibration test platform. The test platform consists of three parts, a semi-anechoic room, electrical system and acoustic measuring instruments [10].

The semi-anechoic room structure is shown in Figure 1 and Figure 2. It is a room-in-room suspension structure. Vibration isolation materials are placed at the bottom of the inside-room floor and its side. The thickness of the vibration isolation layer is 60mm, which is made of rubber. The stiffness of the isolation layer matches the quality of the upper building's mass so that the resonance frequency of the whole structure is about 10Hz.

![Figure 1. Front view of the semi-anechoic room.](image)
Transformer force tests are based on the 10kV transformer noise and vibration test platform. Accelerometers measure the semi-anechoic room ground vibration acceleration when the transformer operates. And further to calculate the transformer excitation force on the floor.

The structure diagram of the transformer vibration test platform and the equivalent diagram of the simplified lumped system are shown in Fig. 1 and 2.

According to the particle kinematics, when the resonance frequency of the system is far less than the excitation frequency, it belongs to the mass control region [11]. The vibration acceleration of the ground is

\[ a_a \approx \frac{F_a}{M_1 + M_2} \]  

Formula 1 means \( F_a \) approximately equals to \( (M_1 + M_2)a_a \), so the transformer's force characteristics can be obtained by measuring the acceleration in the anechoic room. Further, in the experiments, the test results of the instrument are effective values, so:

\[ F \approx (M_1 + M_2)a \]  

In which, \( F \) and \( a \) are effective values for force and acceleration.

3.2. Power supply system

The power supply system consists of a 10kV incoming switchgear, a voltage regulating transformer, a 10kV outgoing switchgear, a short circuit switch, a set of water-cooled adjustable resistance loads, a group of adjustable inductive loads, a group of harmonic generator devices.

Specifically, the 10kV incoming switchgear's input cable is connected with the mains to obtain electricity, and its output cable is connected to the voltage regulating transformer. The voltage regulating transformer is used to adjust the transformer's input voltage under test, and the range is 0 to 12kV.

Three phases on the low voltage side of the transformer under test are connected with the short circuit switch, the water-cooled adjustable resistance loads, the adjustable inductance loads, and the harmonic generator. By setting the voltage regulating transformer's output voltage and the operation mode of devices on the low-voltage side of the transformer under test, various conditions such as different voltages, load power of different resistors and power factors, three-phase unbalance, harmonics, could be set up. Further, the transformer's force characteristics under various operation conditions could be obtained.
3.3. The measuring devices and operating conditions

The measuring system contains a signal collection module and a signal post-processing module. It's based on B&K LNA-XI data acquisition hardware (type 3053) and PULSE platform. Considering that the distribution transformer's vibration frequency is mainly less than 1000Hz, B&K accelerometer (type 4534-B-001) is used for measuring the acceleration. Several key parameters of this kind of acceleration are shown in Table 1. In the experiments, four accelerations were glued to the anechoic room floor, around the transformer, as shown in Figure 3.

| Frequency range | Sensitivity | Inherent Noise | Measuring Range | Operating Temperature Range | Mounted Resonance Frequency |
|-----------------|-------------|----------------|-----------------|-----------------------------|-----------------------------|
| 0.2 to 12.8k    | 10mV/m²     | 130ug          | 70g             | -55°C to +125°C             | > 38kHz                     |

**Figure 3.** Photo of accelerometer arrangement.

The transformer operated under three different conditions: rated voltage, rated current and rated load. The high-voltage side and low-voltage side settings of the transformer under test are shown in Table 2.

| Number | Operating condition | High-voltage side | Low-voltage side |
|--------|---------------------|-------------------|------------------|
| 1      | Rated voltage       | 10kV voltage      | No-load          |
| 2      | Rated current       | Low excitation voltage | Short circle   |
| 3      | Rated load          | 10kV voltage      | 400kVA resistance load |

4. Experimental results and discussion

The acceleration signal is acquired by the signal collection module, which is a time-domain signal. Then the spectrum distribution is obtained by spectrum estimation through signal processing [12,13]. Acceleration spectrum distribution under three working conditions is shown in Figure 4(a), 4(b) and 4(c), the background noise is shown in Figure 4(d). It could be found that the background noise is low, and the values at different frequencies are close to zero. Under the rated current condition, the noise is almost 100Hz component, no harmonic components exist. Under the rated voltage condition, the acceleration frequency is distributed between 100 and 600Hz. The maximum value is about 2.9mm/s² at 200Hz. Compared with the result of the rated current, it could be concluded that the transformer's vibration is much greater and has higher spectral complexity under the rated voltage. The acceleration under rated load condition has little difference with the spectrum distribution and value of acceleration.
under rated voltage. So, combined with Figure 4(a), 4(b) and 4(c), it could be concluded that the vibration of this 10kV oil-immersed transformer mainly comes from the vibration of the iron core.

![Acceleration spectrum distribution under different working conditions.](image)

Further, the acceleration's effective value can be obtained by calculating the vibration energy of all frequencies and taking the square root. The transformer's force on the foundation can be obtained by calculating Formula 2.

Table 3. Acceleration and force results under different operating conditions of the transformer.

| Number | Operating condition | Acceleration/mm/s² | Force/N |
|--------|---------------------|--------------------|---------|
| 1      | Rated voltage       | 3.09               | 223.8   |
| 2      | Rated current       | 0.31               | 22.2    |
| 3      | Rated load          | 3.01               | 218.1   |

The acceleration value under rated voltage, rated current and rated load operating condition is 3.09mm/s², 0.31 mm/s² and 3.01 mm/s² respectively, and the force is 223.8N, 22.2N and 218.1N respectively. The results show that the force under rated voltage and rated load condition is about ten times of that under rated current condition. Again, it indicates that the transformer's main vibration
comes from the core rather than the windings. The most important finding is that this transformer's vibration magnitude is about 220N. Similar results for force source value and spectral characteristics have not been reported before. Usually, in the vibration and noise transmission of distribution transformers in buildings, the value of vibration speed and vibration acceleration are used instead of the value of excitation force, the main reason is that the force of the transformer is difficult to estimate. So, the study in this paper provides data support for related research.

An interesting phenomenon is that the vibration acceleration and force values at rated load are smaller than those at rated voltage. According to the Standard 1094.10, when the transformer running at rated load (rated voltage and rated current), the sound power level should be calculated by adding the sound power energy of rated voltage and rated current. For the same reason, when the transformer running at rated load, it's force should follow the same rule. But the experimental results do not support it. This phenomenon has not been theoretically explained, and it may result from the vibration phase difference between the windings and the core.

5. Conclusions
In order to study the characteristics of force source of distribution transformer, this paper proposes to build a test system by using an anechoic room and analyzed theoretically. Through this system, the vibration force of an oil-immersed transformer is tested. The test results show that the vibration force under the rated voltage, rated current and rated load are is 223.8N, 22.2N and 218.1N, respectively, and the frequency is distributed between 100 and 600Hz. The results can be used for transformer noise and vibration control.

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