Study on noise characteristics of 500kV oil-immersed transformer under no-load voltage condition

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Abstract—With the expansion of urban construction scale, substation noise has attracted more and more attention. Noise characteristics and propagation of the oil-immersed transformers are made important theoretical basis of vibration and noise reduction measures. Based on the 500kV oil-immersed transformer, the noise test of transformer structures had been completed. An advanced optical fiber testing system is adopted in the test, which solves the problem of accuracy and reliability in high electromagnetic field and solid-liquid coupling environment. Time domain analysis and frequency analysis for the test data were carried out. By test and analysis, noise characteristics are obtained by the large power transformers. The frequency spectrum of noise and winding vibration in transformer insulation oil is mainly 100Hz and frequency doubling. With the increase of load, the noise presents obvious nonlinear change process.

1. Introduction
Large oil-immersed transformers are an important part of the transmission and distribution networks of power systems. As economy and society develop and electric loads increase continuously, State Grid Corporation of China is steadily carrying forward the construction of smart grids that take UHV grids as the backbone grid structure, thus the scale of production and operation of large oil-immersed transformers has a rapid growth. However, with the constantly expanding scales of power grids and the scarcity of urban land resources, more and more substations are located to the depth of urban center. Power transformers are the main source of noise in substations. A large number of field tests and experimental studies have shown that the noise of transformers is a kind of low and medium-frequency noise with frequency spectrum mainly concentrated on 50Hz and its frequency doubling components in the range of 1,000Hz. Due to a variety of reasons such as different manufacturing processes of transformers, aging of equipment, long-term operation, and proximity to sensitive points, the noise pollution problem of large power transformers is increasingly prominent. Therefore, the mastery of vibration and noise characteristics of transformers and their propagation rules is a crucial approach for vibration and noise reduction of power equipment. The piezoelectric sensor has been playing its role as a standard device for measuring physical and mechanical phenomena. However, if the test object is a large-scale power device, the piezoelectric sensor is vulnerable to the interference of electric and magnetic fields. For the measurement of internal cores and windings of transformers, ordinary electronic accelerometers and hydrophones can hardly function normally within charged transformers. The application of fiber optic hydrophones for internal vibration and noise testing of transformers with high voltage grade is fairly rare at present. In this article, experimental studies on
noise inside/outside the fuel tank of a 500kV oil-immersed transformer are conducted separately just based on the fiber optic test system.

2. Acting Mechanisms of Transformer Noise

Vibration and noise of an oil-immersed transformer are mostly generated under the actions of magnetostriction of its iron core and electromagnetic force of its windings. The magnetostriction is one of the magnetic properties of ferromagnetic materials that causes the ferromagnetic materials to change their dimensions during the process of magnetization as the ferromagnetic materials have magnetic fields or magnetic flows, i.e. their internal magnetic domains turn over and move along with magnetic domain walls. The vibration of transformer windings is caused by the electromagnetic force generated between the windings, between the pancakes and between the leads when current flows through the windings, and consequently the current-carrying conductors are subject to the electromagnetic force of the leakage magnetic field, thus the transformer is in a state of constant deformation and jitter. In addition, the electromagnetic attraction generated due to magnetic flux leakage at the joints of silicon steel sheets and between laminations, together with the electromotive force produced by the load current will cause parts and the fuel tank wall to vibrate. Experimental studies have shown that the vibration is caused by the magnetostrictive effect of silicon steel sheets inside the transformer and the magnetic force of windings, which propagates to the wall of the fuel tank through the conduction of connecting structures as well as the coupling effect of the filled transformer oil and couples with external air to become the transformer noise. At present, the research on vibration of transformer internal core and propagation rule of noise inside the insulating oil is short of measured data. In particular, there is little research on the role of transformer insulating oil and fuel tank housing. Thus, it is necessary to conduct internal and external noise and vibration synthetic testing research of the transformer.

3. Noise Test Schemes

3.1. Test Conditions

The test was conducted at the test center of the transformer plant with a 500kV single-phase no-load regulating test autotransformer of a certain model. The transformer core took the single-phase three-column structure and its coils were arranged in the order of low voltage (spiral coil), regulating voltage, medium voltage (continuous coil), high pressure (internally shielded continuous coil). The test hall was enclosed and spacious internally, with low background noise. The test transformer was placed in the center of the test hall to reduce reflection interference and reverberation effects. The test was done at night, when air-conditioning equipment inside the workshop was turned off to ensure that the tested acoustic environment was free from interference. The test condition is no-load voltage, including 80% rated voltage and 100% rated voltage.

3.2. Test Equipment

In view of characteristics of the internal sound field testing environment of a large oil-immersed transformer, there are many problems with conventional test equipment. This test conducted in-depth research on test sensors and developed the first fiber optic hydrophone test system for use of transformers in China. The test system developed consists of fiber optic hydrophone, transmission optical cable, FBG regulator and computer. The system uses sound waves to modulate optical phases in the single-mode optical fiber coil, and obtains the sound pressure borne by the fiber optic segment according to changes in optical phases of the optical fiber over a certain length. The fiber optic hydrophone is wholly encapsulated with polyurethane materials, and internally composed of optical passive devices, as shown in Figure 1. Therefore, it is not interfered by the intense electromagnetic field environment of the transformer and will not affect the normal operation of the transformer when hanged inside the insulating oil.
The hydrophone is able to convert the pressure intensity of the sound field fluctuation of the liquid in which it is located to corresponding modulated optical wave signals via the sensing element and then output data signals recordable by acquisition system and computer through demodulation processing of the backend module for the sake of further analysis and research of the changes in each frequency band component of the sound field inside the liquid. Optical cables of all sensors inside the transformer are connected to an external demodulator via through connectors. The demodulator supports both fiber optic accelerometers and strain gauges. Featuring high accuracy, good data stability, and rich sound field spectra, this test system has completely settled the problems of accuracy and reliability of sound pressure testing in strong electromagnetic fields and fluid-solid coupling environments.

3.3. Measuring Points in Transformer External Sound Field
According to GB/T1094 Determination of Sound Levels of Power Transformers, measuring points were arranged corresponding to the two states of the air cooling equipment, OFF and operating, which were located on 0.3m and 2m of the transformer outline, with the interval of 1m and at the height of 1/3H and 2/3H of the tank height respectively. The test was conducted with portable sound level meters. Arrangement of measuring points is as shown in Figure 2.

3.4. Measuring Points for Fiber Optic Hydrophones in Insulating Oil
The sound field inside the transformer insulating oil was measured with fiber optic hydrophones to obtain the values of sound pressure inside the transformer oil under test conditions. In view of the feasibility of suspension points for the hydrophones, a total of six measuring points were distributed inside the oil, four at the low-pressure side and two at the high-pressure side separately. The sampling
frequency of the hydrophone acquisition equipment was 32,000 Hz and the acquisition time was defined 10s. The arrangement positions of hydrophones in the transformer fuel tank are as shown in Figure 3.

(a) Low Pressure Side                           (b) High Pressure Side
Fig.3 Arrangement of Measuring Points for Fiber Optic Hydrophones

4. Test Results and Discussions

4.1. Test on Sound Pressure Level Outside Fuel tank
Test results of sound pressure level outside the fuel tank under the rated voltage condition are as shown in the following Figure 4. It can be drawn out from the figures that the sound pressure levels measured outside the fuel tank under rated voltage conditions is higher than that under the rated current conditions at all measuring points and the sound pressure measured at 1/3H height of the tank is generally higher than that measured at 2/3H height of the tank. It is observed from positions of the measuring points that noise radiation values at both ends of the transformer tank are on the high side. The corrected sound pressure level considering the influence of environmental factors and background noise is 72.6 dB(A).

Fig.4 Sound Pressure Level of Each Test Point outside Fuel tank under Rated Voltage

4.2. Test on Sound Field Inside Insulating Oil
Figure 5 shows time-domain waveforms of sound pressure at measuring point 1 inside the fuel tank under the working conditions of 80% and 100% rated voltage. It can be observed from the figure that
the sound field of the fuel tank is generally in a steady mode under all working conditions and basically presents composite waveforms with multiple harmonic frequency components. The difference in sound pressure amplitudes of different measuring points is not significant under the same working conditions, which indicates the sound field distribution in the oil is relatively uniform. For the same measuring point, as the rated voltage increases, its waveform becomes compact and the high-order frequency increases significantly.

![Fig. 5 Time-domain Oscillogram of Hydrophone Measuring Point 1](image)

Figure 6 gives the spectra of sound pressure levels of hydrophone measuring points inside the fuel tank under 100% rated voltage conditions. It can be concluded that when the working conditions rise to the rated voltage, the fundamental frequency of 100Hz is not the only major constituent of the fluid-solid coupled noise inside the fuel tank generated due to the magnetostrictive vibration of silicon steel sheet structure of the iron core, and its sub-harmonic components are significant constituents of the same importance; compared with constituents of oil internal noise under the short-circuit current, the 100Hz component in the oil internal noise takes a relatively smaller proportion under rated voltage, but high-order harmonic components increase remarkably and carry considerable weight in A-weighted sound level that deserve particular emphasis. Sound pressure levels of different measuring points are approaching. The sound pressure levels of the measuring points are not much related to winding distance.

![Fig. 6 Sound Pressure Level Spectra of Hydrophone Measuring Point 1 and Point 2 Under 100% Rated Voltage Conditions](image)
5. Conclusion
The following several important conclusions can be concluded from testing and analysis of vibration and noise inside/outside the fuel tank of a 500kV oil-immersed transformer:

(1) When the transformer is working under the rated voltage conditions, the fundamental frequency of 100Hz is not the only major constituent of the noise inside the fuel tank, and its sub-harmonic components are significant constituents of the same importance; Sound pressure levels of measuring points are no longer much related to winding distance.

(2) When the transformer is working under the rated voltage conditions, the sound pressure inside the oil shows significant non-linear changes because of the remarkable non-linear effect caused by high-voltage intense magnetic field. The structural non-linear vibration caused by magnetostriction of silicon steel sheets of the icon core is coupled with insulating oil and transmitted to the outside of the fuel tank.

(3) Compared with the normal working conditions, the 100Hz component in the oil internal noise takes a relatively smaller proportion under rated voltage, but other high-order harmonic components increase remarkably and carry considerable weight in A-weighted sound level that deserve particular emphasis.

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References
[1] Anthony, J.M., Philip, L.A., Teeraphon, P. (2016) Localized surface vibration and acoustic noise emitted from laboratory-scale transformer cores assembled from grain-oriented electrical steel. IEEE Transactions on Magnetics. 163: 7100615
[2] David, S. (2008) Measurement of noise associated with model transformer cores. Journal of Magnetism and Magnetic Materials. 320: 535-538.
[3] Ramsis, S.G., Mats, S.B., Scott, T. (2011) Development of ultra-low-noise transformer technology. IEEE Transactions on Power Delivery. 26: 228-234.
[4] Ludger, L., Chaoyong, W., Andreas, A. (2012) Improved transformer noise behavior by optimized laser domain refinement at thyssenkrupp electrical steel. IEEE Transactions on Magnetics. 48: 1453-1456.
[5] Youhao, Y., Baozhi, C., Andreas, A. (2007) Noise Analysis and Control of Large Power Transformer. Transformer. 44: 23-26. (in Chinese)
[6] Guoxing, G., Xueyun, R., Zhiyuan, L. (2016) The Vibration Test of Power Transformer Scale Model and Its Acoustic Model. Journal of Vibration, Measurement &Diagnosis. 36: 1116-1122. (in Chinese)
[7] Cranch, G.A., Nash, P.J., Kirkendall, C.K. (2003) Large-scale remotely interrogated arrays of fiber-optic interferometric sensors for underwater acoustic applications. IEEE Sensors Journal. 3: 16-30.
[8] Chang, Y.H., Hsu, C.H., Chu, H.L. (2011) Magneto mechanical vibrations of three-phase three-leg transformer with different amorphous-cored structures. IEEE Transactions on Magnetics. 47: 2780-2783.
[9] Enokizono, M., Shimoji H., Ikariga A. (2005) Vector magnetic characteristic analysis of electrical machines. IEEE Transactions on Magnetics. 41: 2032-2035.
[10] Lihua, Z., Qingxin, Y., Rongge, Y. (2013) Numerical computation for a new way to reduce vibration and noise due to magnetostriction and magnetic forces of transformer cores. Journal of Applied Physics. 113: 17A333.