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Vibration transmission from internal structures to the tank of an oil-filled power transformer

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ABSTRACT

The vibration of a transformer tank is related to the transformer's noise radiation and health condition. Therefore, it is important to understand the transmission of vibration from internal vibration sources in the windings and core to the transformer tank. The characteristics of this transmission are determined by direct mechanical coupling between the internal structures and the tank, and by indirect coupling through fluid–structure interaction induced by the transformer's cooling oil. In this paper, the transmission of vibration is examined experimentally in a 110-kV power transformer with and without cooling oil. Under respective mechanical and electrical excitations, vibrations of the internal structures and transformer tank are measured simultaneously. The results allow an evaluation of the transmission efficiency of vibration from the internal structures to the tank, and the effects of fluid–structure coupling on the transmission. This experimental work improves understanding of vibration transmission in oil-filled power transformers, and explains the characteristics of a transformer's on-line vibration.

1. Introduction

The main sources of transformer vibration are located in the core and windings of the transformer. The vibro-acoustical properties of the core and windings have been the focus of many previous investigations [1–4]. However, for noise control and vibro-acoustical condition monitoring of in-service power transformers, only the tank vibration is readily accessible. As a result, understanding of the transmission of vibration from internal vibration sources to the tank is important for controlling the vibration at the sources and correlating the internal and tank vibration signatures.

In an oil-filled power transformer, the vibration generated in the core and windings can be transmitted to the tank via two paths. As shown in Fig. 1, one path is through the mechanical joints between the core and the tank at the bottom of the tank via structure-to-structure coupling. The other path is through the cooling oil via structure-to-fluid and fluid-to-structure couplings. Because of the complexity in the transformer structures and fluid–structure interaction, the transmission of vibration in oil-filled power transformers has been rarely discussed in the literature.

This paper describes experimental work on a 110-kV power transformer, which involved the simultaneous measurement of the vibration frequency responses of the core and tank. The transformer was tested with and without cooling oil, so that the effect of cooling oil on tank vibration can be examined via comparison. The transformer's internal structure was excited by two mechanisms. One was mechanical excitation by an impact hammer at specific locations on the core structure, allowing the measurement of a mechanically excited frequency response function. The other was electrical excitation by an applied operating voltage, allowing a determination of electrically excited vibration at twice the operating frequency and its harmonics. Although the two excitations differ in their location and force magnitudes, the measured vibration responses at the same locations on the tank as a result of different excitations are both affected by the same modal characteristics of the transformer structure. As a result, the measured frequency response of the transformer structure to the mechanical excitation can be used to explain some features of the transformer's on-line vibration.

The mechanisms involved in the high-order harmonic components of the vibration of a transformer tank are still a pending issue [5,6]. Vibration at those high-order harmonics contributes significantly to both radiated sound that is sensitive to human hearing, and to the monitoring of the health condition of the transformer. Thus, an improved understanding of their generation and transmission mechanisms is practically important. Some previous

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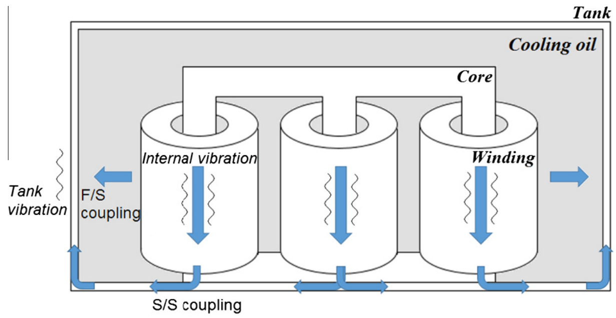

Fig. 1. Vibration transmission in an oil-filled power transformer.

research has demonstrated that the high-order harmonics of vibration in the transformer tank are caused by a hysteresis phenomenon occurring in the core, due to the large current loading [6]. Other research has indicated that they are related to the nonlinear properties of the insulation material and mechanical faults, such as looseness in clamping force [7]. However, it is still not clear why the measured harmonic components can be much larger than the vibration components at the fundamental frequency for some damaged transformers and even for undamaged transformers with low loading. This paper provides a possible explanation to this question, based on an experimental analysis of the measured online vibration of a 110-kV transformer.

2. Experiment on the 110-kV power transformer

A three-phase 110-kV power transformer manufactured by JSHP Transformers Ltd (see Fig. 2) was used for the experiment. During the experiment, some accessory structures, including cooling fans and transformer top cover, were removed. The dimensions of the transformer are listed in Table 1.

In the experiment, the core was secured by a clamping frame with insulation materials in between. The clamping frame stood firmly on the tank floor as a result of its heavy weight and that of the core. The coupling of the active part of the transformer with the top cover was neglected as the top cover was removed for accessibility of the transformer core during the experiment. For a typical transformer installed in the field, the active part is generally coupled with the top cover through electrical cables at a few locations via insulating bushings. Because of the flexibility of the cable and because the core has no other direct contact with the top cover, the measured vibration response from this experimental transformer structure should still carry the general features of the transformer in the field. For some transformers, however, the active part is suspended from the tank cover. For such a configuration, the transmission of vibration to the tank cover will have a non-negligible coupling path. The importance of this coupling path should be examined through future experimental work (with some difficulty, however, because the tank cover is close to the high-voltage cable) or through numerical analysis.

Fig. 3 shows the experimental setup for the mechanical excitation, which is provided by a large impact hammer at the middle of the top yoke of the core in the *z*-direction of the coordinates. The frequency response functions of the acceleration at various locations $\vec{r}_m$ of the transformer structure to an impact force at $\vec{r}_s$ are expressed as $H(\vec{r}_m, \vec{r}_s|\omega)$. These frequency response functions show the resonance features of the transformer structure. The amplitude distribution of $H(\vec{r}_m, \vec{r}_s|\omega)$ as a function of the measurement location $\vec{r}_m$ at the resonance frequencies also shows the spatial properties of the corresponding vibration mode. Although the amplitude of $H(\vec{r}_m, \vec{r}_s|\omega)$ is also dependent on the impact location $\vec{r}_s$, the general resonance and mode shape characteristics of the transformer structure can still be extracted from the frequency response functions, owing to the single point excitation, unless the excitation location is very close to the nodal point of a specific mode. The measurements of the frequency response functions due to excitations at other locations indicate that this is not the case in the frequency range of interest.

More specifically, accelerometers C1, C3, and C5 in Fig. 3(B) were for measuring the vibration in the *z*-direction of the yoke. They are located above the three limbs of the core. Accelerometers C2, C4, and C6 were for the yoke vibration in the *y*-direction, which is perpendicular to the plane of the core structure. Accelerometers C7 and C8 were used to measure the vibration at the two ends of the top yoke in the *x*-direction. Another fifteen accelerometers were distributed along three columns, evenly located on the front wall of the transformer tank between the stiffening ribs and denoted T1 to T15 (see Fig. 3(B)). All the accelerometers used in the experiment were single-axis and used for the measurement of the vibration component perpendicular to the surface of the structure. Several impact locations were selected for the measurement of the mechanically excited frequency response functions. One was located at C3 above the central limb and the other was near C1, directly above the limb of phase A. It was found that the general resonance features of the frequency response functions and the relative vibrations of the transformer tank were largely independent of the excitation location. Thus, the results due to the excitation point at C3 are utilized in the following sections.

For electrical excitation, the input voltage was 10 kV at the high-voltage terminal (which is 9.1% of the rated voltage), and the transformer was loaded by the rated load current (1580 A). For this online excitation, the measured core vibration was still much larger than the winding vibration, and it is regarded as the main vibration source. The measured vibration at the core and the windings showed that the core vibration is around one order of magnitude higher than that of the winding at 100 Hz. The arrangement of the accelerometers was the same as for the mechanical excitation experiment. Because the input voltage is at a single frequency (50 Hz) and because of the nonlinear electromagnetic magnetostrictive excitation mechanism, the transformer structure is only excited at 100 Hz and its harmonics.

Although different in the distribution of the excitation forces, the same resonance frequencies and modal characteristics of the transformer structure were involved in the generation of the system response. Therefore, if one of the resonance frequencies of the transformer structure determined through the mechanical excitation experiment overlaps with, for example, the 100 Hz component of the electrical excitation, then the response of the transformer structure to the electrical excitation is expected to be enhanced by the resonance at this frequency. If for some reason (such as loading of cooling oil or change of clamping pressure on the core or windings) the resonance frequency determined by the mechanical excitation shifts away from 100 Hz and the amplitude of the frequency response function at this frequency is significantly reduced, then the corresponding vibration of the structure to the electrical excitation will also be reduced. For this case, the electrical excitation is not altered, and the change in the resonance characteristics in the frequency response functions causes the change in the response.

3. Vibration transmission in a dry transformer

To test the dry transformer, the cooling oil was drained. In this case, only the transmission path via the mechanical joints at the bottom of the tank is responsible for transformer tank vibration. Fig. 4 shows the results for mechanical excitation, where Fig. 4(a)