An experimental study of winding vibration of a single-phase power transformer using a laser Doppler vibrometer

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A B S T R A C T

Transformer tank vibration has been used for the condition monitoring and fault diagnosis of power transformers, as well as for the evaluation of radiated sound power from such power transformers. In both applications, seeking a correlation between transformer tank vibration and the vibration of the transformer windings and core becomes a challenge for fault identification and noise control at the sources of vibration and noise. The purpose of this paper is to experimentally investigate the winding vibration of an electrically live power transformer and characterize the changes in the spatial and frequency features of the vibration as various mechanical faults are introduced to the transformer winding. To avoid the effects of transducer loading and electromagnetic fields on the measurement results, a laser Doppler vibrometer was used to make non-contact measurements of the winding vibration.

1. Introduction

Power transformers are vital components of power network infrastructure. Failures of transformers may cause considerable economic losses and disruption of power supply. Low-frequency humming noise from power transformers in service also causes serious environmental issues. The evolution of transformer faults and variations in the radiated transformer noise can often be related to changes in the transformer tank vibration. This is why several vibration-based techniques have been developed for transformer condition monitoring and fault diagnosis [1,2], and passive and active noise control [3–5]. The main sources of transformer tank vibration and its noise radiation are the magnetostrictive and electrodynamic forces in the core and windings [6,7]. The vibration generated by these forces is transmitted to the transformer tank through the mechanical joints and transformer oil [1].

Recognizing the sources of faults and noise, researchers have begun to look inside a transformer for insights into the generation, distribution, and transmission of the vibrations. It has become a common belief that mechanical changes in the active parts of a transformer may significantly change the spatial and frequency properties of their vibration, which may in turn be observed in the transformer tank vibration and radiated sound. Previous work on the internal vibrations of transformers has largely focused on analysis of the axial vibration of transformer windings [8–11]. The radial vibration of transformer winding plays an important role in transmitting winding vibration to the transformer tank via the cooling oil. However, there is a lack of experimental and modeling evidence for the radial components of transformer-winding vibration.

Using traditional accelerometers for vibration measurements of live transformer windings requires direct contact with high voltage components. Thus, a non-contact laser Doppler technique is often preferred. However, only few studies on laser-based measurements of transformer vibration have been found. Mizokami Masato et al. [12] developed a laser-based vibration measurement system. They applied the system to a three-phase three-limb transformer core, in order to examine the vibration pattern of a transformer core under a normal steady-state condition. Hackl and Hamberger [13] measured the velocity of an experimental tank surface with a laser scanner vibrometer, to understand the fundamental effects of changes in the surface velocity pattern and fluctuations in sound pressure level. Those previous works shed some light on the vibration performance of both the transformer's core and its assembled structure. However, no detailed measurements on the vibration of the transformer winding have yet been made.

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This paper presents the spatial and frequency properties of vibration on the surface of a winding of a single-phase 10-kVA disk-type power transformer measured using a laser Doppler vibrometer (LDV). The advantage of using LDV technique is that the measurement of vibration is free from the effect of leakage magnetic field. As the first part of a complete transformer vibration measurement program, this paper will focus on the winding vibration excited by magnetostriction in the transformer core. This was achieved by leaving the secondary winding in the open circuit condition and thus applying negligible current and negligible electromagnetic forces in the winding. This stage of the measurement already has practical significance as the vibration of many power transformers is dominated by magnetostriction in the core material. Extraction of current-induced winding vibration from the combined excitation of electromagnetic forces and magnetostriction is the second part of this measurement program.

In order to investigate vibration performance under abnormal operating conditions, the winding vibration was also measured as various artificial faults were introduced into the winding. The results were then analyzed by comparing the vibration patterns of the winding with and without faults.

2. Description of experiments

Fig. 1 shows the single-phase 10-kVA power transformer for the test. The rated voltages of the transformer are 415/240 V. During the test, the primary voltage of the transformer was set at the rated value (415 V), while the secondary was left in the open-circuited condition.

The LDV was utilized to measure vibrations of the winding with and without faults. To acquire an adequate detailed radial vibration pattern of the transformer winding, one side of the winding surface was selected as the scanning area. Fig. 2 shows the 11 × 11 scanning points on the winding surface. The distance between two adjacent scanning points in the horizontal direction was approximately 1.6 cm, and the vertical distance was about 2 cm, which is nearly twice the thickness of the winding disk. Although only part of the winding surface is measured, useful spatial information of the winding vibration can be extracted by the symmetrical structure of the winding.

The vibration amplitude and frequency are extracted point by point by the focused laser beam that moves rapidly in the scanning process defined in Fig. 2. It should be noted that the scanning surface is slightly curved in the horizontal direction. The measured winding vibration at the scanning points away from the center vertical line did not exactly equal the winding vibration in the radial direction. As a result, the measured winding vibration at these locations may be interpreted as the vector contribution of the radial (major) and in-plane (minor) components of the winding vibration.

Four cases of transformer winding vibration are studied. The first case is for transformer operation in a normal condition. The other three cases are for transformer operation in various abnormal conditions.

Case 1

The settings of the winding, including the winding clamping pressure and insulation blocks, were all at normal operating
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