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Transformer winding fault detection by vibration analysis methods

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ABSTRACT

In this paper, the vibration of power transformer windings is studied with the aim of identifying the winding structural condition. A winding vibration model coupled with electromagnetic force analysis is proposed to obtain the steady-state vibration distribution along the axial direction. During the experiment, the model was validated on a full size, 50 MVA, three phase power transformer. Good agreement was found between the measured vibrations and the vibrations that were calculated from the model developed in this study for a healthy winding. The effect of the winding clamping force on vibration is studied to assess the winding clamping state, and different types of winding deformations were simulated to extract diagnostic information. The preliminary study shows that it is feasible to predict the mechanical faults of transformer windings with the vibration method.

1. Introduction

The operational safety of power transformers is very important for the electrical power networks. Compared with other components, windings are the most important and vulnerable components in transformers. Most failures are caused by the windings according to the statistics of transformer breakdowns [1], which also indicates that mechanical failures are more likely to occur than dielectric failures. Besides, the winding structure is a main source of noise emission during operation. The winding vibration excited by the electromagnetic force is closely connected with the modal parameters of the related windings [2], so the induced vibration is highly dependent on the winding structure. Compared with other available techniques [3–5], such as dissolved gas analysis (DGA), frequency response analysis (FRA) and leakage reactance measurement, nonintrusive and live line measurement for transformers are more attractive. In this paper, the steady-state vibration of a disassembled transformer winding is studied with the aim of extracting diagnostic information from winding vibrations.

Although much research has been conducted on the transformer vibration, there has been little in-depth research on winding vibration [6–10]. The study of winding vibration can be divided into two steps. The first step is to obtain the distributed electromagnetic forces within the winding. Next, the winding vibration is calculated through an equivalent mathematical model. The prediction of electromagnetic force has a long history. Approaches developed by Rogowski and Roth solve the magnetic vector potential by means of a Fourier series [11–13]. The method of images is another widely used solution, where the boundary conditions are replaced by an infinite series of image conductors [14]. The above approaches, however, are found to be powerless when complex geometry is involved, so finite element analysis (FEA) techniques are proposed to solve these problems [15]. It has been concluded that an appropriate 2-D model is adequate for the purpose of obtaining accurate results [16].

So far, several works have explored the inherent mechanical characteristics of windings [17–21], and the mass-spring model was successfully used to obtain the axial vibration characteristics. Moreover, some research work has been devoted to the stress-strain characteristics of insulations [22]. Currently, fully coupled magneto-mechanical analyses with FEM (2D and 3D) are state of the art [23]. However, most of the existing research focuses on the winding vibration under normal conditions. Few experiments have been conducted to correlate winding vibrations with the fault identification of an actual transformer winding. In this paper, the winding vibration characteristics are studied through an equivalent mathematical model combined with electromagnetic force analysis. During the experiment, the vibration of a disassembled winding was studied to validate the proposed model. Then, specially designed tests including clamping force adjustment and winding fault simulation were carried out.

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2. Theory

2.1. Electromagnetic force analysis

In this paper, a basic arrangement of a transformer with two windings for each phase is investigated to calculate the electromagnetic force. The transformer windings are represented in a 2D axisymmetric model due to the winding structure is cylindrical and coaxial. Although the coils are constructed by multiple layers of copper wires, they are treated as solid cylindrical conductors. The vertical section through the windings of one phase is shown in Fig. 1, which is taken outside the core window. The tank (including the clamping device) is represented by regular planes under simplifying approximations. J_1 and J_2 are the current density of the low-voltage (LV) and the high-voltage (HV) windings, respectively. The HV winding is split into individual blocks in the model to obtain the electromagnetic force for each coil. The whole space is assumed to be rectangular in the r-z plane, in which r is the radial direction and z is the axial direction (along the height of the winding).

On-load experiment is a traditional way to simulate the winding condition under different loads. During the experiment, the ampere-turns of the LV winding are equal to those of the HV winding, and the magnetic leakage field can be obtained without considering the magnetizing current component. The power transformer works at a low frequency (50 Hz in China), so the electromagnetic quasi-static analysis is used if the time-dependent effects are ignored. In addition, the eddy current is ignored because the windings are formed by many layers of wires with negligible cross-sections. The proposed model is also based on the assumption that the non-saturated cores and iron materials have infinite magnetic permeability, and the boundary condition is given as magnetic field is perpendicular at their boundaries.

The electromagnetic fields in the air and in the space of the conductive material are investigated using Maxwell's differential equations and the related magnetic vector potential (***A***) is introduced. The electromagnetic boundary condition is also shown in Fig. 1. In the air spaces, the Laplace differential equation shown in (1) must be satisfied.

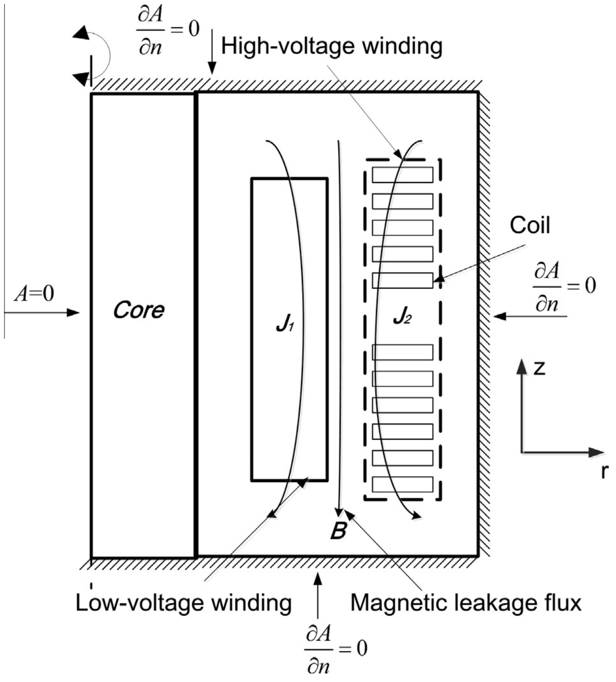

Fig. 1. Axial symmetry model of a two-winding transformer.

$$\nabla^2 A = 0 \tag{1}$$

In the area occupied by the conductive material, the Poisson's differential equation shown in (2) is required for constant current density.

$$\nabla^2 A = \mu J \tag{2}$$

where μ is the magnetic permeability and J is the current density. Then, the magnetic flux density vector (***B***) can be derived as

$$B = \nabla \times A \tag{3}$$

According to the Lorentz law, the interaction of the current and leakage flux density results in electromagnetic forces acting on the winding. Mathematically, the electromagnetic force density (***F***) in the coil volume can be represented by the outer vector product of the current density (***J***) and the magnetic flux density (***B***):

$$F = J \times B \tag{4}$$

Because the current density and the magnetic flux density are both proportional to the current, the resulting electromagnetic force is proportional to the current squared [8], which is shown as

$$f(t) = Ki^2(t) \tag{5}$$

where K is a constant proportional coefficient. If the current of the HV winding has the form of

$$i(t) = \sqrt{2}I\sin(\omega t + \varphi) \tag{6}$$

where I, ω and φ is are the effective value, angular frequency and phase angle of the current, respectively. The corresponding electromagnetic force of each coil has the form of

$$f_i(t) = F_i[1 - \cos(2\omega t + 2\varphi)], \quad F_i = K_i I^2 \tag{7}$$

where K_i is the proportional coefficient for the i-th coil. Compared to (5), F_i is numerically equal to the static electromagnetic force of the i-th coil when a DC current I is applied to the primary winding. In this paper, the finite element model is built using the FEM software ANSYS following the approximations stated above, and the static electromagnetic analysis is used to obtain the electromagnetic force distribution under the DC current excitation. In addition, finite element type PLANE13 and current-loaded coil are used in the model. Without considering the winding geometry affected by the forced vibration, the force of each coil is calculated by ANSYS. In practice, the electromagnetic force is decomposed into axial and radial directions, and only the axial force is applied to the following mathematical model.

2.2. Winding mathematic model

Transformer windings are classified into different types, such as the layer type and disk type. This paper only focuses on analyzing disk-type windings, which are widely used in large-capacity transformers. A disk-type winding is generally treated as a multi-degree of freedom system (MODF), and the mathematical model shown in Fig. 2 is successfully used to represent the winding structure. In the model, a single coil is equivalent to a mass (m_i), the insulation between two continuous coils is equivalent to a spring (k_i), and the damping factor is c_i. m_{top} and m_{bottom} are the masses of the top and bottom clamps respectively. The top and bottom clamps are fixed on the top and lower yokes, which have the equivalent stiffness k_{bottom} and k_{top} and damping coefficient c_{bottom} and c_{top}, respectively.

The forced vibration of an N degrees-of-freedom system can be defined as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \tag{8}$$