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Analysis of Power Transformer Vibration Modes

Amir Esmaeili Nezhad, Mohammad Hamed Samimi*
School of Electrical and Computer Engineering
College of Engineering, University of Tehran
Tehran, Iran
amir.esmaeili.nej@ut.ac.ir, *m.h.samimi@ut.ac.ir

***Abstract*—Understanding the vibrational characteristics of power transformers in the design and monitoring stages has attracted the attention of many researchers recently. The analysis of vibration characteristics of a power transformer is presented in this paper. The structural dynamic response analysis is included in an enhanced finite element modeling. The main goal of this simulation is to look for indicators related to different structural elements for vibration monitoring purposes. This research also aids in the understanding of some interesting vibration behaviors in transformers, allowing for a virtual simulation of the transformer rather than costly factory tests.**

Keywords—*Finite element modeling; frequency response; natural frequency; power transformer; transformer vibration.*

I. INTRODUCTION

Power transformers are the most critical component in the power system and, therefore, multiple diagnostic tools are currently being developed for them [1]. Transformer failures can be classified as electrical, mechanical, or thermal, according to recent researches [2]. Mechanical structure failure is the most difficult of these issues. As a result, methods for detecting the transformer's mechanical condition, such as vibration analysis, are essential [3].

Vibration diagnostics are used to determine the mechanical condition of the windings and magnetic core in large power transformers. In most cases, these measurements are made by installing vibration sensors on the transformer tank's surface and acquiring vibration data [4-6]. These vibration measurement systems are designed for applying to running transformers [7]. The vibration data are normally converted into an electric signal, which is then analyzed in a digital form. These approaches provide general information and identify the possibility of mechanical failure, but it does not provide a clear understanding of the physical reasons and mechanical structural dynamics of the transformer. In this context, the knowledge of different vibration modes in a transformer can ease the subsequent assessment.

In addition to detecting vibration signals, some researchers present analytical models based on the structure of the transformer and its operating conditions. Some of these researches can be found in the analytical modeling of transformer windings and core [8, 9]. Analytical models and experimental data, on the other hand, can only provide limited information because they focus on some vibration characteristics and are unable to describe the mechanism of transformer vibration. Due to the limitations of analytical solutions and the complex system of transformers, numerical simulations are now a good substitution for investigating the analysis of power transformer vibrations. The finite element method (FEM) is used as an alternate tool to solve electromagnetic and structural dynamic problems in this context [10-12]. The dynamic response is very important in the vibration analysis since it reflects the transformer structure and a clear understanding of it provides a further assessment of the health of the transformer.

The electromagnetic force in the windings and the magnetostrictive force in the core are well-recognized sources of transformer vibration [13, 14]. Moses measured transformer core vibration for a variety of old and modern materials under different tension stresses [15]. In the test results, the amount of vibration in new materials is less. A study has been conducted on the audible sounds of transformers due to magnetostriction vibrations and magnetic forces by the vibrations of the core materials in [16]. In this research, a silicon steel material with SiFe composition is considered. In previous works, the vibration characteristics of the winding have also been investigated. Windings vibration modeling is presented in radial and axial directions in [17, 18]. Ertl and Landes provided modeling considerations and mechanical evaluations, along with a brief discussion of the winding mode shapes [19]. Flexural modes, longitudinal oscillation, and mixed modes were used to classify the transformer winding modes in general (with flexural and longitudinal components). The mode shapes of the windings are graphically shown in their paper, however, it does not include the complete transformer structure.

This paper provides a FEM simulation technique for transformer modeling concerning the aforementioned points to explore the dynamic response of the power transformer. The complex vibration behavior of the transformer is investigated in this work. Furthermore, combining the proposed model with vibration measurement may give a method for diagnosing power transformer failure modes.

II. MODEL DESCRIPTION

The vibration modeling transformer is an 8 MVA three-phase transformer based on a large power transformer's disc-type winding arrangement. Due to the non-axial symmetry of the transformer structure, a comprehensive 3D FEM model is required to investigate dynamic responses without losing important vibration characteristics. As illustrated in Fig. 1, the FEM model of the core and winding assemblies must be defined in such a way that it provides a simulation of the transformer vibration at an acceptable cost from the time of calculation point of view. The primary winding has a nominal current of 419.9 A and 162 turns, while the secondary winding has a current of 230.9 A and 510 turns. Table I lists the features of the various materials that create the transformer assembly.

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A. Modeling of the transformer core

Due to the layered nature of the core in practical transformers, the core mesh is impossible to model vibrations for each SiFe layer. The large size of the system matrix results in high computational costs. In transformer vibration modeling, how to deal with this challenge is crucial. An analogous methodology based on Young's modulus of the transformer core structure is offered to overcome this problem [20]. Young's modulus is a mechanical property that measures the tensile stiffness of a solid material. The test specimen for this similar approach is made up of SiFe sheets, as shown in Fig. 2. The specimen is made up of 100 layers of SiFe sheets with a thickness of 0.2 mm. A bolt hole is bored at each end of the SiFe sheet to clamp the laminations once assembled.

According to the Euler–Bernoulli beam theory, the simulation test is carried out to determine the natural frequencies and hence Young's modulus:

$$\omega_n = (\beta_n L)\sqrt{\frac{EI}{\rho A_0 L^4}} \quad (1)$$

where ω_n is the natural frequency, E is the elastic modulus, βnL is a constant relating to each natural frequency, A_0 is the area of cross-section, ρ is the material density, L is the length of core laminate, and I is the area moment of inertia.

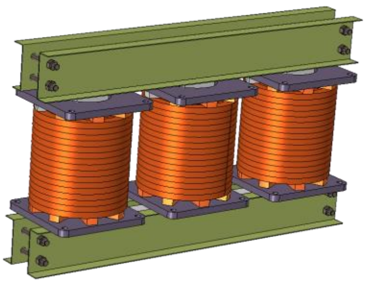

Fig. 1. Transformer model for structure analysis.

TABLE I. MATERIAL PROPERTY DATA.

Component	Material	Density (kg/m3)	Young's Modulus (GPa)	Poisson ratio
Windings	Copper	8900	115	0.35
Core	SiFe	7650	180	0.25
Clamping plate	PBT	900	7.69	0.48
Bolts	Steel	7850	210	0.3
Brace	Steel	7850	210	0.3

The anisotropic Young's modulus of the test specimen is determined by measuring the vibration in both the in-plane and out-of-plane directions independently. The out-of-plane direction is along the Z-axis in Fig. 2.

The input mobility test results for in-plane and out-of-plane direction vibrations are shown in Table II. Two resonance frequencies of 2562 Hz and 5584 Hz are detected in the in-plane testing findings. Equation (1) calculates the test specimen modulus of elasticity to be E =174.5 GPa, while SiFe has an elastic modulus of around 180 GPa, which is close to the estimated elastic modulus in the in-plane direction. This means that the SiFe sheet's lamination has little effect on material characteristics in the in-plane direction, and the core lamination can be thought of as a solid. Compared to the in-plane direction, the natural frequencies in the out-of-plane direction are significantly lower. This means that the vibrational properties of the core are very anisotropic. The core stiffness is controlled not only by the elastic modulus of the SiFe core but also by the clamping forces in this case. Based on the aforementioned points, the core is modeled as a solid body with different Young's Modulus along various axes.

B. Modeling of the transformer windings

In practical transformers, to transmit current with low eddy current losses, in contrary to solid conductors, windings are usually composed of copper strands that are continuously transposed. This design meets the electrical requirements, but it complicates the vibration modeling. The winding structures must be replaced with a homogenized 3D model with the same form and dimension in order to optimize the time of solving the FEM model. To make the winding model easier to understand, the materials are assumed to have the same stiffness, mass, and damping ratio. It is noteworthy that for modeling transformer windings, regardless of the type of problem, cylindrical coordinates have the best computational performance. In addition to the core and windings modeling considerations, no dynamic changes are considered in the material behavior since this numerical analysis is limited to linear mechanics.

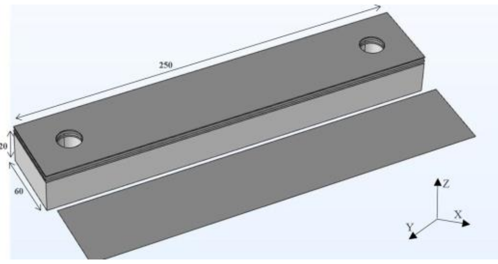

Fig. 2. Test specimen laminated by SiFe sheets.

TABLE II. TEST RESULTS FOR THE IN-PLANE AND OUT-OF-PLANE DIRECTION VIBRATIONS.

ID	Natural frequency (Hz)	Young's Modulus (GPa)
In-plane vibration	2562	174.5
Out-of-plane vibration	135	1.9

III. TRANSFORMER STRUCTURE DYNAMIC ANALYSIS

The dynamic response of the power transformer is modeled using FEM in this section. Fig. 3 shows the average frequency response function (FRF) of the transformer vibration. The resonant behavior of the transformer structure is clearly visible in the frequency ranges so that the response amplitude gradually increases with increasing frequency. This means that at high frequencies, vibrations are excited simpler by an input force. Because of the sensitivity of human hearing, restrictions on noise output at higher frequencies are critical. As a result, it is important for transformer designers to optimize their models to reduce high-frequency responses. Furthermore, the number of resonant peaks in the low-frequency range, i.e., in the operating frequency range (50 Hz and its harmonics), is greater than in the high-frequency range. This necessitates the optimal design of power transformers to avoid resonant modes in the low-frequency range.

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In the frequency response in the range of 380 to 480 Hz, a group of resonances is observed. The other resonance peaks, on the other hand, have distinct and smooth curves. This region receives special attention in order to determine whether it is caused by the winding or core modes. After analyzing the frequency responses of the core and the set of windings, it is observed that the resonances in this frequency range are merely related to the windings. Local resonances can be found around the global natural frequency, according to this observation. The local stiffness of the winding is the cause of the local resonances. Because local stiffness changes at different measurement places, the spatially averaged FRFs have a complicated distribution. Table III summarizes the measured FRFs by listing the transformer's first fifteen natural frequencies. The frequency response in Fig. 3 shows the vibrational resonances up to the range of 1400 Hz, and their mode shapes are divided into three types based on their participation in the vibration of the transformer structure. The three types of transformer modes are core-related modes, windings-related modes, and coupled modes. If the highest contribution to the vibrations of the transformer structure is related to the core vibrations, the vibration mode is called the core-related. Winding-related modes have a similar definition. If both the winding and the core have a significant role, the mode distribution is said to be coupled.

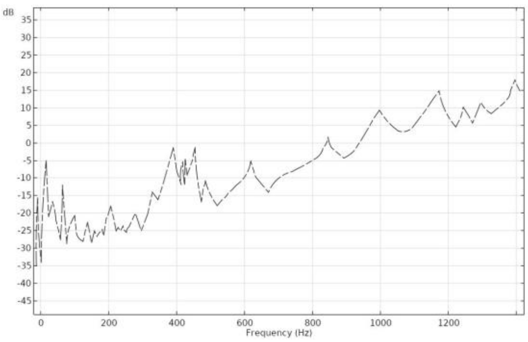

Fig. 3. Spatially averaged FRF of the power transformer.

TABLE III. CLASSIFICATION OF THE TRANSFORMER'S FIRST FIFTEEN MODES BASED ON MODE SHAPE TYPE.

ID	Natural frequency (Hz)	Mode shape summary
	32	symmetrical twist
	56	asymmetrical deformation
	79	asymmetrical deformation
	105	asymmetrical bending
	203	symmetrical bending
	296	symmetrical bending
	302	asymmetrical bending
	320	axial bending
	398	cylindrical mode
	401	axial bending
	468	cylindrical mode
	520	radial bending
	14	out-of-plane deformation
	21	out-of-plane deformation
	54	out-of-plane bending

IV. RESULTS AND DISCUSSIONS

As shown in Table III, the vibration modes of the core and the coupling are in the lower frequency response range, while the vibration modes of the windings are often in the higher frequency range. Since a quantitative understanding of the resonance of the transformer structure can benefit from mode shape analysis, representative mode shapes are provided for each of the three defined categories in the rest of this section.

A. Core-related modes

The first four core-related modes are shown in Fig. 4 at 32 Hz, 56 Hz, 79 Hz, and 105 Hz. To better demonstrate the shapes of the measured modes, the mode shapes are shown from two separate screens. As can be seen, there is no windings vibration observable in the core-related modes.

The first four modes, as shown in Fig. 4, are out-of-plane core modes with low frequencies. The transformer core twists symmetrically in the first mode. The asymmetric deformation of the limbs is associated with the second and third modes, respectively. Considering the fourth mode, it is seen that all of the core-related modes are associated with core deformation in the out-of-plane direction. Such out-of-plane modes are likely to be present in the five-limb core-form transformer. They will be in the low-frequency range, although being at different frequencies. The anisotropy characteristics of the transformer core allow for more out-of-plane vibrations in the low-frequency band, according to the study carried out in the core modeling considerations and the results of this section. These results are important for optimizing vibration properties and reducing audible noise for transformer manufacturers, which can be carried out by changing the design of the structure to change natural frequencies in the low-frequency range.

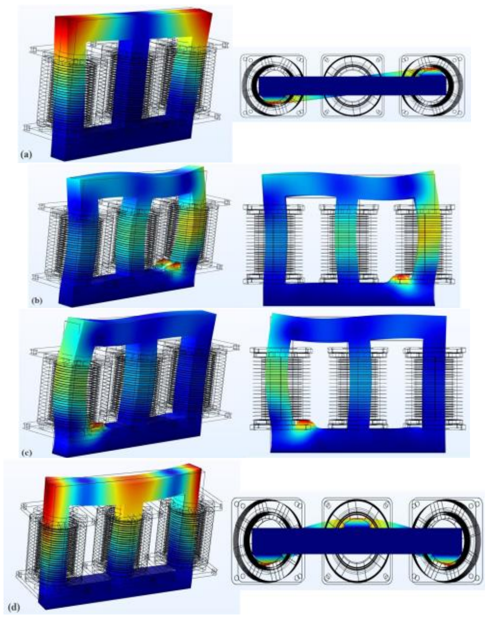

Fig. 4. The first four core-related modes at (a) 32Hz, (b) 56Hz, (c) 79Hz, and (d) 105Hz.

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B. Winding-related modes

Since most windings of practical power transformers are cylindrical, the results obtained from the shape of the winding modes can also be useful for the winding-related modes of other power transformers. The winding-related mode is mostly induced by the vibration of transformer windings, similar to the definition of the core-related modes. Fig. 5 shows the calculated vibration resonance mode shapes of the winding-related cases.

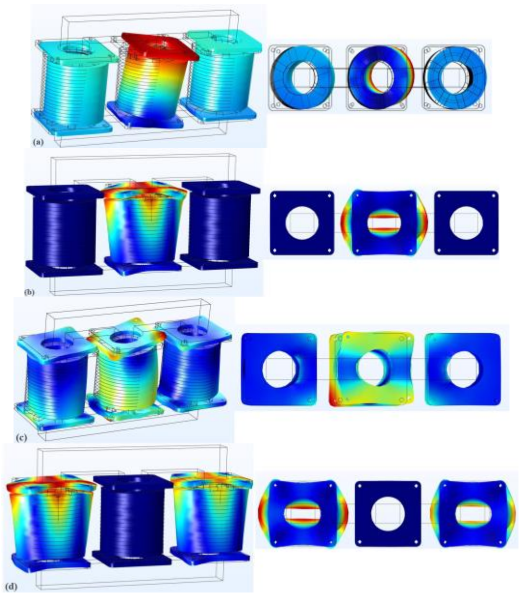

Fig. 5. The first four winding-related modes at (a) 320Hz, (b) 398Hz, (c) 401Hz, and (d) 468Hz.

The windings in Fig. 5 shows associated modes with the winding. Based on these mode shapes, it can be concluded that the vibrations of the windings are most likely similar to a cylindrical shell. As a result, the winding assembly cannot be regarded as a ring stack or a collection of lumped masses. Furthermore, the transformer windings vibration resonances can be thought of as a combination of axial and radial vibrations that deform the transformer windings in both directions simultaneously. Excessive vibration in this situation produces buckling and deformations in the windings.

C. Core–winding coupled modes

According to the definition of coupling mode, if the windings and the core both play an important role in vibrational resonances, the mode distribution is said to be coupled mode. The bottom pressboard and the winding stand, which is connected to the core and bears the winding weight, mechanically connect the transformer core and winding, determining the winding assembly's support state. The transformer's first two coupled-mode shapes are shown in Fig. 6.

In the first coupled mode, the structure of the transformer, i.e., the core and the windings, have an out-of-plane bending relative to the bottom yoke. The second mode involves out-of-plane vibration of the winding and core while the coupled parts move in opposite directions. All coupled modes are connected to the support conditions for mounting the windings assembly to the core yoke. In principle, these modes exist for all core-type transformers, regardless of their design and manufacturing configurations. According to the above discussions, vibrational resonances related to coupled modes are very important because they usually occur at low frequencies.

Fig. 7 describes the overall result of identifying the resonance ranges of the transformer dynamic response. Due to the reflection of the transformer structure, the dynamic response is very important, and a clear understanding of it leads to the best transformer design in terms of noise, mechanical faults, and further transformer health diagnostic.

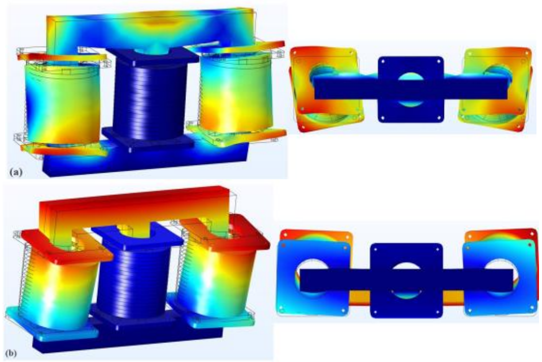

Fig. 6. The first two core-winding coupled modes at (a) 14Hz, and (b) 21Hz.

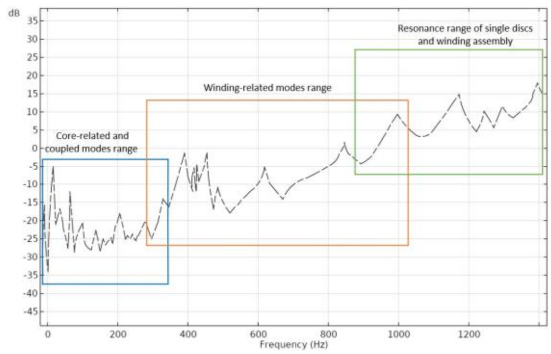

Fig. 7. Dynamic response bands and their sensitivity to related modes.

V. CONCLUSIONS

This work presents numerical modeling based on the FEM approach that is used to evaluate the vibration response of a power transformer. The above research provides a general knowledge of the power transformer vibration features. Because of the modeling considerations, the given model is acceptable and recommended in general. Furthermore, this modeling methodology is applicable to a wide range of transformers.

The transformer vibration modes have been divided into three types based on their participation in the vibration of the transformer structure. This method improved the specificity of the description of transformer vibration. Despite the fact that the transformer is largely made of copper and steel with high stiffness values, the modes are not usually in the high-frequency range. The results revealed that low-frequency modes are typically associated with the core and coupled modes. When studying the dynamic responses of the transformer vibration, it is also discovered that it cannot be considered as a lumped parameter system. As a result of its

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modal analysis, it resembles a cylindrical construction with both ends confined. Overall, this work recommends the use of FEM analysis as an alternate approach for factory testing and a helpful tool in evaluating the dynamic response of a power transformer.

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