Study of winding vibration and transmission characteristics of three-phase oil-immersed distribution transformer based on FEA

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Abstract. In this paper, the magnetic-structure-acoustic multi-physical field model of S13-M400/10 distribution transformer is established through the FEA software. The harmonic response analysis method is used to study the winding vibration and transmission characteristics of the transformer. The simulation results show that the flux leakage distribution of windings on each core column is mainly determined by the current flowing through these windings. The radial and axial acceleration distributions of the windings are U shape and M shape respectively along the winding height. The acceleration of B phase windings is smaller than that of A and C phase windings. The vibration of the oil tank surface is concentrated in its middle and lower part. The tank side vibration is mainly affected by the vibration of the nearest phase windings, while the tank front vibration is affected by the vibration of the three-phase windings together. This study is of great significance for further studies of the vibration characteristics of the transformer under unbalanced load and proposing the vibration reduction and noise reduction measures for the distribution transformer.

1. Introduction
Due to the shortage of land for residents and the acceleration of urbanization, many distribution transformers are close to the residential area, and the noise generated by them affects the normal life of people. Therefore, it is vital to reduce the vibration noise of the transformers [1, 2]. The vibration of the transformer core is linear with its potential square, and the vibration of the windings is linear with the load current. Therefore, it is reasonable to study the vibration of the transformer core and the windings separately. Silvesterh and Anderson respectively used two-dimensional high order finite element method and symmetric finite element method to analyse and calculate the constant magnetic field inside the transformer [3, 4]. Considering the radial and axial vibration of the windings can reduce the large error caused by the simulation analysis [5]. Many researchers focused on the disk winding vibration and its transmission characteristics of single-phase power transformer, while there were few studies about the layer winding vibration and transmission of the three-phase power transformer [6, 7, 8]. This research aims to establish a simplified multi-physical field model of three-phase oil-immersed distribution transformer and investigate the vibration and transmission
characteristics of the layer windings. And this will be fundamental for further studies about vibration and noise reduction for the distribution transformer. The remainder of this paper is organized as follows: section 2 provides model of the three-phase oil-immersed distribution transformer and relevant material parameters. Section 3 introduces a method to simulation the vibration and transmission characteristics of the windings. In the section 4, the performance of the simulation, result and discussion are presented. Section 5 concludes the entire work of this paper and future work for the paper.

2. Model of three-phase oil-immersed distribution transformer

In order to reduce the computational workload of simulation and the purpose of simulation is to explore the rules, some necessary simplifications and assumptions are made to the model. Without considering the influence of the heat sink on the simulation acoustic characteristics, the heat sinks are removed. Bushings have little influence on the vibration generation and transmission of the distribution transformer, so bushings are ignored in the model. The core of the simulation model is simplified a whole, which is conducive to the simulation calculation. The structure of the S13-M400/10 distribution transformer windings is layered, so they are simplified into cylinders. Figure 1 shows the structure of the transformer, and Table 1 shows the main structure dimensions and parameters of the model transformer.

![Figure 1. The structure of three-phase oil-immersed distribution transformer](image)

### Table 1. Parameters of three-phase oil-immersed distribution transformer

| Name of parameter               | Value       | Name of parameter               | Value       |
|---------------------------------|-------------|---------------------------------|-------------|
| Transformer type                | S13-M400/10 | Window size of core/mm          | 350/147     |
| Nominal voltage/kV              | 10/0.4kV    | Core size/mm                    | 630/696     |
| Nominal current/A               | 13.3/577.4  | Working frequency/Hz            | 50          |
| Turns of HV winding             | 1182        | Turns of LV winding             | 26          |
| Inside/outside diameter of HV   | 130/103     | Inside/outside diameter of LV   | 95/73       |
| winding /mm                     |             | winding /mm                     |             |
| Height of HV winding/mm         | 320         | Height of LV winding/mm         | 320         |

HV is abbreviation of high voltage.
LV is abbreviation of low voltage.

This transformer is connected in the form of (D, yn11), so the high and low voltage windings of each phase are located on the same core column. Different minimum and maximum unit sizes are selected for different structures, and this model is intelligently partitioned using free tetrahedral elements. The number of model division units is 897261.
3. Simulation method
This study does not consider the influence of nonlinear factors, so the vibration frequency of the transformer is twice the working frequency. In harmonic response analysis, the used field analysis frequency is set to 100Hz, while the original analysis frequency of the magnetic field is 50Hz, so there is an equivalence.

The electromagnetic force density of the windings is defined as:

\[
\begin{align*}
f_v &= J \times B = J_m \cos(\omega t + \varphi_0) \times B_m \cos(\omega t + \varphi_1) \\
&= J_m B_m (\cos(2\omega t + \varphi_0 + \varphi_1) + \cos(\varphi_0 - \varphi_1))/2
\end{align*}
\]

While \(J\) is current density of windings, \(B\) is flux leakage density of windings, \(J_m\) is the amplitude of current density, \(B_m\) is the amplitude of flux leakage density, and \(\omega\) is the working frequency. In harmonic response analysis, only the alternating components are retained, so the electromagnetic force density of the windings is showed as:

\[
\begin{align*}
J_m B_m \cos(2\omega t + \varphi_0 + \varphi_1)/2
\end{align*}
\]

Therefore, the electromagnetic force density is defined in the software as shown in equation 2 above. The simulation flow chart is illustrated in figure 2.

![Figure 2. Winding vibration electromagnetic-structure-fluid coupling calculation process.](image)

In this study, Comsol Multiphysics software is used to realize the electromagnetic-structure-fluid coupling analysis of the three-phase oil-immersed distribution transformer. Considering that the skin effect and excitation current of the transformer winding structure can be neglected in the AC magnetic field, the harmonic response steady-state calculation is adopted for the magnetic field and electromagnetic force distribution of the transformer. Through the calculation of the magnetic field winding force density, and unidirectional coupled with the structural mechanics module, accurate transmission of data is implemented, which avoids the inaccuracy caused by applying concentrated force and cumbersome calculation process by using multiple FEA software. At the same time, two-way coupling is adopted in the analysis of winding structure-transformer oil fluid-box structure, which fully takes into account the interaction between two types and three physical fields and improves the calculation accuracy.

4. Result and discussion
In order to better analyse the transmission characteristics of three-phase windings vibration and the internal structure of the transformer is symmetrical, so this study simulates the winding vibration and its transmission characteristics of full three-phase load, single A phase load and single B phase load...
respectively. This phase current is the rated current under single-phase load, and that of the other two phases is zero. The current of each phase winding under three-phase load is the rated current.

4.1. Distribution of leakage magnetic field and electromagnetic force in windings

It can be seen from figure 1 that the transformer is symmetric about the XZ plane, so the distribution of leakage magnetic field in windings is showed in this plane and is illustrated in figure 3.

![Figure 3](image)

**Figure 3.** Distribution of leakage magnetic field in windings under three conditions.

Figure 3 shows that the distribution of magnetic flux leakage in windings with excitation source under single-phase condition is basically the same as that of three-phase excitation source windings, so it can be argued that the flux leakage distribution of windings on each core column is mainly determined by the current flowing through these windings. This is because the two windings on the same core column are very close, and the current in the HV winding is in the opposite direction with that in LV winding and the current in the two windings is inversely proportional to the ratio of turns, so the magnetic field, generated by windings of one phase, in windings of other phases is almost zero. The distribution of electromagnetic force in windings is showed in figure 4-5.

![Figure 4](image)

**Figure 4.** The distribution of the radial and axial electromagnetic force on the HV windings.

![Figure 5](image)

**Figure 5.** The distribution of the radial and axial electromagnetic force on the LV windings.

It can be seen from figure 4-5 that the radial electromagnetic force of the region where the HV and LV windings are close is large, while the radial electromagnetic force of the outer part of the HV windings
and the inner part of the LV windings is small. The radial electromagnetic force of the winding is larger than the axial electromagnetic force, and the axial electromagnetic force is concentrated near the end of the winding, which conforms to the theory of force analysis of the winding.

4.2. Distribution of leakage magnetic field and electromagnetic force in windings

The windings of B phase in concentric three-phase three-column transformer is located in the middle, and the windings of the other phases are structure symmetry, so only the vibration acceleration amplitude distribution of the windings of A and B phases is shown, illustrated as the figure 6-9.

![Figure 6](image6.png)

**Figure 6.** The vibration acceleration amplitude distribution of HV winding of A phase.

![Figure 7](image7.png)

**Figure 7.** The vibration acceleration amplitude distribution of HV winding of B phase.

![Figure 8](image8.png)

**Figure 8.** The vibration acceleration amplitude distribution of LV winding of A phase.

![Figure 9](image9.png)

**Figure 9.** The vibration acceleration amplitude distribution of LV winding of B phase.

It can be seen from the figure 6-9 that the radial acceleration is greater than the axial acceleration in winding, which is because the radial magnetic induction strength component is relatively small, so the
axial vibration acceleration is smaller than the radial vibration acceleration in winding. It can be seen that the amplitude of vibration acceleration of the A-phase windings is greater than that of the B-phase windings. Because the structure of the B-phase winding is more stable due to the restraint of the upper and lower iron yoke, so the vibration of the B-phase windings is smaller than that of the A-phase windings. At the same time, it can be seen that the radial acceleration distribution of the winding is U shape, which means that the vibration acceleration in the middle of the winding is greater than other regions. And the axial acceleration distribution of the winding is M shape, which means the axial vibration acceleration in the 1/5 and 4/5 height of winding is strongest.

4.3. Distribution of leakage magnetic field and electromagnetic force in windings

The vibration of transformer comes from the vibration transferred from the vibration of inner structure by solid fasteners and transformer oil. The vibration of inner structure is mainly resulted from the vibration of windings caused by electromagnetic force and iron core caused by magnetostrictive force. The vibration acceleration amplitude distribution of the tank is illustrated in figure 10-12.

![Figure 10](image1.png)

**Figure 10.** The vibration acceleration distribution of the tank under three-phase current load

![Figure 11](image2.png)

**Figure 11.** The vibration acceleration distribution of the tank under single A-phase current load

![Figure 12](image3.png)

**Figure 12.** The vibration acceleration distribution of the tank under single B-phase current load

It can be seen from the figure 10-12 that the vibration acceleration amplitude on the side of the oil tank is greater than that on the front of the oil tank under full three-phase load, which is attributed to the fact that the radial x component of the winding vibration is greater than the radial y component. At the
same time, under full three-phase load, the parts with large vibration on the surface of the oil tank shell are distributed at the lower part of the oil tank. This is because the parts with large vibration of the windings are located at the middle part of the winding corresponding to the lower part of the oil tank. Because the vibration of B phase windings is less than that of A-phase windings, so the vibration acceleration amplitude of oil tank under single A-phase current load is greater than that under single B-phase current load. The vibration on the side of the tank is mainly affected by the nearest windings, while the vibration of the front of the oil tank is affected by three-phase windings together.

5. Conclusion
In order to understand the vibration of three-phase windings and their transmission characteristics, the magnetic-structure-acoustic multi-physical field model of S13-M400/10 distribution transformer is established through FEA software in this paper. The paper presents the results of the flux leakage distribution of windings, electromagnetic force distribution in windings and the vibration of windings and the oil tank. The flux leakage distribution of windings on each core column is mainly determined by the current flowing through these windings. And the radial and axial acceleration distributions of the windings are U shape and M shape respectively along the winding height. The vibration of the oil tank surface is concentrated in its middle and lower part, and the tank side vibration is mainly affected by the vibration of the nearest phase windings, while the tank front vibration is affected by the vibration of the three-phase windings together.

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