Multi physical field coupling simulation analysis of power transformer vibration and noise

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Abstract. The generation, propagation and distribution of power transformer vibration and noise are studied by modeling and simulation. Based on the theoretical analysis of the mechanism of power transformer vibration and noise, the correlation between the characteristics of power transformer vibration noise and the influencing factors is determined. The solid model of single-phase power transformer is established by using multi physical field finite element analysis software. The multi physical field coupling simulation of electromagnetic field, structural force field and pressure acoustic field is carried out. The spatial distribution and frequency characteristics of vibration and noise signal of single-phase power transformer in each solution domain are displayed. It provides theoretical and technical support for smart grid equipment detection and environmental noise comprehensive control.

1. Introduction
Power transformer is the most basic and important electrical component of the whole power system, which undertakes the important function of power conversion in the process of power transmission\cite{1}. With the continuous expansion of transformer capacity and the increase of transformer voltage level, the failure rate and repair time of transformer are also increasing. The severe vibration of high voltage and large capacity power transformer during operation will not only affect the normal operation and service life of equipment, but also reduce the reliability of equipment, and the noise generated by vibration will have adverse effects on people's work and life\cite{2}.

At present, the research on transformer vibration and noise mainly focuses on theoretical analysis and experimental research, but the simulation research on transformer vibration and noise is not deep enough\cite{3}. Using COMSOL multi physical field coupling analysis software to establish the physical model, from the perspective of multi field coupling, the magnetic field distribution, core magnetostrictive stress, strain and winding Lorentz force of transformer under different conditions are calculated respectively, which can better reveal the physical characteristics of transformer in electromagnetic, mechanical and structural aspects, not only for the production and assembly of transformer and low noise design It can provide reliable guidance and lay a foundation for the optimization design of transformer noise performance in the future, and provide an important and effective research method for the vibration and noise research of power transformer.

2. Characteristic analysis of vibration and noise
There are many components involved in transformer vibration noise, and the causes are different, which can be summarized into several aspects. One is the operation state. The operation state of transformer determines the magnetic flux density and load current of its core, and the magnetic flux density directly affects the magnetostriction of silicon steel sheet. A large number of test data at home...
and abroad show that the increase of magnetic flux density will increase the noise level of transformer. The second is the structure of the transformer[4]. The size of the silicon steel sheet affects the vibration and noise intensity of the iron core, and the magnetic path of the iron core, as an important factor leading to high-order harmonic generation in the electromagnetic field of the transformer, will directly affect the frequency distribution characteristics of the noise. The third is material technology, which mainly includes the model, material and quality control of silicon steel sheet used for iron core[5].

3. Simulation modeling of transformer vibration and noise

3.1. Electromagnetic model
The model consists of a pair of E cores, which form a closed magnetic circuit. The primary and secondary coils in the transformer are placed around the leg in the center of the core, as shown in Figure 1.

![Figure 1. Geometric model](image)

The nonlinear $B-H$ curve including saturation effect is used to simulate the magnetic properties of soft iron core. The hysteresis effect in the core is ignored. The model assumes that the primary and secondary windings are composed of thin wires with a large number of turns[6]. Assuming that the wire diameter is less than the skin depth and there are many turns, the "coil" feature is used to simulate these windings. In addition, the eddy current in each coil is not considered in this model[7]. The primary winding is connected to the primary resistance $R_p$ and the AC voltage source $V_{ac}$, and the secondary winding is connected to the secondary load resistance $R_s$, as shown in Figure 2.

![Figure 2. Circuit](image)

The model is solved in the time domain when the line frequency is 50Hz. In modeling, several important design parameters such as input voltage, line frequency, coil turns and coil resistance are parameterized, which can be easily changed.

| name     | expression | value | description |
|----------|------------|-------|-------------|

Table 1. Circuit parameters
The transformer operates according to Faraday’s law of electromagnetic induction, which indicates that the induced voltage ($V_{in}$) in the coil is proportional to the flux change rate ($\Phi$) and the number of turns ($N$) in the coil, as shown in equation 1

$$V_{in} = -N \frac{d\Phi}{dt}$$

If two coils are coupled, equation 1 can be used to infer that the induced voltage voltage ($V_s$) in the secondary coil is proportional to the induced voltage ($V_p$) in the primary coil

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Here $N_s$ and $N_p$ are the number of turns in the secondary and primary coils respectively. $N_p/N_s$ is called the turn ratio.

Figure 3 shows the curved surface of the flux density mode distribution and the arrow diagram of the current in the winding at t=50ms. Figure 4 shows the arrow diagram of the flux density mode in the core at t=50ms.

| $R_p$  | 100[ohm]  | 100Ω  | Primary winding resistance |
|-------|-----------|--------|----------------------------|
| $R_s$ | 10[kohm]  | 10000Ω| Secondary winding resistance|
| $N_p$ | 300       | 300   | Number of turns in primary winding |
| $N_s$ | 300       | 300   | Number of turns in secondary winding |
| $n_u$ | 50[Hz]    | 50Hz  | Frequency of supply voltage |
| $V_{ac}$ | 25[V]    | 25V   | supply voltage |

**Figure 3. Current density**

**Figure 4. Magnetic flux density**
Figures 5 and 6 induced voltages in primary and secondary windings

**Figure 5.** Primary windings Induced voltage

**Figure 6.** Secondary windings Induced voltage

Figure 7 and Figure 8 current flowing through primary winding and secondary winding

**Figure 7.** Primary windings Induced current

**Figure 8.** Secondary windings Induced current
3.2. Structural field model

If two coils are coupled, equation 1 can be used to infer that the induced voltage voltage \( V_s \) in the secondary coil is proportional to the induced voltage \( V_p \) in the primary coil.

The stress in magnetostrictive material is simulated as
\[
S = C_{ii}[\varepsilon_{el} - \varepsilon_{me}(M)]
\]

Assuming that the material is isotropic, the stiffness matrix \( CH \) can be expressed by young's modulus and Poisson's ratio. The magnetostrictive strain is represented by a quadratic isotropic function of the magnetization field \( M \), as shown in the following formula
\[
\varepsilon_{me} = \frac{3}{2} \lambda_s M_s \text{dev}(M \otimes M)
\]

The tensor product of two vectors is defined as
\[
(M \otimes M)_{ij} = M_i M_j
\]

\( \lambda_s \) is the saturation magnetostrictive coefficient, which is the maximum magnetostrictive strain at the saturation magnetization \( M_s \). Note that the magnetostrictive strain is represented by a deviator tensor\[^8\]. This is because the deformation may be related to the domain rotation associated with the magnetization of the material; this process does not change the volume of the material\[^9\]. The nonlinear magnetization in magnetostrictive materials is shown by the following nonlinear relations
\[
M = M_s L(|H|) H
\]

Where \( L \) is the Langevin function
\[
L = \coth\left(\frac{3\chi_m |H|}{M_s} \right) - \frac{M_s}{3\chi_m |H|}
\]

\( \chi_m \) is the susceptibility in the initial linear region, and the effective magnetic field in the material is given by the following equation
\[
H_{eff} = H + \frac{3\lambda_s}{\mu_0 M_s^2} S_{ed} M
\]

The second term in the above relationship represents the contribution of mechanical stress to the effective field, and therefore to the magnetization of the material, which is called the villary effect. The elastic stress deviator is related to the elastic strain \( \varepsilon_{el} \) in the material, and the relationship is as follows
\[
S_{ed} = \text{dev}(C_{ii} \varepsilon_{el})
\]

In addition, magnetization and magnetic field are related to each other, and they are related to B field. The relationship is as follows
\[
B = \mu_0 (H + M)
\]

The material properties used to describe magnetostrictive materials are shown in the table below

**Table 2. Properties of magnetostrictive materials**
| Material property | Value          | describe                  |
|-------------------|----------------|---------------------------|
| $E$               | $60 \times 10^9 \text{Pa}$ | Young's modulus          |
| $\nu$             | 0.45           | Poisson's ratio           |
| $\rho$            | 7870 kg/m$^3$ | density                   |
| $\sigma$          | $5.96 \times 10^6 \text{S/m}$ | conductivity          |
| $\varepsilon$     | 1              | Relative permittivity     |
| $\lambda_s$       | $2 \times 10^{-4}$ | Saturation magnetostriction coefficient |
| $M_s$             | $1.5 \times 10^6 \text{A/m}$ | Saturation magnetization |

Figure 9 stress surface diagram

Figure 9. Stress

3.3. Sound pressure field model

If the external fluid is air (or any other light fluid), it can be assumed that the coupling is unidirectional. This means that the vibration of the core will affect the surrounding fluid, while the acoustic feedback to the structure is ignored. This model uses this approach$^{[10]}$.

This model uses "pressure acoustics, frequency domain" interface to solve frequency domain problems. The modified Helmholtz equation is used to solve the sound pressure $p$:

$$
\frac{1}{\rho_0 c^2} \frac{\partial^2 p}{\partial t^2} - \nabla \cdot \left( \frac{\nabla p}{\rho_0} \right) = 0
$$

$\rho_0$ is the density and $c$ is the speed of sound.

Figure 10 shows the sound pressure level (db) and structural deformation (mm)
4. Epilogue

Aiming at the main noise source of power transformer, the generation mechanism of core magnetostrictive force and winding electromagnetic force is analyzed. The generation process of vibration and noise of transformer core and winding is studied, and its propagation process in surrounding space is considered. The geometric model of transformer is established by using multi physical field coupling software COMSOL. Based on the geometric model, geometric processing and mesh generation are carried out. The magnetic field, electromagnetic force, magnetostrictive force and sound field are coupled to calculate the magnetic field distribution, vibration, displacement and noise distribution caused by electromagnetic force and magnetostriction. The validity of the simulation results is verified by comparing with the measured noise data of the transformer.

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