Simulation Analysis of Vibration and Noise Characteristics of High Voltage Shunt Reactor Based on Multi-physical Field Coupling

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Abstract. In order to study the vibration characteristics of the high-voltage shunt reactor, a finite element model of the single-phase reactor was established based on the analysis of the vibration mechanism of the reactor body, by using COMSOL multi-physical field coupling simulation software. The magnetic flux density distribution of reactor core, windings, stress distribution and vibration displacement of iron core were analysed by simulation. The sound pressure distribution of the iron core was analysed based on the pressure sound field model. The results indicate that the magnetostrictive effect of the iron core reactor, the electromagnetic attraction between the iron core cakes and the ampere force on the winding are the main factors for its vibration. In addition, the reactor vibration to be mainly concentrated at the core air gap. The results obtained by multi-physics simulation are basically consistent with the measured data, which verifies the effectiveness of the simulation method. The conclusions can provide theoretical basis for the analysis and monitoring of reactor vibration and noise.

Keywords: High voltage shunt reactor; Magnetostriction; Vibration; Noise.

1. Introduction
As the key equipment for reactive power compensation and reducing the increase of power frequency voltage, high-voltage shunt reactors play an important role in compensating the capacitive current of long-distance transmission lines, limiting overvoltage, protecting electrical equipment, and reducing active power loss of lines[1-3]. Therefore, the safe and stable operation of high-voltage shunt reactor is very important for the whole AC transmission system.

The structure of the shunt reactor is mainly composed of iron core and windings, and the segmented iron core structure is adopted. After the long operation at the full load of the shunt reactor, the leakage of magnetic field is large, and the mechanical vibration is more serious than that of the transformer[4,5]. The high-voltage shunt reactor will easily cause the coils, iron cores (clamps), bolts and fasteners to loosen during long-term operation, which will further aggravate the occurrence of vibration, and may also cause defects such as overheating and discharge inside the equipment[7-9]. Therefore, vibration has become an important indicator to measure the safety and long-term operation of large reactor equipment. Liu Ji et al[2] calculated the magnetic field distribution, the magnetostrictive displacement...
of the iron core, the Maxwell force between the discus, the stress and the sound pressure level of a three-phase series iron core reactor, the result shows that the magnetostriction is the main cause of reactor core vibration. The sound pressure, sound intensity and vibration methods were used to measure and discuss the sound power level characteristics of the reactor[5], the result shows that the vibration distribution of shunt reactor on each surface is quite different, and the vibration acceleration is linearly related to the operating voltage.

Based on the brief analysis of the vibration mechanism of reactor body, the finite element model of single-phase reactor is established by COMSOL multi-physical field coupling simulation software. The magnetic flux density distribution, stress distribution and vibration displacement of reactor core and winding are simulated and analyzed.

2. Model Building and Multi-physical Field Coupling Principle

When the reactor works, the power frequency current enters the winding to produce alternating magnetic field. In the magnetic field, the size of ferromagnetic materials will change in all directions, causing magnetic hysteresis deformation. Because of the air gap between each core cake of the reactor, the core cake will be subjected to electromagnetic force in the alternating magnetic field. When the current enters the winding, the current-carrying wire will also be subjected to the ampere force of the magnetic field leakage. Alternating electromagnetic excitation will cause the core and winding to produce vibration, and transfer outward through the fixed connection structure, resulting in the shell surface vibration. The vibration of the shell causes the surrounding air to vibrate and produce audible noise.

2.1. Model Building

A finite element software COMSOL is used to simulate the reactor. The finite element simulation process is shown in figure 1.

![Figure 1. Simulation flow chart.](image)

The reactor components include iron core, discus, windings, air gap pad and pull rod, etc., and its structural diagram is shown in Figure 2.

![Figure 2. Schematic diagram of shunt reactor structure.](image)
When modeling, the reactor core and winding were appropriately simplified, and the geometric model was established according to its shape and structure, as shown in Figure 3. Based on the approximate material characteristics of the structure as the basis for finite element analysis, all the fasteners of the reactor will be connected after the finite element geometric model is established, and the function of the connector will be realized by adding constraint conditions, which approximates the actual operating conditions. After the model is established, the material properties are assigned to the model according to the actual material properties. The core and windings are partially refined and divided, and the remaining positions are freely meshed, and the divided graph shown in Figure 4 is obtained.

2.2. Multiple Physical Field Coupling

Under the normal working state of the reactor, the winding current of the reactor produces an alternating magnetic field in the magnet composed of the iron core, in which the differential equation of the magnetic field is:

$$\sigma \frac{\partial A}{\partial t} + \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times A) = J_e$$

(1)

Where $\mu_0$ is the vacuum permeability, its value is $4\pi \times 10^{-7}$ Hmax m, $\mu_r$ is the relative permeability, $A$ is the vector function magnetic vector potential. The magnetic induction intensity $B$, magnetic field intensity $H$ and $m$ in the reactor magnet calculated by the software are substituted into the solution domain equation to realize the coupling of magnetic field and structural force field. The equation is established as follows:

$$m \frac{d^2 u}{dt^2} + \zeta \frac{du}{dt} + ku = F_v$$

(2)

Where $m$ is the mass matrix, $\zeta$ is the damping coefficient matrix, $k$ is the stiffness matrix and $u$ is the displacement vector.

The magnetostrictive and Maxwell forces calculated in the iron core are coupled with the structural force field, in which the magnetostrictive linear elastic equation is:

$$\nabla \cdot \sigma = -F_v$$

(3)

In the formula, $\sigma$ is the stress tensor and $F_v$ is the volumetric force. The magnetostrictive force is set as the initial strain parameter of the reactor core, where the magnetostrictive force is a function that can be magnetized in any direction, and the equation can be expressed as follows:
\[
\lambda_i = \frac{3}{2} \lambda_s \left( \alpha_i^2 - \frac{1}{3} \right) = \frac{3}{2} \lambda_s \left( \frac{M_i}{M_s} \right)^2 - \frac{1}{3}
\]

(4)

The Maxwell force is set as the initial strain parameter of the reactor core, in which there is an air gap in the reactor core, and the adjacent cores are anisotropic magnetic poles at any time, so the Maxwell force in the adjacent cores is attractive. The equation is as follows:

\[
F = B_0 S = \frac{\Phi^2}{2\mu_0 S}
\]

(5)

The volume strain of the iron core is calculated in the structural force field module, and the band is substituted into the iron core as the initial value of vibration. The sound generated by the vibration of the iron core propagates to the air domain, and the coupling of the structural force field and sound field is realized. The differential equations are as follows:

\[
\frac{1}{\rho_0 c^2} \rho \frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left( -\frac{1}{\rho_0} \right) \nabla p = q
\]

(6)

In the formula, \( \rho_0 \) is the air density, \( p \) is the sound pressure, \( q \) is the dipole source and \( Q \) is the monopole source.

3. Simulation Results and Analysis

The electromagnetic force is loaded on the core domain and the magnetostrictive strain is loaded on the core domain. Even if the structural force field is coupled with the magnetic field, the vibration process of the core and winding under the electrodynamic and magnetostrictive effect is simulated and analyzed.

3.1. Flux Density Distribution

The main parameters of the iron core reactor are shown in Table 1 and the parameters of the core, winding, air gap and air material parameters are shown in Table 2. Input the set material parameters and set the boundary conditions, the simulation results show that the distribution of the magnetic flux density of the core and winding at a certain time is shown in figure 5, and the distribution and direction of the magnetic flux density of the central section of the core is shown in figure 6. According to the distribution of the flux density of the core and winding at each time, the flux density on the core column is higher than that on the side column, and the flux density on the winding is lower, because there is no air gap in the side yoke relative to the core cake. Compared with the upper and lower yoke, the size of the side yoke is larger, and most of the magnetic field direction does not need to be changed in the magnetic circuit of the side yoke. The magnetic flux density at the edge and corner of the inner frame of the core is higher, and that of the outer frame of the core is lower, which is due to the difference of the magnetic circuit length between the inner frame and the outer frame of the core, and it is also the reason for the existence of high-order harmonics in the core noise.

Table 1. 750kV single-phase shunt reactor parameters.

| Item                     | Parameter |
|--------------------------|-----------|
| Rated Capacity /Mvar     | 100       |
| Phase                    | Single    |
| Cooling method           | ONAN      |
| Winding rated voltage /kV| 800\sqrt{3} |
| Winding rated current /A | 216.5     |
| Rated frequency /Hz      | 50        |
Table 2. Model material parameters.

| Material parameters          | Iron core | Winding | Air | Air gap |
|-----------------------------|-----------|---------|-----|---------|
| Relative permeability       | 7000      | 1       | 1   | 1       |
| Poisson's ratio             | 0.3       | 0.45    | -   | 0.38    |
| Young's modulus/Pa          | 1.2×10¹¹  | 1.1×10¹¹| -   | 1.7×10⁹ |
| Density/(kg/m³)             | 7870      | 8700    | 1.29| 2000    |
| Sound velocity/(m/s)        | 5200      | 3400    | 343 | 5200    |

Figure 5. Magnetic flux density distribution of core and winding.
Figure 6. Magnetic flux density distribution and direction of the central section of the core.

The average value of the magnetic circuit component along the magnetic field direction in the side yoke is about 1.48T, and that in the discus is about 1.25T, which is consistent with the operating state of the actual reactor.

3.2. Stress Distribution and Displacement of Iron Core

The solid mechanics module built in COMSOL is used to solve the displacement of the iron core, and the acceleration and strain of each point in the solution domain along the x, y and z directions can be output. The stress distribution on the core surface of the reactor is calculated as shown in figure 7, and the deformation distribution is shown in figure 8. It can be seen from the diagram that the deformation of the yoke beside the core is larger, and the closer to the middle of the yoke, the larger the deformation, and the deformation between the upper and lower surface of the core and the core cake is very small, this is because in the actual substation, the bottom and top of the reactor core will be fixed, so the top and bottom of the core are taken as fixed constraints in the boundary conditions of the simulation process.

Figure 7. Stress distribution of iron core.
Figure 8. Cloud map of total displacement of iron core.
3.3. Stress Distribution and Displacement of Iron Core
The sound velocity and density of the air domain adopt the standard air parameters, and the outer boundary of the air domain is set as plane wave radiation. The acceleration and strain of the core and winding are applied to the air domain, even if the pressure sound field and the structural sound field are coupled, the process of noise caused by the vibration of the core and winding is simulated and analyzed. Through the coupling calculation of the structural force field and the sound field, the cloud images of the sound field distribution of the reactor noise in the Xmurz section and the YmurZ section are obtained as shown in Fig. 9 and 10, respectively.

![Cloud picture of sound pressure distribution in Xmurz section.](image1)

![Cloud picture of sound pressure distribution in YmurZ section.](image2)

As can be seen from the figure, because the deformation at the bottom of the core is very small, it can be seen that the sound pressure at the bottom is lower than that in other positions. And the sound pressure on the axis of the core column of the single-phase reactor is slightly higher than that near the side yoke.

4. Experimental Verification
The sound pressure level of the measuring points in the simulation cloud map of the sound field is converted and compared with the measured noise sound pressure level in the corresponding position of the actual measurement in the field. Besides, the comparison diagram of the sound pressure level attenuation characteristics of the simulation results of the reactor and the measured sound pressure level attenuation characteristics of the reactor is shown in Figure 11.

Both the maximum value and the minimum value appear in the noise sound pressure level attenuation characteristic graphs of the simulation calculation results and the actual measurement results, indicating that interference occurs in the noise attenuation process of the two results. Whether it is the actual measurement result or the simulation calculation result, the noise of the reactor conforms to the law of geometric divergence and attenuation, so the sound field around the reactor should be the superposition of the coherent sound field and the incoherent sound field. The noise and sound field simulation results near the high-voltage shunt reactor have some deviations from the actual measurement results, but they are basically consistent with the maximum error of no more than 15%, which proves that the multi-physical coupling analysis method can be used to predict the noise of the shunt reactor.
Figure 11. Comparison diagram of reactor simulation and measured sound pressure level attenuation characteristics.

5. Conclusion
In this paper, the COMSOL finite element software is used to analyze the vibration and noise of the reactor core through the multi-physics coupling method, and the following conclusions are obtained:
(1) Under alternating electromagnetic excitation, the magnetostrictive effect of the iron core reactor, the electromagnetic attraction between the iron core cakes and the ampere force on the winding are the main factors that cause its vibration. The vibration is transmitted to the surface of the shell through the connecting device, and then causes the vibration of surrounding air and production of audible noise.
(2) The magnetostrictive effect and Maxwell force cause the reactor vibration to be mainly concentrated at the core air gap, so the air gap is the main cause of reactor vibration and noise. Compared with the transformer, the transformer core has no air gap, so the noise of the reactor is much greater.
(3) The simulation results provide theoretical basis for the monitoring and selection of reactor equipment. Considering the equipment itself, the impact of different core materials and structural designs on vibration and noise should be focused on, and materials and product structures with better performance should be selected accordingly to achieve the vibration suppression effect.

Acknowledgement
The research work was funded by the Science and Technology Project of the State Grid Corporation of China, "Research on Defect Detection Technology and Diagnosis Method of High Voltage Shunt Reactor Based on Acoustic Vibration Signal" 52199919000A.

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