Winding Vibration Analysis of UHV Shunt Reactor With Finite Element Method

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Abstract. In order to investigate the winding vibration characteristics of UHV shunt reactors, a scale model of UHV reactor is designed and manufactured with rated voltage 29.27 kV and rated current 669.9 A. The magnetic-structure coupled finite element model is proposed to analyze the winding vibration of the reactor. With this model, the distribution and time variation magnetic flux density (MFD) of the reactor is calculated. The Lorentz force in the winding is used as load input for structure analysis. The vibration displacement and acceleration distribution and variation process of the reactor winding is obtained.

1. Introduction
With the rapid development of power grid construction in China, more and more power transmission and transmission project appear around residential areas, the resulting noise impact problem increasingly prominent, and the numbers of complaint and dispute about the power-equipment noise problem is rising. These problems severely restrict the power grid construction and development and have become an urgent problem that must be faced in the process of power grid construction. As the main sound source equipment in UHV station, UHV shunt reactor have characteristics of high noise level and close to station boundary, which is the main reason for the station boundary noise exceeding the standard. The noise of UHV shunt reactor mainly comes from the vibration of its inner core and winding. Therefore, it is of great significant for noise efficient control to study the winding vibration feature of UHV shunt reactor.

In this paper, the electromagnetic force calculation model of reactor windings is studied according to geometric structure and material parameters of reactor windings, so as to establish a calculation model which can accurately describe its electromagnetic force characteristics. The corresponding electromagnetic force distribution characteristics on the winding are calculated and analyzed according to electromagnetic power calculation model of reactor winding. Based on the structure of the winding, the vibration physical model of the winding was established, the results of the electromagnetic force of the winding were taken as the excitation source of the vibration model, the influence of the winding structure parameters on the vibration characteristics of the winding was analyzed, and the design method to reduce the vibration characteristics of the winding was proposed.
2. Calculation of Electromagnetic Force of UHV Shunt Reactor Winding

2.1. Finite Element Model

Taking the reduced ratio model of a certain type of single-phase oil-immersed UHV shunt reactor as the research object, the reactor body and core structure are shown in Figure 1, and the main parameters of the reactor winding and core are shown in the Table 1.

![Figure 1. Reactor model and structure](image)

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(a) Body structure  
(b) Core structure

| Parameter                  | Parameter value       | Parameter                  | Parameter value       |
|----------------------------|-----------------------|----------------------------|-----------------------|
| Rated voltage              | 29.27 kV/√3          | Silicon steel sheet grade  | B30P105               |
| Rated current              | 669.9A                | Coil turns                 | 210                   |
| Total weight               | 15.4t                 | Core size                  | 1.62*0.68*0.99 m      |
| Magnetic shield inner      | 0.110m                | Magnetic shield outer      | 0.974m                |
| diameter                  |                       | diameter                   |                       |
| Magnetic shielding thickness| 0.0275m               | Inner diameter of discus   | 0.127m                |
| Outer diameter of discus   | 0.464m                | Discus thickness           | 0.1275/0.06 m         |
| Winding resistivity        | 1.733e-7 Ω·m          |                            |                       |

The reactor body is symmetrical. In order to reduce the calculation scale and improve the calculation efficiency, the 1/8 winding and the core model are used to establish the electromagnetic field numerical analysis model in the actual calculation, as shown in Figure 2.
The three-dimensional electromagnetic field control equation of the reactor based on the edge element method is

$$\nabla \times (\nabla \times A) = \frac{n}{S_e} I$$

$$V = RI + E$$

$$E_t = \frac{N_e}{S_e} \int_{v_e} n^t \cdot \frac{\partial A}{\partial t} dv$$

(1)

As shown in Figure 3, perform hexahedral sweep meshing for windings, iron core cakes and other parts, and intelligent free meshing for iron cores and air.

2.2. Calculation Results and Analysis

The type of the reactor core silicon steel sheet is B30P105, and the B-H curve of this type of silicon steel sheet is shown in Figure 4. Within 1s time frame, the reactor winding voltage is shown in Figure 5, and the time interval of different time points is 0.5ms.
Figure 4. B-H curves of B30P105

Figure 5. Voltage waveform of the reactor

The magnetic induction intensity distribution result of the iron core is shown in Figure 6. Under the action of the core leakage magnetic field, the Lorentz force distribution of winding at \( t=1s \) is shown in Figure 7. In the time range of 2s, the winding current of the reactor changes with time as shown in Figure 8. The change process of the magnetic induction intensity of reactor iron yoke measuring point 1 and discus measuring point 2 is shown in Figure 9. The change process of Lorentz force of reactor winding is shown in Figure 10.

(a) cloud map of iron core magnetic induction intensity distribution
(b) Iron core magnetic induction intensity vector distribution

Figure 6. Magnetic flux density distribution of the core at \( t=1s \)

Figure 7. Lorentz force distribution of the coil at \( t=1s \)

Figure 8. Current variation process of the reactor coil
3. Calculation and Analysis of Winding Vibration of UHV Shunt Reactor

3.1. Three-Dimensional Structure Analysis Model

The model solution domain only contains the winding area, as shown in Figure 11.

![Figure 11. Solution region of structure analysis](image)

The dynamic finite element equation of the element can be expressed as

\[
\begin{bmatrix} \mathbf{m} \end{bmatrix} \ddot{\mathbf{u}} + \begin{bmatrix} \mathbf{c} \end{bmatrix} \dot{\mathbf{u}} + \begin{bmatrix} \mathbf{K} \end{bmatrix} \mathbf{u} = \begin{bmatrix} \mathbf{R} \end{bmatrix}
\]

(2)

Assuming that the reactor winding is reliably fixed, a fixed constraint is imposed on its upper end surface, namely: \( U_x = U_y = U_z = 0 \). On the symmetry plane of the winding, the constraint normal displacement is zero, that is: in the YZ plane, the constraint \( U_x = 0 \); in the XZ plane, the constraint \( U_y = 0 \); in the XY plane, the constraint \( U_z = 0 \).
3.2. Calculation Results and Analysis of Reactor Winding Vibration

Under the rated voltage condition, the calculation result of the vibration displacement of the reactor winding in each direction (cylindrical coordinate system) at t=2s is shown in Figure 12.

\[ \text{(a) Radial displacement} \quad \text{(b) Tangential displacement} \quad \text{(c) Axial displacement} \]

**Figure 12.** Displacement distribution of the reactor winding in each direction at t=2s

At t=2s, the calculation results of the vibration displacement and acceleration amplitude of the reactor winding are shown in Figure 13.

\[ \text{(a) Winding vibration displacement} \quad \text{(b) Winding vibration acceleration} \]

**Figure 13.** Vibration distribution of the reactor winding at t=2s

The centre point of the outer surface of the winding is selected as the observation point. In the time range of 2s, in the cylindrical coordinate system, the vibration displacement and acceleration change process in the x direction (radial) of this point is shown in Figure 14.

\[ \text{(a) Variation process of winding radial vibration in the time range of 0–2s} \quad \text{(b) Variation process of winding radial vibration in the time range of 1.9–2s} \]

**Figure 14.** Vibration variation process of the reactor winding outer surface

4. Conclusion

1) The noise and vibration signal of the high-voltage shunt reactor is mainly at 100Hz frequency, and contains less other even-numbered harmonic frequencies of 50Hz.

2) Under the action of transient voltage, the amplitude of the winding current reaches a stable state after about 1s of oscillation, and the error between the calculated value and the design value is only
2.06%. There is skin effect between the core and discus magnetic density. Due to the leakage magnetic field, the surface magnetic induction intensity of different iron core cakes is not strictly equal; the maximum magnetic induction intensity of the winding is 0.42T, which is located at 1/2 height inside the winding. From this position, the magnetic induction intensity gradually decreases in the axial and radial directions; the winding electromotive frequency is 100Hz. Mainly based on radial electric power, the maximum total electric power amplitude is 1.125×10⁴N.

3) Under the condition of constraining the end displacement of the winding, the winding vibration in all directions is mainly the 1/2 height radial vibration, the axial vibration is second, the tangential vibration can be ignored, and the maximum radial vibration displacement is approximately the maximum axial displacement. The maximum displacement and acceleration position of the winding appear at 1/2 height of the winding, the maximum displacement amplitude of the winding is 0.663um, and the maximum vibration acceleration amplitude is 0.140m/s²; the vibration displacement and acceleration waveforms of the winding are both sine waves, The frequency is 100Hz; along the winding radial direction, the winding vibration displacement only has a positive value, and the maximum displacement at the center position of the outer surface of the winding is 0.373um; the amplitude of the positive and negative half-axes of the winding radial vibration acceleration is approximately equal, and the peak value is about 0.077 m/s².

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References
[1] Ni Yuan, Zhou Bing and Pei Chunming, Analysis of acoustic interference characteristics around 1000 kV UHV shunt reactor, High Voltage Engineering. 12 (2014) 3926-3932.
[2] Tian Cong, Li Lin and Song Yawu, Model experiment and simulation study of shunt reactor core vibration, Advanced Technology of Electrical Engineering and Energy. 3 (2018) 64-70.
[3] Zhang Pengning, Li Lin and Cheng Zhiguang, Comparison of simulation and test of shunt reactor and transformer model core vibration, Transactions of China Electrotechnical Society. 22 (2018) 5273-5281.
[4] Xu Linfeng, Mao Qiwu and Ou Xiaobo, Design of 10000 kvar Dry-Type Iron Core Shunt Reactor Used in Urban Network, Transformer. 7 (2015) 19-22.
[5] Lin Ruicong, Miao Xiren and Guo Moufa, Summary of latent fault characteristics and coupling analysis of reactor, High Voltage Apparatus. 1 (2015) 150-155.
[6] Xu Linfeng, Mao Qiwu and Ou Xiaobo, Analysis and countermeasures of noise problems of dry-type iron core series reactor after operation, M&E Engineering Technology. 5 (2015) 44-47.
[7] Guan Junjun, Measures to reduce the loss and noise control of high voltage shunt reactor, Electrical Equipment. 12 (2006) 15-17.
[8] Zhou Bing, Song Qian and Ni Yuan, Noise Characteristics and Control of High Voltage Shunt Reactor, High Voltage Engineering. 6 (2016) 1819-1826.
[9] Wu Yiming, Wu Peng and Liu Hongjun, Research on Low Noise Reactor Based on Low Magnetostrictive Magnetic Material, High Voltage Apparatus. 11 (2019) 268-272.