Magnetic Leakage Simulation of Converter Transformer and Shielding Analysis of Different Material Shielding Devices

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Abstract. Due to the complex structure and large winding current of converter transformer, the magnetic flux leakage was more serious, which was prone to local overheating and affected the safe and stable operation of transformer. Therefore, it was necessary to study the distribution of magnetic flux leakage in transformer. In this paper, the three-dimensional model of 500kV converter transformer was established based on the actual drawings, and the magnetic flux of iron core, fuel tank and distribution of magnetic flux leakage between high and low voltage winding was calculated under time-harmonic field by using the finite element method. The shielding method combining strip shielding plate and lung lobe shielding device was adopted, and the influence of different material shielding devices on the distribution of magnetic flux leakage was compared and analysed. The research results showed that when the shielding device adopted new material, the maximum magnetic flux leakage of the fuel tank decreased to 0.22T, decreasing amplitude of 65.62%, and the magnetic flux leakage in winding space decreased by 20.83%, which significantly improved the shielding effect.

1. Introduction
The distribution of energy resources and the distribution of power generation, load in China was extremely uneven, and the reverse distribution of energy resources and energy demand determined the inevitability of large-scale, cross-regional flow of energy and power. UHVDC power transmission had the advantages of long distance, large capacity and low loss, so the development of UHVDC power transmission was crucial to realize the inter-regional resource allocation of the west-east power transmission, the south-north power transmission, and to ensure the economic development and energy security of the central and eastern part of the country [1-3]. In UHVDC transmission system, converter transformer was at the core of alternating current and direct current exchange, and its safe and stable work was the key to the reliable operation of the system. Compared with ordinary transformer, converter transformer had more complex structure, more serious distribution of magnetic flux leakage, easy to cause local overheating and reduce the service life of transformer [4]. Therefore, it was necessary to calculate the magnetic flux distribution of converter transformer, and reduced the flux leakage of transformer components by installing appropriate magnetic shielding devices.

In this paper the 500kV converter transformer was taken as the research object, the transformer 3D simulation model was established, the material properties of iron core and fuel tank was actually measured, the finite element method was used to calculate the magnetic flux of core, fuel tanks, and distribution of magnetic flux leakage between high and low voltage winding when the transformer under fundamental operation. The shielding method combining strip shielding plate and lung lobe shielding
device was adopted to improve transformer magnetic flux distribution, the influence of different material magnetic shielding device on the magnetic flux field distribution was compared and analysed. The research results could provide reference for the design and application of converter transformer magnetic shielding.

2. Magnetic flux distribution in converter transformer without shielding device

2.1 Theoretical foundation
To solve the distribution of magnetic field in transformer was to solve the maxwell equations under given boundary conditions. The equations included ampere's law, Faraday's law of electromagnetic induction, gauss's law of flux and gauss's law of electric flux, as shown in formula.1:

\[ \nabla \times \vec{H} = J + \frac{\partial \vec{D}}{\partial t} \]

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]

\[ \nabla \cdot \vec{B} = 0 \]

\[ \nabla \cdot \vec{D} = \rho \]

Where: \( H \) —— magnetic field intensity \( /A \cdot m^{-1} \); \( J \) —— current density \( /A \cdot m^{-2} \); \( E \) —— electric field intensity \( /V \cdot m^{-1} \); \( B \) —— magnetic induction intensity \( /T \); \( D \) —— electrical displacement \( /C \cdot m^{-1} \).

Among them, the relation between related field quantities in each physical field was shown in formula.2:

\[ \vec{D} = \varepsilon \vec{E} \]

\[ \vec{B} = \mu \vec{H} \]

\[ \vec{J} = \gamma \vec{E} \]

The basic wave frequency of the converter transformer was 50Hz, the conductivity in the metal body was constant, and the displacement current could be ignored compared with the conduction current.

2.2 Simulation model
According to the actual drawings, the 3D model of 500kV converter transformer was established, as shown in figure 1. The transformer was of single-phase double winding structure, the iron core adopted single-phase four-column structure. The low-voltage winding was 917 turns, rated current 866.02A; High voltage winding was 2688 turns, rated current 309.29A.

![Figure 1. Three-dimensional simulation model of converter transformer.](image)

The properties of transformer materials were shown in table 1, in which both the iron core and the fuel tank were magnetic conductive materials. The B-H curve of the material was shown in figure 2, and the iron core magnetic permeability was much higher than that of the fuel tank.
Table 1. Material properties of components in converter transformer.

| Component               | Relative permeability | Relative conductivity | Relative dielectric constant |
|-------------------------|-----------------------|-----------------------|-----------------------------|
| Winding                 | 1                     | 5.77×10^7             | 1                           |
| Iron core/fuel tank     | B-H curve             | Loss curve            | 1                           |
| Pressing plate          | 1                     | 0                     | 3.19                        |
| Transformer oil         | 1                     | 0                     | 2                           |

2.3 Magnetic flux distribution of transformer

Considering the effect of skin effect on magnetic field distribution and winding loss, the current loading mode was selected. The applied boundary conditions were tangential boundary conditions for flux, that was, parallel lines of magnetic force were applied on the external surface, satisfying the first boundary conditions. Compared with the transient field, using time-harmonic field could not only accurately obtain the distribution of the transformer's internal magnetic field, but also simplify the calculation \cite{5}. After loading, the finite element analysis software was used to solve the magnetic flux distribution of 500kV converter transformer. The calculation frequency was 50Hz, and all the field quantities changed sinusoidal with time, without considering the influence of higher harmonics.

The magnetic flux distribution of the iron core was shown in figure 3. It could be seen from the figure that the magnetic flux distribution of the iron core was symmetrical due to the structural symmetry. The maximum magnetic flux of the iron core was 1.74T, which appeared in the middle part of the upper and lower iron yoke. The magnetic flux of the core column was 1.47T and that of the side yoke core column was 1.19T. The magnetic flux at the corner of the core was not of practical significance.

Figure 3. The magnetic flux distribution of the iron core

The magnetic flux distribution of fuel tank was shown in figure 4. It could be seen from the figure that the flux leakage mainly concentrated on the front panel of the fuel tank, with the maximum flux
leakage of 0.83T. The maximum flux leakage was 0.72T at the top or bottom panels, and 0.58T at the left or right panels.

Figure 4. The magnetic flux distribution of the fuel tank.

To analyse the distribution of leakage flux between windings, three sampling paths were selected from transformer oil to extract the magnetic flux at the sampling path. The sampling path and flux leakage distribution curve was shown in figure 5: Path 1 was between the low-voltage winding and the core, path 2 was between the high-voltage winding and the low-voltage winding, and path 3 was between the fuel tank and the high-voltage winding. According to the figure, in the space of axial height of transformer winding, the distribution of leakage magnetic field at different positions had obvious differences. The winding end had the most serious magnetic flux leakage, and the magnetic flux leakage reached the maximum value, which was mainly transverse magnetic flux leakage. Since path 1 was close to the iron core and path 3 was close to the fuel tank, the magnetic conductivity of the iron core and oil tank was far greater than that of transformer oil, and the leakage flux at the winding end will gradually entered the iron core and oil tank, so the magnetic flux at the middle position of path 1 and path 3 was very small. The flux distribution in path 2 showed a distribution trend of low at both ends and high in the middle, and the maximum magnetic flux was 0.21T.

Figure 5. Path selection and magnetic flux distribution on it

3. Shielding analysis of different material shielding devices

3.1 Model of magnetic shielding device
The high leakage flux of the fuel tank and winding end would produce large eddy current, which would easily cause local overheating of the fuel tank and winding, affecting the safe and stable operation of the transformer. Therefore, it was necessary to design the magnetic shielding device to reduce the eddy current loss in the transformer. In this paper, combined shielding method was adopted to reduce magnetic flux leakage in transformer components [6]: copper plate was installed at the concentrated position of magnetic flux in the fuel tank, and demagnetization of eddy current in the copper plate was used to reduce magnetic flux leakage in the fuel tank; A pulmonary magnetic shielding device was installed at the upper and lower ends of the winding. The magnetic conductivity of the shielding device enabled more magnetic flux leakage to enter the core through the shielding device, thereby reducing the
magnetic flux leakage at the end of the winding. The magnetic shielding device was shown in figure 6. The fuel tank shielding plate was composed of 6 strip copper plates, which were 4600mm long, 300mm wide and 30m thick. The shape of the lung lobe shielding device was similar to that of the fan, with a thickness of 60mm. The magnetic shunt was formed around the two ends of the core.

(a) Strip shielding plate  
(b) Lung lobe shielding device  

Figure 6. Schematic model of magnetic shielding device.

3.2 Shielding analysis of raw material shielding device

After installing the magnetic shielding device, the distribution of magnetic flux leakage in fuel tank was shown in figure 7. It could be seen that the distribution of magnetic flux leakage in fuel tank was significantly improved after installing shielding device. In the area covered by the copper plate in front of the tank, due to the demagnetization effect of eddy current in the copper plate, the leakage flux was further reduced, and the maximum magnetic flux was reduced to 0.55T. The flux leakage was still high in no copper plate covering area, with the maximum flux leakage being 0.64T, a decrease of 22.89%. The maximum magnetic flux leakage was 0.32T at tank bottom plate, and 0.19T on the side plate.

Figure 7. The magnetic flux distribution of the fuel tank (raw material shielding device).

The transverse path above the winding tangent to path 2 was selected, and the contrast of magnetic flux on the path before and after shielding was shown in figure 8. It could be seen that the change trend of transverse flux leakage above the winding was the same. When there was shielding, part of the flux leakage entered into the pulmonary lobe shielding plate, and the maximum flux leakage decreased from 0.088T to 0.085T, a decrease of 3.4%.
3.3 Shielding analysis of new material shielding device

Although the initial magnetic shielding device had a certain shielding effect, but the shielding effect was not obvious, and the leakage flux and loss were still high. In order to further reduce the flux leakage in transformer components, keeping the geometric shape of the magnetic shielding device unchanged, high permeability steel was used in fuel tank shielding plate and lung lobe shielding device. Calculating the distribution of transformer flux leakage and loss under the new shielding material, the distribution of magnetic flux leakage of the fuel tank shielding plate and the lung lobe shielding device was shown in figure 9. It could be seen from the figure that, due to the high conductivity of the shielding device, the magnetic flux leakage almost completely entered the fuel tank shielding plate, and the maximum magnetic flux leakage was 1.5T, appearing in the middle section. The maximum magnetic flux leakage of the lung lobe shielding device was 0.48T and appeared at the bottom edge.

Taking path 1 as an example, the comparison of flux distribution under different material shielding devices was shown in figure 10. There was no significant change in flux distribution trend in path 1, and the maximum flux leakage decreased from 0.048T to 0.038T, a decrease of 20.83%.
Under different material shielding devices, the maximum flux leakage of transformer components was shown in table 2.

Table 2. Maximum magnetic flux leakage of each component under different material shielding devices (T).

|                        | Fuel tank | Strip shielding plate | Lung lobe shielding device |
|------------------------|-----------|-----------------------|----------------------------|
| Raw material shielding device | 0.64      | 0.056                 | 0.60                       |
| New material shielding device | 0.22      | 1.5                   | 0.48                       |

It could be seen that the magnetic flux leakage of transformer components was significantly reduced after the shielding device was adopted with new materials. The maximum magnetic flux leakage of the fuel tank changed to 0.22T, reducing by 65.62%. Because the initial material of the strip shielding plate was copper plate, which was almost non-magnetic, and the shielding effect was not obvious only relying on the demagnetization effect of the eddy current, the new material changed to high magnetic permeability steel plate, and most of the magnetic leakage entered the strip shielding plate, making the magnetic flux leakage of the fuel tank greatly reduced. There was no significant change in leakage flux of lung lobe shielding device.

4. Conclusion
In this paper, a 500kV converter transformer was taken as the research object. Finite element method was adopted to simulate and calculate the distribution of transformer magnetic flux leakage. Combined shielding method was adopted for flux leakage shielding. The shielding effect of different material shielding devices was compared and analyzed, and the following conclusions were obtained:

1) When there was no shielding device, the maximum magnetic flux of the transformer was 1.74T, which appeared in the middle of the iron yoke, because the magnetic field generated by winding current was superimposed and the magnetic flux was higher. The magnetic flux of fuel tank mainly concentrated on the front and rear tank plates, with a maximum value of 0.83T. The leakage flux in transformer oil was related to the position. As the position between high and low voltage windings was far from the core and the fuel tank, the leakage flux was almost unchanged at 0.21T.

2) When shielding device used the raw material, the maximum magnetic flux leakage of fuel tank decreased to 0.64T, a decrease of 22.89%. The maximum transverse magnetic flux leakage above the winding decreased from 0.088T to 0.085T, a decrease of 3.4%. The shielding effect was not obvious.

3) When shielding device used the new material, the flux distribution of transformer components was significantly improved. Compared with the original shielding results, the maximum magnetic flux leakage of the fuel tank decreased by 65.62% to 0.22T. Taking path 1 as an example, the maximum magnetic flux leakage decreased from 0.048T to 0.038T, a decrease of 20.83%. Compared with the raw material shielding device, the new material shielding device could better reduce the flux leakage, avoid local overheating, and protect the safe and stable operation of the transformer.

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