A Method for Calculating the Internal Magnetic Field Distribution of the Modular Multilevel Converter Valve

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Abstract. This paper presents a simple calculation method for the magnetic field distribution in the converter valve tower of the DC transmission system. The current inside the IGBT is decomposed into the superposition of the low-frequency sinusoidal current and the high-frequency spike current. According to the shielding mechanism of the metal shielding layer at different frequencies, the original model is divided into two sub-models. Then the final result is the superposition of the results calculated by the two sub-models. This method can calculate the magnetic field distribution in the converter valve tower in a short time.

1. Introduction

There are sophisticated power electronic equipment and complicated working conditions in the flexible DC transmission converter valve tower[1]. When the converter valve is working, a special strategy is used to control the turn-on and turn-off of the IGBT, which will cause high-frequency electromagnetic interference. In particular, the electromagnetic interference generated by Modular Multilevel Converter (MMC) valves is far greater than that of traditional DC converter valves[2-3], with a frequency of up to tens of MHz. Therefore, it is necessary to study the magnetic field distribution in the MMC tower in engineering applications. In addition, in order to suppress electromagnetic interference effectively, some metal shielding devices are often added around the valve tower, which also makes the structure more complicated.

For the calculation of magnetic field distribution, the existing methods can be divided into two categories: analytical methods and numerical methods. The analytical method derives the expression of magnetic field calculation through the basic electromagnetic field formula and boundary conditions. It is suitable for situations where the geometric structure of the problem model is clear. The most representative numerical method is the finite element method, which divides the mesh inside the conductor. In order to ensure the accuracy of the calculation, the size of the grid must be smaller than the penetration depth. The penetration depth at high frequencies is very small, so the mesh is refined. The increase in the number of grids leads to a large consumption of memory and CPU. For the complex structure of MMC, the analytical method is obviously not applicable, and the calculation speed of numerical simulation is very slow. Therefore, a fast and accurate calculation method is needed.

In this paper, the MMC model is decomposed into two sub-models for calculation based on the shielding characteristics of the metal shielding device[4-6]. This paper is organized as follows. Section
II describes the models and the states the corresponding theory. Section III presents the application of the sub-models to the magnetic field in the MMC. Finally, Section IV concludes this paper.

2. Model and theory
The shielding effect of the metal with finite conductivity on the magnetic field can be equivalent to the superposition of two models, as shown in the figure 1. The original complex current can be decomposed into a low-frequency sinusoidal current and a high-frequency spike current.

For low-frequency current, the sub-model (a) is a metal material with finite conductivity. When the frequency is as low as 50 Hz, the shielding effectiveness (SE) of the metal shield is close to zero and the surrounding conductor can be ignored. In the case of high-frequency spike current, the SE of the metal shield is very large. At this time, the metal shield of the sub-model (b) can be equivalent to a perfect electric conductor (PEC). Superimpose the magnetic fields calculated by the two sub-models, and then the magnetic field of the original model under complex currents can be obtained.

3. Applications
Figure 2 shows a simplified model of the internal circuit of the MMC. According to the distribution position and function of IGBT, the internal structure is simplified as the current paths and is represented by $I_{up}$, $I_{down}$, $I_{igbt}$, $I_1$, and $I_2$, respectively.

Taking a working condition as an example, the complex current waveform is shown in the figure 3. The black curve is the actual current, and the red one is a sine waveform with the same amplitude and phase as this waveform. Subtract the sine waveform from the complex waveform in figure 3 to separate the high-frequency waveform with spikes, we can get figure 4. In this way, the original current curve is decomposed into the superposition of a low-frequency sinusoidal current and a high-frequency spike current.
3.1. Power frequency sinusoidal current

The 50 Hz sinusoidal current corresponds to the sub-model (a) without metal shielding device. The total magnetic field generated by these energized straight wires can be calculated using Biot Savart’s law

\[ dB = \frac{\mu_0 I dl \times e_R}{4\pi R^2} \]  

(1)

Wherein \( R \) is the distance from the source point of the current source \( I dl \) to the observation point, and \( e_R \) is the unit vector from the source point to the observation point. The magnetic field strength in the three directions is shown in the figure 5 and are denoted by \( H_{ax} \), \( H_{ay} \), and \( H_{az} \), respectively. In addition, simulation software can also be used to obtain the magnetic field of sub-model (a) and the calculation speed of this sub-model is very fast.

3.2. High frequency spike current

The sub-model (b) is used to calculate the high-frequency current with spikes, which can be calculated using magnetic field simulation software. Set \( I_{up} \), \( I_{down} \), \( I_{igbt} \), \( I_1 \) and \( I_2 \) as the unit current in turn. When a certain current is set to 1 A, other currents are set to 0. Calculate the magnetic field at this time and mark them as \( H_{up} \), \( H_{down} \), \( H_{igbt} \), \( H_1 \) and \( H_2 \), respectively. The vector magnetic field \( H_b \) can be calculated as

\[ H_b = H_{up} I_{up} + H_{down} I_{down} + H_{igbt} I_{igbt} + H_1 I_1 + H_2 I_2 \]  

(2)

Wherein \( H_b \) has three components \( H_{bx} \), \( H_{by} \), and \( H_{bz} \). The results are shown in the figure 6.
3.3. Final results
The magnetic fields calculated by the two sub-models are superimposed together and calculated according to the following formulas:

\[
H_x = H_{ax} + H_{bx}, \quad H_y = H_{ay} + H_{by}, \quad H_z = H_{az} + H_{bz}
\]

\[
H = \sqrt{H_x^2 + H_y^2 + H_z^2}
\]

Figure 7 is the calculation result of the superposition of the two sub-models. It can be seen that the moment when the IGBT is turned on or off, a large impact magnetic field is generated.

4. Conclusions
In order to calculate the magnetic field generated in the MMC more quickly, we use two sub-models to calculate separately and then superimpose the results. According to the shielding characteristics of metal to frequency, the two sub-models are: (a) the unshielded model and power frequency sine current, and (b) the PEC model and high-frequency spike current. The sub-model (a) can be simply calculated by Biot Savart’s law and the sub-model (b) can be simulated using software. When calculating the original model directly, we need to divide the inside of the conductor into a refined grid, which requires much calculation time and computer memory. However, when calculating the sub-model (b), only the PEC surfaces need to be meshed. It greatly improves the calculation speed. Besides, the unit current is used when calculating the magnetic fields \((H_{up}, H_{down}, H_{ligh}, H_{1} \text{ and } H_{2})\) of the sub-model (b). The result is magnified and superimposed in proportion to the waveform. Therefore, the magnetic field data is suitable for other situations, and the magnetic field under a new working condition can be obtained by superimposing \(H\) on different currents, which can also save calculation time.

Acknowledgments
This project is supported by the Science and Technology Project of SGCC under Grant 5200-201956058A-0-0-00.
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