Study on the Electromagnetic Shielding Characteristics of GIS Shell

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***Abstract*—With the gas insulated substation (GIS) becoming more and more intelligent, secondary equipments with control and communication functions are applied in it. Since the GIS switch operation will produce a series of very fast electromagnetic transient phenomena (VFT), these electromagnetic transient phenomena will affect the secondary intelligent equipment as electromagnetic interference sources, causing its malfunction and even damage. The metal shell of GIS has certain shielding ability for electromagnetic radiation, but there is still no systematic theoretical research on the electromagnetic shielding performance of GIS shell. To this end, this paper quantitatively analyzes the electromagnetic shielding performance of the GIS shell. In order to obtain the shielding performance of GIS shell, a simulation calculation model of electromagnetic wave propagation characteristics in GIS shell based on finite element method is established. The model is used to quantitatively calculate the effectiveness of the GIS shell shielding internal radiant electromagnetic field, and the shielding effectiveness and its relationship with the shell thickness and the shell conductivity are obtained.**

***Index Terms*—GIS shell, electromagnetic transient, electromagnetic shielding, finite element method**

I. Introduction

A series of very fast transient phenomena, such as very-fast transient over-voltage (VFTO) and very fast transient over-current (VFTC) will be generated by GIS switching operations. When VFTO and VFTC propagate in GIS, catadioptric reflection will occur and then couple to the GIS shell, and radiated to the external space through the GIS shell.

With the continuous advancement of digital substations and intelligent substations, more and more secondary intelligent electronic devices with control, protection and communication functions are applied to GIS. However, electronic equipment is highly susceptible to electromagnetic interference caused by switching operations, which may cause malfunction moreover damage, endangering the safe and reliable operation of the substation.

A large number of researchers have conducted research on GIS electromagnetic interference. The paper [1], [2] mainly studied the influence of electromagnetic interference of switch operation on electronic transformers and proposed corresponding suppression measurements; paper [2]-[5] studied the characteristics and measurement methods of electromagnetic interference; the paper [6], [7] established a coupling model for intelligent components, and simulated the impact of electromagnetic interference on electronic devices.

However, most of the researchers focus on electromagnetic radiation outside the GIS, and there is no research on the transient process of internal electromagnetic waves radiating outside through the shell. To this end, this paper quantitatively analyzes the electric field shielding performance and magnetic field shielding performance of the GIS shell to obtain the electromagnetic shielding performance of the shell. It provides a theoretical basis for further establishing the connection between internal and external electromagnetic interference, and is also of great significance for analyzing the complex electromagnetic environment in GIS substation and the electromagnetic compatibility design of secondary equipment.

The results of this paper show that the GIS metal shell has a strong shielding effect on the internal high-frequency electromagnetic waves, and the change of the thickness of the shell has little effect on the shielding effectiveness. The main influencing factor is the conductivity of the shielding material.

II. GIS Shell Electromagnetic Shielding Principle

The electromagnetic field shielding of the GIS shell means that the internal electromagnetic interference

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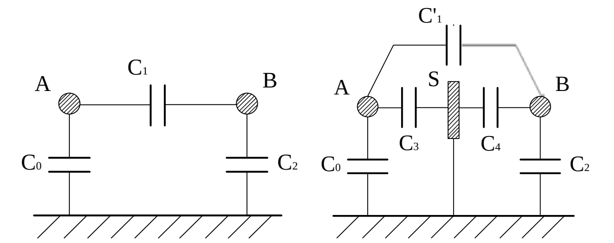
source is surrounded by the use of the metal shell to attenuate the radiated electromagnetic field energy in the internal space of the shell, thereby prevent the internal radiated electromagnetic wave from transmitting outside.

A. Electric Field Shielding Theory

When the switching operation is carried out in the GIS substation, the electromagnetic interference source is rapidly changing with time. And the electric field caused by the electromagnetic interference source should be an alternating electric field. A brief analysis is made to use the shield to shield the alternating electric field caused by the interference source. The principle can be explained by the equivalent circuit model shown in Fig. 1. In the figure, A is the interference source that causes the spatial alternating electric field, B is the device to be protected, and S is the shielding body.



(a) Equivalent circuit model without the shielding body (b) Equivalent circuit model with the shielding body

Figure 1. Note how the caption is centered in the column.

Fig. 1(a) shows the case where no shield is added between the interference source and the protection device. The voltage applied to the field source A is V_A. The distribution capacitance between A and B and their respective grounds is C_1、C_0 and C_2. According to the circuit theory, the voltage induced on the protected device B is:

$$V_B = \frac{C_1}{C_1 + C_2} V_A \tag{1}$$

Fig. 1(b) shows a case where a shielding body is added between A and B, and the shield is well grounded. At this time, the induced voltage on the protected device B can be expressed by the following formula:

$$V'_B = \frac{C'_1}{C_2 + C_3 + C_4} V_A \tag{2}$$

Comparing the analytical formulas (1) and (2), $V_B' << V_B$ can be obtained. When a shielding body is added between A and B, and the shield is well grounded, the induced voltage on the protected device A is much smaller than that without shield.

B. Magnetic Field Shielding Theory

When the magnetic field frequency is high, the shielding of the magnetic field can be understood as the use of a shielding body with good electrical conductivity to surround the electromagnetic interference source. Since the magnetic field frequency is high, the induced current will be generated in the shield. And the induced magnetic field generated by the induced current is always opposite to the direction of the magnetic field caused by the electromagnetic interference source. Thereby, the induced magnetic field can interact with the magnetic field generated by the electromagnetic interference source to cancel the radiation magnetic field in the space. The shielding principle can be expressed by the relationship between the current and the spatial magnetic field shown in Fig. 2.

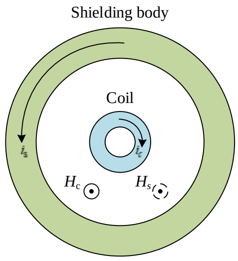


Figure 2. The relationship between current and magnetic field.

The equivalent circuit model of the magnetic field shielding can be obtained according to the relationship between the current and the spatial magnetic field as follows.

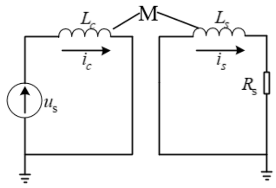


Figure 3. Equivalent circuit model of magnetic field shielding.

According to the equivalent circuit analysis shown in Fig. 3, the induced current in the shield can be expressed as:

$$i_s = \frac{j\omega M i_c}{R_s + j\omega L_s} \tag{3}$$

where, i_C is the current in the coil, A; L_s is the shield inductance, Wb/A; R_s is the resistance of the shield, V/A; M is the mutual inductance between the coil and the shield conductor. At high frequencies, $R_s << \omega L_s$, then:

$$i_s \approx \frac{M}{L_s} i_c = k \frac{n_c}{n_s} i_c \tag{4}$$

where, k is the coupling coefficient of the electromagnetic interference source and the shield; n_c is the number of coil turns; n_s is the number of shield turns. For a common shield, take n_s=1.

III. Electromagnetic Shielding Effectiveness of GIS Shell

A. Definition of Electromagnetic Shielding Effectiveness

The shielding effect of the metal shell on electromagnetic waves can be regarded as a process of continuously consuming electromagnetic wave energy. The consumption of radiated electromagnetic wave energy includes three processes: (1) When the radiated electric field and magnetic field propagate to the metal shell surface, the inner surface of the shell will reflect part of the radiated electromagnetic wave, which is reflected loss; (2) Electromagnetic waves that are not reflected on the surface of the metal shell will be incident into the metal casing. And the electromagnetic energy will also be continuously decreased during the process of propagating inside the casing, which is the absorption loss; (3) After the attenuation of the electromagnetic energy by the reflection loss and the absorption loss, the electromagnetic wave whose energy is not attenuated propagates to the outer surface of the metal casing, and the reflection and transmission occur between the outer surfaces of the metal casing which is multiple reflection loss. The propagation of electromagnetic waves is shown in Fig. 4.

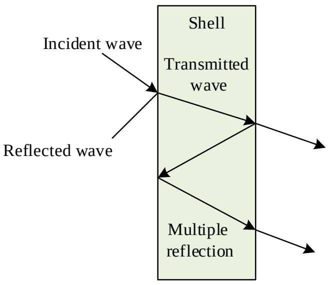


Figure 4. Electromagnetic wave propagation process.

In order to quantitatively analyze the electric field and magnetic field shielding ability of GIS metal shell, Shielding Effectiveness (SE) is introduced in this paper.

$$\begin{aligned} SE &= -20\lg\left|T^C\right| \\ &= -20\lg\left|pe^{-\Gamma_2 t}\left[1-qe^{-2\Gamma_2 t}\right]^{-1}e^{\Gamma_1 t}\right| \\ &= 20\lg\left|e^{(\Gamma_2-\Gamma_1)t}\right| - 20\lg\left|p\right| + 20\lg\left|1-qe^{-2\Gamma_2 t}\right| \\ &= SE_A + SE_R + SE_M \end{aligned} \quad (5)$$

where, SE_A is the absorption loss of the shielding material, dB; SE_R is the single reflection loss of the shielding surface, dB; SE_M is the multiple reflection loss inside the shield, dB.

The expression of SE_A is:

$$SE_{\mathrm{A}} = 131.43t\sqrt{f\mu_r\sigma_r} \quad (6)$$

where, SE_A is the absorption loss of the shielding material, dB; SE_R is the single reflection loss of the shielding surface, dB; SE_M is the multiple reflection loss inside the shield, dB is the thickness of the shielding material is the relative magnetic permeability of the shielding material.

where, f is the electromagnetic wave frequency, Hz; t is the thickness of the shielding material, m; μ_{r} is the relative magnetic permeability of the shielding material; σ_{r} is the relative conductivity.

The expression of SE_R is:

$$SE_{\mathrm{R}} = \begin{cases} 168.2 + 10\lg\left(\dfrac{\sigma_r}{f\mu_r}\right) \\ 20\lg\left(5.35r\sqrt{\dfrac{f\sigma_r}{\mu_r}} + 0.354 + \dfrac{1.17\times10^{-2}}{r}\sqrt{\dfrac{\mu_r}{f\sigma_r}}\right) \\ 3.217 + 10\lg\left(\dfrac{\sigma_r}{f^3 r^3\mu_r}\right) \end{cases} \quad (7)$$

where, the frequency of electromagnetic wave is f is the electromagnetic wave frequency, Hz; t is the thickness of the shielding material, m; r is the distance from the field source to the shielding material, m; μ_{r} is the relative magnetic permeability of the shielding material; σ_{r} is the relative conductivity.

The expression of SE_M is:

$$SE_{\mathrm{M}} = 10\lg[1 - 2\times10^{-0.1SE_{\mathrm{A}}}\cos(0.23SE_{\mathrm{A}}) + 10^{-0.2SE_{\mathrm{A}}}] \quad (8)$$

where, SE_A is the absorption loss of the shielding material, dB.

Applying the shielding effectiveness defined above to the simulation calculation of the GIS shell, the quantitative results of the shielding performance can be obtained.

B. Quantitative Calculation and Results Analysis of GIS Shell Shielding Performance

1) GIS shell electromagnetic shielding calculation model

The electromagnetic shielding calculation model is established as shown in Fig. 5.

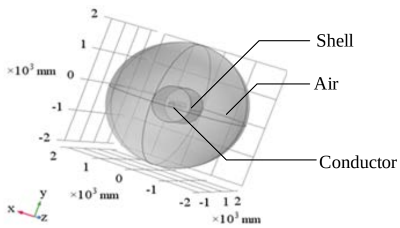


Figure 5. Calculation model.

The geometric dimensions and material parameters of the calculation model are shown in Table I.

TABLE I. MODEL GEOMETRY

	Value（mm）
Conductor radius	85
Radius of the inner surface of the shell	570
Radius of the outer surface of the shell	576、590

When simulating the electromagnetic shielding characteristics of the GIS shell, the shell thickness is an important parameter value. In the calculation process, the shell thickness is taken as a different value (576mm, 590mm), and its influence on the electromagnetic shielding performance is studied.

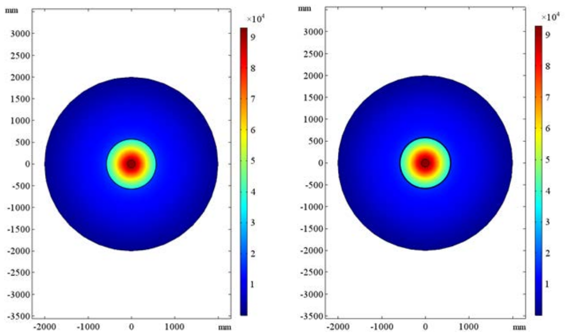
The GIS busbar consists of an aluminum cylinder and a concentric stainless steel cylinder. The internal space is filled with SF_6 gas and the outside of the shell is air. The physical parameters of the model material in the finite element simulation calculation software are shown in the following Table II:

TABLE II. MATERIAL PARAMETERS

	Relative permeability	Relative permittivity	Conductivity (S/m)
SF_6	1	1	0
Air	1	1	0
Aluminum	1	1	3.774×10^7

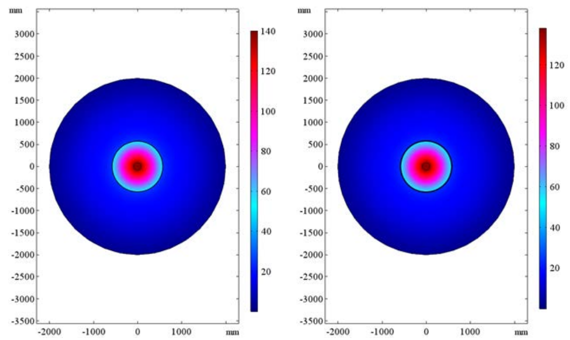
2) Calculation results and analysis

Because the main frequency of VFTO is 50MHz. Set the electromagnetic interference source frequency to 50MHz, and set the thickness of the GIS shell to 6mm and 12mm respectively. The electromagnetic field distribution of the inside and outside of the shell is obtained as follows (Fig. 6 and Fig. 7).



(a) Shell thickness is 6mm (b)Shell thickness is 20mm

Figure 6. Electric field distribution inside and outside the shell.



(a) Shell thickness is 6mm (b) Shell thickness is 20mm

Figure 7. Magnetic field distribution inside and outside the shell.

Select a cut line on the central axis of the GIS busbar as shown in the red line in Fig. 8. Analyze the variation of the electric field and magnetic field strength from the inside to the outside along this cut line.

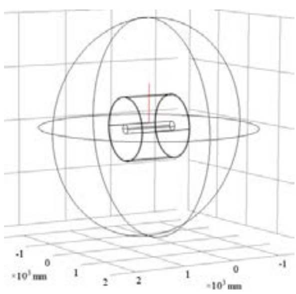
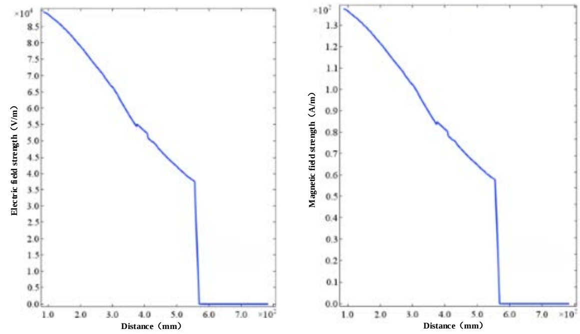


Figure 8. Calculation cut line.

When the electromagnetic interference source frequency inside the casing is 50MHz and the thickness of the casing is 20mm, the distribution of electric and magnetic fields on the selected calculation line is as shown in the following Fig. 9:



(a) Electric field strength curve (b) Magnetic field strength curve

Figure 9. Electromagnetic field distribution on the line.

It can be seen from the electromagnetic field variation curve that the electromagnetic field has a large attenuation when it propagates to the casing. The GIS metal shell has a good shielding effect on the radiated electromagnetic field caused by the electromagnetic interference source during switching operation.

TABLE III. MATERIAL PARAMETERS

Shell thickness (mm)	Electric field strength (V/m) with shell	Electric field strength (V/m) no shell	SE_E(dB)	Magnetic field strength (A/m) with shell	Magnetic field strength (A/m) No shell	SE_H(dB)
6	3.68×10^4	7.47×10^{-10}	273.9	139.44	1.31×10^{-10}	240.5
20	3.68×10^4	3.65×10^{-10}	280.0	139.44	0.83×10^{-10}	244.5

According to the above Table III, the magnitude of the electric and magnetic fields caused by the electromagnetic interference source is 10^4 and 10^2 respectively when the casing is not added; after adding 6 mm metal casing, the external electric field strength of the casing is 7.47×10^{-10} V / m, the magnetic field strength is 1.31×10^{-10} A/m, the external electromagnetic field strength of the shell is almost close to 0. When the electromagnetic interference source frequency is 50MHz and the shell thickness is 6mm, the electric field shielding effectiveness of the GIS shell is 273.9dB, and the magnetic field shielding effectiveness is 240.5dB. The GIS shell has a good shielding effect on high frequency electromagnetic waves.

With 20mm metal shell, the external electric field strength of the shell is 3.65×10^{-10} V/m, the magnetic field strength is 0.83×10^{-10} A/m, and the external electromagnetic field strength of the shell is almost close to 0. When the electromagnetic interference source frequency is 50MHz and the shell thickness is 20mm, the electric field shielding effectiveness of the GIS shell is 280.0dB, and the magnetic field shielding effectiveness is

244.5dB. The shielding effect of GIS shell on high-frequency electromagnetic waves has a certain enhancement effect with the increase of shell thickness. However, the effect of increasing shell thickness to improve the electromagnetic shielding effectiveness of the shell is not obvious, and the construction cost of GIS substation will be greatly increased.

The calculation results of the electric field and magnetic field shielding effectiveness of the shell with the conductivity of the shell material are shown in the Fig. 10 below.

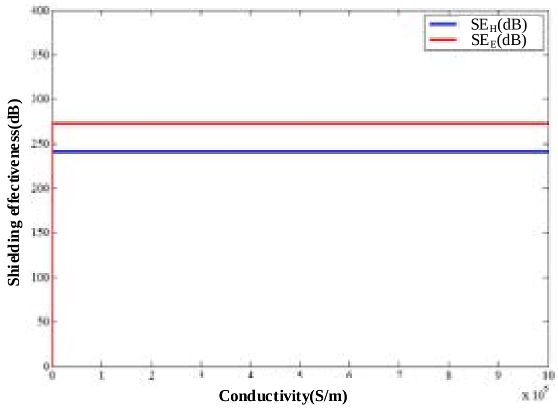


Figure 10. Effect of conductivity on electromagnetic shielding effectiveness.

It can be seen from the simulation results in the above figure that the metal casing has a strong shielding effect on the radiated electric field and magnetic field inside the casing. However, when the conductivity of material is approximately to 0, the electromagnetic shielding effectiveness is poor.

IV. Conclusion

In this paper, the electromagnetic shielding model of GIS shell is established. Based on the electromagnetic field shielding theory and the electromagnetic shielding effectiveness analysis of single-layer shielding, the electromagnetic shielding effectiveness of GIS shell is analyzed:

1) GIS metal shell has a strong shielding effect on the high-frequency electromagnetic waves inside the shell, which can basically shield the radiated electromagnetic field generated by the electromagnetic interference source along the GIS busbar.

2) When the thickness of aluminum GIS shell is 6mm, the electric field shielding effectiveness is 273.9dB, and the magnetic field shielding effectiveness is 240.5dB. The shielding effect of GIS shell on high frequency electromagnetic wave has a certain enhancement effect with the increase of shell thickness, but in electromagnetic wave In the case of a high frequency, when the thickness of the casing is on the order of millimeters, the effect of increasing the thickness of the casing to improve the electromagnetic shielding effectiveness of the casing is not obvious.

3) The conductivity of the shielding material has a great influence on the shielding effectiveness of the shielding body. The radiated electromagnetic field inside the GIS shell can propagate outward through the discontinuity of the medium on the shell. Reducing the discontinuity of the GIS metal shell medium can greatly improve the electromagnetic shielding performance of the shell and inhibit the electromagnetic waves inside the shell from propagating to the external space of the GIS.

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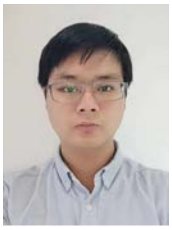

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