Analysis of cavity coupling characteristics in VFTO space field

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Abstract. The VFTO generated by the switch operation in the GIS substation will radiate the electromagnetic waves with great amplitude and high frequency components. The high frequency part of the electromagnetic wave will be coupled into the interior of the equipment through the gap on the secondary equipment shell, which will affect the normal operation of the equipment. In this paper, the electromagnetic simulation software, which is based on the finite element method (FDTD), would be applied to the cavity coupling analysis under these circumstances. The results show that the polarization direction of the electric field is parallel to the short side of the rectangular opening, the larger the aspect ratio of the rectangular opening, the easier the space field generated by the VFTO to be inside the device; transforming the single slit into to the same area of the rectangular slot array can effectively suppress the field amplitude, and this performance is more obvious in the resonant area. The media plate can improve the shielding effectiveness of the cavity. The closer the dielectric plate is to the opening, which causes less energy of the coupling into the cavity, as well as larger size will get better shielding effect of the cavity.

1. Introduction

With the increase of the voltage level, the electromagnetic environment in the substation has become very bad, especially in the gas-insulated substation (GIS). Since very fast transient overvoltage (VFTO) and transient ground potential rise (TGPR), which is generated by disconnector operation, will radiate to the space electromagnetic waves with large amplitude and rich high-frequency component, electronic equipment in the substation is susceptible to interference. Under normal circumstances, equipment shell is used to reduce the interference of space electromagnetic waves on the electronic circuit. However, due to ventilation and cooling as well as in and out of power lines or signal lines on the shell of the device, it will inevitably occur that openings or seams appear on equipment shell. Through these holes, the high frequency part of the external electromagnetic wave is easy to enter into the equipment and then coupled to the electronic circuit, so-called “back door coupling”, thus affecting the normal work of the equipment and even leading to damage to the electronic circuit. The dis-connector operation is a conventional operation in the substation, so it is important to study the effect of the opening on the cavity of the device housing in the space field generated by the VFTO. This also has important practical significance in the design of the secondary equipment shell.

There have been extensive literature on the coupling properties of different forms of open cavities for empty, such as changing the shape of the opening, the different lengths of the gap on the shell, the different forms and the area of the open-cell array, changing the excitation source, different directions of incident waves and so on. However, most of these literature use Gaussian wave or sine wave as the
excitation source to study, research aimed at the coupling effect analysis of cavity under the space field
generated by VFTO are relative less. Based on this situation, we used the approximate space field
waveform measured in the 1000kV GIS substation as the simulation excitation source, and established
the simulation of the cavity with the dielectric plate according to the actual size of the secondary
equipment shell, and used the time domain finite difference method (FDTD) to simulate the
electromagnetic field software. After these steps, we analyzed coupling field characteristics inside the
cavity when the cavity belongs to different forms of openings and when the cavity contains a dielectric
substrate.

2. The Establishment of Coupling Model
The open-hole shield cavity model calculated in this paper and the establishment of the coordinate
system is shown in Figure 1. The length, height and width dimensions of the shielded cavity, which
use aluminum material, were Z = 50cm, X = 25cm, Y = 25cm respectively, and the thickness of the
cavity was 0.2cm. A rectangular hole is opened on the cavity’s surface which is exactly opposite the
incident wave, and the plane wave is incident on the opening. Assuming the maximum electric field
field intensity is 10000V / m and the electric field is the long side of the vertical rectangular opening.
Analyzing the built model according to the time domain finite difference method, we got that the
meshing way is \( \Delta x = \Delta y = \Delta z = 1cm \), the upper limit is \( f = 3GHz \), and the PML boundary is used to
truncate.

Using the approximate spatial rupture wave measured in the isolation switch operation in the
1000kV GIS substation as the excitation source, and restricted by computing time, we used the data of
the first 500ns of the measured space field as the excitation source of the spatial field simulation. The
frequency distribution of the waveform and that of the complete waveform is consistent, and the
waveform curve is shown in Figure 2.

![Fig.1 spatial calculation model diagram](image1)

![Fig.2 VFTO simulation excitation source waveform](image2)

The finite difference method (FDTD) is used as the theoretical basis of simulation. The whole
physical process satisfies the passive Maxwell equations, and the symmetric form of Maxwell's two
spin equations is as follows:

\[
\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} - \frac{\sigma}{\mu} \vec{H} \\
\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon} \nabla \times \vec{H} - \frac{\sigma}{\varepsilon} \vec{E}
\]

In the Cartesian coordinate system, six equations can be derived from the component representation.
Using the central differential form, it can be expressed as the deviation of space and time, therefore
achieving the dispersion of space and time and facilitating the calculation of the computer. The
following is an example of the time domain equation of the electric field in the y direction.

\[ E_{yi}^{n+1}(i, j + \frac{1}{2}, k) = \frac{\varepsilon/\Delta t - \sigma/2}{\varepsilon/\Delta t + \sigma/2} E_{yi}^{n}(i, j + \frac{1}{2}, k) \]

\[ + \frac{1}{\varepsilon/\Delta t + \sigma/2} \left[ H_{zi}^{n+\frac{1}{2}}(i, j + \frac{1}{2}, k + \frac{1}{2}) - H_{zi}^{n-\frac{1}{2}}(i, j + \frac{1}{2}, k - \frac{1}{2}) \right] \Delta z \]

\[ - \frac{1}{\xi/\Delta t} \left[ H_{zi}^{n+\frac{1}{2}}(i + \frac{1}{2}, j + \frac{1}{2}, k) - H_{zi}^{n-\frac{1}{2}}(i - \frac{1}{2}, j + \frac{1}{2}, k) \right] \Delta t \]

3. Simulation Analysis of Hole Coupling Effect

3.1. Influence of different rectangular openings on the coupling field under the same area

Set the width of the rectangular opening to: 15cm*2cm (The direction of polarization is perpendicular to the long side), 10cm*3cm, 6cm*5cm, 2cm*15cm (The polarization direction is parallel to the long side). Set the point which is along the central axis and has a 2cm distance from the hole as the observation point.

![Cavity coupling field waveform with different aspect ratios](image)

According to the results shown in Fig. 3, only the smaller part of the space field produced by VFTO can be coupled into the cavity through the hole and have high frequency oscillation in the cavity. Then, the coupling field of the cavity is coupled to the cavity through the openings in the cavity. However, the field intensity attenuation is slow, resulting that the high-frequency oscillation process...
will continue for a long period of time. Comparing Fig. 3 (a) with (d), we found that the field intensity with a distance of 2 cm from the opening is the largest when the aspect ratio of the rectangular opening is 15: 2, and the energy coupled into the cavity in the VFTO space field is also the largest at this point. As the ratio of length to width decreases, the field strength decreases. Comparing figure 3 (a) and 3 (d), we found that the amplitude of the field intensity in the cavity is significantly reduced when the aperture size is 20 mm * 150 mm, even if the long side of the rectangular opening is perpendicular to the direction of the electric field. Thus we can arrive at a conclusion------ when the polarization direction of the electric field is parallel to the short side of the rectangular hole, the energy coupled to the cavity is the largest; When the direction of polarization of the electric field is parallel to the long side of the rectangular hole, the energy coupled into the cavity is relatively small.

3.2. The influence of the gap array on the coupling field
On the end face of the cavity, divide a rectangular opening pair of 15 cm * 2 cm into two halves to make each with dimensions of 7.5 cm * 2 cm and be equal to the original rectangular opening area. Keep the long sides of the two gaps in parallel with a distance of 1 cm and the orientation of the openings unchanged. For the sake of comparison, we regard the point which has a distance of 2 cm from the hole as the observation point.

According to the simulation waveform shown in Figure 4, we can see that when the rectangular hole on the original cavity is changed to two parallel openings in the same area, the maximum value of the time domain amplitude of the coupling field of the VFTO space field in the cavity is obviously smaller than that of the single gap at the same observation point. Thus we can draw a conclusion that changing the single hole into the same area of the hole array form can improve the suppression of cavity on the VFTO space field. Therefore, in the practical application, large holes and other openings should be designed as the form of hole array as far as possible.

![Fig.4 Time-domain waveform of coupled field in double-slit cavity](image)

4. The Influence of the Dielectric Plate in the Cavity on the Coupling Field in the Cavity
In practical applications, there is a dielectric substrate in the cavity, which is used to arrange the electronic circuit. Therefore, it is more practical to study the influence of the dielectric plate on the coupling field in the space field generated by VFTO. A dielectric substrate is arranged in the open cavity, the distance between the dielectric plate and the opening is d = 50 cm, the aspect width is 23 cm * 23 cm, the thickness is 0.5 cm. The dielectric plate is placed on the hole, the center point and the hole (15 cm * 2 cm) of the center point are in the same axis, and the relative dielectric constant of 4.3 to the center of the cavity as the observation point.
According to the simulation results shown in Fig. 6, it is known that the existence of the dielectric plate in the cavity affects the time domain characteristics of the space field generated by the VFTO into the cavity. When the dielectric substrate is present in the cavity, the intensity of the field strength coupled to the cavity through the dielectric substrate will be attenuated. This is because after the incident wave is coupled into the cavity, the dielectric substrate is encountered and the dielectric loss occurs, and the coupling field energy through the dielectric plate will be reduced. Compared with the cavity, when there is dielectric plate in the cavity, the maximum field strength of the coupling field will be reduced. As we can see in Figure 6, the coupling field decreases obviously with time after 500ns. Therefore, it can be concluded that the dielectric plate in the cavity has a strong inhibitory effect on the high frequency oscillating part of the coupling field in the cavity.

Then we change the distance between the dielectric substrate and the opening, and place the dielectric plate at \( d_1 = 50\text{mm} \) and \( d_2 = 200\text{mm} \) respectively. Taking the center of the cavity as the observation point, we examine that under the space field generated by VFTO, what effect will the change of the distance between the medium plate and the opening have on the electric field intensity. When there is no dielectric plate in the cavity, resonance occurs at about 670MHz, which coincides with the resonant frequency of the main mode (TE101) of the cavity. That is:

\[
 f_m = \frac{c}{2} \sqrt{\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{l}{c}\right)^2}
\]

In this formula, \( a, b, c \) represent the size of the shield chassis and \( m, n, l \) respectively represent electromagnetic waves in the X, Y, Z direction of the half wave.

According to Figure 7, when there is no dielectric plate in the cavity, the resonant point of the cavity is 695.65MHz. Besides, when the distance between the dielectric substrate and the opening is \( d_1 \) and \( d_2 \) respectively, the resonant points of the cavity are 711.1MHz and 816.5MHz respectively. So the dielectric plate in the cavity causes the resonant point of the cavity to move and move towards the high frequency as the distance increases. According to the size of the simulated waveform, we know that there is a substrate in the cavity, which decrease the amplitude of the electric field behind the substrate in the cavity, especially in the resonant region.
Fig. 7 Cavity center’s electric field intensity at different distances

Placing the media plate at a distance of 5 cm from the opening, meanwhile changing the width of the media plate size to be 5 cm * 5 cm, 15 cm * 15 cm, 23 cm * 23 cm respectively and the keeping the thickness of the medium plate constant, we observe the effect of the change in the size of the dielectric plate on the electric field intensity at the center point of the cavity.

According to the simulation results shown in Figure 8, when the size of the dielectric substrate in the cavity is changed, the distribution of the electric field intensity behind the dielectric plate in the cavity exhibits different characteristics in the resonant region and the non-resonant region.

Changing the size of the dielectric plate in the non-resonant region has little effect on the electric field intensity amplitude of coupling field in the cavity. However, as for the resonant area, when the size of the dielectric plate is 5 cm * 5 cm, 15 cm * 15 cm, 23 cm * 23 cm, the maximum value of the electric field amplitude at the corresponding resonance point is 496.5 V/m, 147.3 V/m, 54.38 V/m respectively. Therefore, the conclusion can be drawn that the larger the size of the dielectric plate, the greater the magnitude of the reduction of the electric field amplitude of the cavity. Since the dielectric plate exists in the cavity, making the dielectric plate and the original cavity form a new cavity, the cavity of the resonant point slightly changed under different sizes of the dielectric plate.

Fig. 8 Cavity center’s electric field intensity under different sizes of dielectric plates
5. Summary
In the GIS substation, the dis-connector operation is conventional operation, and the resulting VFTO will radiate outward very large amplitude and rich high-frequency component electromagnetic waves. In this paper, we use the electromagnetic field simulation software which is based on time domain finite difference method to analyze the coupling field characteristics in the rectangular cavity under the VFTO space field and in the presence of a dielectric plate. The simulation results indicate: With the increase of rectangular opening’s length and width ratio, the coupling field intensity of the space field generated by VFTO in the cavity also increases; When the direction of polarization of the space electric field is parallel to the short side of the rectangular opening, the energy coupled into the cavity is the largest and when it is parallel to the long side of the rectangular opening, the energy coupled into the cavity is the smallest; Dividing the single form of the hole into the same area of the gap array can effectively improve the shielding effectiveness of the cavity.

At the same time, the simulation results also show that the dielectric plate in the cavity also affects the characteristics of the coupling field in the cavity. When the dielectric plate is present in the cavity, the coupling field amplitude of the region behind the dielectric plate in the cavity is reduced. In the case of a certain size of the dielectric plate, the closer the dielectric plate in the cavity is to the opening, the smaller the field intensity of the cavity, which is more obvious in the resonant region of the cavity. Besides, the larger the size of the dielectric plate, the smaller the coupling field into the cavity through the dielectric plate, and the greater the reduction in the electric amplitude of the field. According to the frequency domain analysis, the dielectric plate in the cavity will change the resonant point distribution in the cavity.

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