Field Enhancement Effect in High-Altitude Nuclear Electromagnetic Pulse Electric Field Measurement

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Abstract. In order to solve the problem that the enhancement effect of cylindrical pulsed electric field sensor on the field in nearby space causes the measurement result to be too large, the principle of the midfield enhancement effect of electric field measurement is analyzed first, and the definition of field enhancement factor is given. The approximate formula of field enhancement factor is given by analytic method, and the influence of different parameters on field enhancement factor is analyzed qualitatively. The results show that the negative correlation between the field enhancement factor and the radius of the electric field sensor is positively correlated with the height of the electric field probe. Finally, the field enhancement factor under different parameters is given quantitatively by using the method of all-electromagnetic simulation, and the analytical formula is modified according to the simulation results. The calculated field enhancement factor is in good agreement with the simulation results. Using this formula, the field enhancement factor caused by different parameters of sensor shell can be calculated quickly and accurately, and the measurement precision of electric field sensor can be improved.

Keywords: Field enhancement effect, Electric field measurement, CST simulation

1. Introduction
High-altitude nuclear electromagnetic pulse has the characteristics of high field strength, wide frequency band and wide range of action [1-4]. It can cause interference or damage to electric electronic equipment. In order to protect against the effect of electromagnetic pulse, it is necessary to study the mechanism of its action, and the measurement of electric field is one of the basic and important work. We can understand the waveform characteristics of electromagnetic pulse and lay a foundation for further protection work.

Traditional pulsed electric field sensors include two kinds of sensors, which are based on the original waveform measurement and differential measurement. Both of them are composed of antenna and a metal shielding shell or metal ground [5-9]. According to the theory of electromagnetic field, the electric field around the metal will be distorted, and the metal surface perpendicular to the direction of space electric field will have the enhancement effect, which is related to the structural parameters of the metal shell. In order to improve the measurement precision, the field enhancement effect of the metal shell must be taken into account and the measurement result should be corrected. There are few public studies
on the problem, in ref.10, the upper limit of the additional field strength caused by a metal shell is \( \pi dE / (2R) \), in which the height and radius of the shell are \( d \) and \( R \), but because the interval range of the result is too large, it is of little significance to the actual measurement work. In this paper, the field enhancement effect of metal shell is studied by means of analysis and CST simulation respectively, and the analytical formula of field enhancement factor with practical value is given.

2. Analysis of principle
The traditional pulsed electric field sensor, shown in Figure 1, is divided into an antenna and a cylindrical metal shell. The antenna is designed in a thin line with a length less than 1/8 of the wavelength. The cylindrical metal shell is placed in the space with electric field intensity \( E \). Under the action of electric field, the upper and lower surface of the metal body is separated by positive and negative charges, thus creating an additional field \( E' \).

It is assumed that the positive and negative charge distribution of the upper and lower shell is uniform, and the surface charge density is all equal \( \sigma \), and the additional field \( E' \) can be solved by analytical method. \( E' \) Under the action of the electric field shown in Figure 1, the upper surface of the sensor converges the positive charge and the lower surface converges the negative charge, and \( E' \) is the superposition of the electric field on the upper and lower surface of the shell. The radius of the shell is \( R \) and the thickness is \( d \), and the additional electric field at \( h \) above the axis of the shell is given by formula (1):

\[
E' = \int_0^h \left( \frac{2\pi \sigma \sigma_0 \sqrt{h^2 + r^2}}{4\pi \varepsilon_0 ((h + d)^2 + r^2)} - \int_0^{h+d} \frac{2\pi \sigma \sigma_0 \sqrt{h^2 + r^2}}{4\pi \varepsilon_0 ((h + d)^2 + r^2)} \right) \, dr
\]

\[
= \frac{\sigma}{2\varepsilon_0} \left( \int_0^h \frac{hrdr}{(h^2 + r^2)^{3/2}} - \int_0^{h+d} \frac{(h + d)rdr}{((h + d)^2 + r^2)^{3/2}} \right)
\]

\[
= \frac{\sigma}{2\varepsilon_0} \left( \frac{h + d}{\sqrt{h^2 + R^2}} - \frac{h}{\sqrt{(h + d)^2 + R^2}} \right)
\]

A parallel plate capacitor is formed on the upper and lower surface of the sensor. Because the electric field inside the shell is 0, the electric field generated by the separation charge is equal to the applied electric field, and the direction is opposite. The voltage between the upper and lower surfaces is:

\[
U = Ed
\]

The separation charge generated on the surface of the sensor is as follows:

\[
Q = UC
\]

\[
= Ed \frac{\varepsilon_0 \pi R^2}{d}
\]

\[
= E \varepsilon_0 \pi R^2
\]
On the other hand, \( Q = \sigma \pi R^2 \), a combination of formulas (3) can be obtained:

\[
\sigma = \varepsilon_0 E
\]  

(4)

Bring the formula (4) into the formula (1) and you can get:

\[
E' = \frac{E}{2} \left( \frac{h + d}{\sqrt{(h + d)^2 + R^2}} - \frac{h}{\sqrt{h^2 + R^2}} \right)
\]  

(5)

Defining the field enhancement factor as \( f = (E' + E) / E \), the approximate expression of \( f \) is:

\[
f = \frac{1}{2} \left( \frac{h + d}{\sqrt{(h + d)^2 + R^2}} - \frac{h}{\sqrt{h^2 + R^2}} \right) + 1
\]  

(6)

In fact, the upper and lower surfaces of the sensor can be equivalent to parallel plate capacitors only if \( R >> d \) is satisfied, so the larger the value of \( R/d \), the more accurate the calculation results obtained by formula (6) will be. Because of the edge effect, the charge distribution on the shell surface is not uniform, which will result in some error of the calculated field enhancement factor.

The range of \( R \) is 5 cm-15 cm, \( d \) is 1 cm-5 cm, \( h \) is 1 cm, and the field enhancement factor calculated by formula (6) is given in Figure 2.

![Figure 2. Field enhancement factor for variation of shell radius R and thickness d](image)

As can be seen in figure 2, the field enhancement factor decreases with the radius of the sensor shell and increases with the height of the sensor shell. At the same time, with the increase of sensor radius and sensor height, the change rate of field enhancement factor decreases gradually.

On the other hand, set \( R = 10 \) cm and \( d = 5 \) cm, the value range of \( h \) is 0.1 cm-2 cm, figure 3 shows the variation curve of field enhancement factor.
Figure 3. Field enhancement factor with the change of distance from shell height $h$

It can be seen that the farther the distance sensor, the smaller the field enhancement factor. This is because the farther from the sensor shell, the weaker the field enhancement effect produced by the shell.

The variation of field enhancement factor with the parameters of the sensor shell and the distance from the shell is given, but the formula (6) is obtained by the approximate processing method, and the calculated field enhancement factor is not accurate, so as to verify the law obtained by the analytical method. The results of the field enhancement factor are given by using the method of all-electromagnetic simulation, and compared with the analytical results.

3. CST simulation calculation

The field enhancement factor $f$ is simulated by CST microwave studio. The excitation source is a square wave with a range of 1 V/m, a rising and drop edge of 0.2 ns and a flat top of 10 ns, the electric field direction is parallel to the antenna direction (Figure 4 shows), the simulation precision is 60 dB, the upper limit frequency is 5 GHz.

Figure 4. Schematic diagram of simulation calculation model

First, the value of $h$ is 1 cm, the value range of $d$ is 1 cm-5 cm, and the value range of $R$ is 5 cm-15 cm, and the results of enhancement factor $f$ were calculated as shown in figure 5:
Figure 5. Simulation results of enhancement factor when d, R changes

It can be seen that the simulation results are consistent with the analytical results. The field enhancement factor decreases with the increase of R and increases with the increase of d. Compared with the results in figures 2 and 5, we find that the analytical results are smaller than the simulation results, which is consistent with the above analysis.

The field enhancement factor with different R and d conditions under h = 1cm is recalculated by using the formula (6), and the results are compared with the simulation results.

Figure 6. Field enhancement factor obtained by the analytical and simulation methods when R and d change

It can be seen that the larger the value of R/ d, the better the agreement between the analytical results and the simulation results, which is consistent with the conclusion of the theoretical analysis, the deviation between the analytical results and the simulation results is represented by $\Delta f$, and the statistical results of table 1 are obtained.
Table 1. Error between analytical results and simulation results

| R / d | > 1 | > 2 | > 3 | > 4 | > 5 |
|-------|-----|-----|-----|-----|-----|
| Δφ    | <9% | <3.1% | <1.2% | <1% | <0.8% |

For common electric field sensors, the conditions are usually satisfied R / d > 2, and the difference between the analytical results and the simulation results is very small, so the field enhancement factor caused by the sensor shell can be calculated accurately by the formula (6).

The variation of the field enhancement factor with h is calculated. The calculated field enhancement factor is calculated by R = 10cm, d = 5cm and h is from 1mm to 20mm, as shown in figure 7.

![Figure 7. Simulation results of field enhancement factor with h variation](image)

The field enhancement factor decreased with the increase of h, and it was found that the effect of h on the enhancement factor was very small, and the change of the enhancement factor was less than 1% when the change of h was 1 mm to 20 mm.

The variation law of field enhancement factor with h is recalculated by formula (5), and the results are compared with the simulation results, and the results obtained by two methods are given in figure 8.

![Figure 8. Field enhancement factor obtained by analysis and simulation method with h variation](image)

It can be seen that the variation law of field enhancement factor obtained by the two methods is consistent, and the analytical results are smaller than the simulation results. The maximum difference of field enhancement factor between the two methods is 1.8% in the range of h variation.
4. Conclusion
In this paper, the approximate formula of field enhancement factor is obtained by analytical method, and the following rules of field enhancement factor are obtained: 1) Decrease with increase of shell radius $R$; 2) Increase with the increase of the shell thickness $d$; 3) The farther the distance from the shell, the smaller the enhancement factor. The above rules are verified by CST simulation, and the application condition of the analytical formula is given according to the comparison between the analytical results and the simulation results. Under this condition, the field enhancement factor caused by the shell of the electric field sensor can be calculated quickly and accurately. It is of great significance to improve the measurement precision of electric field sensor.

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