Overshoot of D-dot sensor in measurement of electric field

Jinghai Guo*, Liang Ma, Yinhui Cheng, Xutong Wang, Yifei Liu, Jinxi Li, Wenbing Wang
National Key Laboratory of Intense Pulsed Radiation Simulation and Effect(Northwest Institute of Nuclear Technology)Xi’an, China

*Corresponding author: gihai@mail.ustc.edu.cn

Abstract. This paper analyzes the cause of the overshoot of the signal measured by D-dot sensor, and points out that the second-order RLC equivalent circuit model can explain the overshoot. Taking the asymptotic conical antenna as an example, the inductance L of the second-order model is obtained by using CST simulation and Pspice parameter scanning method. The first-order model and the second-order model are used to calculate the electric field waveform. Under the given conditions, the first-order model is used to obtain the electric field waveform, the waveform overshoot is serious, the maximum overshoot reaches 27%, while the second-order model is used to improve the ringing phenomenon, and the maximum overshoot is reduced to 5%. The results show that the second-order model is more accurate than the first-order model and can improve the precision of electric field measurement using D-dot sensor.

Key words: D-dot; Ringing phenomenon; second-order model; Pspice.

1. Introduction
Electromagnetic pulse has the characteristics of high amplitude, fast rising edge and wide frequency band[1]. It can interfere and destroy power electronic equipments. Pulse electric field measurement is an important work in the field of electromagnetic pulse research. It is of great significance to study the effect mechanism and protection method of electromagnetic pulse.

D-dot electric field probe has wide frequency band and simple structure[2],[3], and its sensitivity is determined by structure and size. It is widely used in electric field measurement. D-dot is a kind of differential measurement. After the signal is integrated, the waveform of electric field can be obtained. But when measuring the pulse signal with a fast rising edge, the measurement result appears different level overshoot, and the faster the front edge of the measured signal, the more obvious the overshoot of the measured signal, which will affect the measurement precision to some extent. In the published paper about D-dot detector, the equivalent model of D-dot detector mostly uses first-order RC model, which does not take into account the overshoot problem into account[5],[6],[8],[10], this has little effect when the measured signal rises slowly, but it seriously affects the measurement precision when measuring the fast rising edge signal. In this paper, the reason of overshoot is analyzed, and the method of improving overshoot in D-dot measurement is put forward.
2. Basic principle

2.1. principle of D-dot sensor
The output of the D-dot sensor is the differential of electric displacement vector [4],[5], and the electric displacement vector \( D \) and electric field strength \( E \) in free space are satisfied \( D = \varepsilon_0 E \), so the probe output can be transformed into the electric field strength which is to be measured [7,8]. In general, the equivalent circuit of the D-dot electric field sensor is shown in figure 1[11]-[14].

\[
i = A_e \dot{D}_v
\]

![Figure 1. D-dot sensor equivalent circuit](image)

In figure 1, \( A_e \) is the equivalent area of the sensor, \( C \) is the equivalent capacitance of the sensor, \( R \) is the load, and \( V_o \) is the output voltage on the load.

The current source term of equivalent circuit in figure 1 can be obtained from the relation between electric displacement vector and electric field intensity in free space:

\[
i = A_e \frac{dD}{dt} = \varepsilon_0 A_e \frac{dE}{dt}
\]

(1)

In time domain, the circuit satisfies the following relations:

\[
i = C \frac{dV_o}{dt} + \frac{V_o}{R}
\]

(2)

Combined with (1), (2) and Laplace transform, the transfer function of the sensor is obtained as follows:

\[
G(s) = \frac{V(s)}{E(s)} = \frac{s\varepsilon_0 A_e R}{sRC + 1}
\]

(3)

2.2. Reasons for the phenomenon of ringing
Figure 1 is a first-order \( RC \) system in which overshoot does not occur when measuring signal with a slow rising edge [5], and in practical applications, for example, when square wave signal with a fast rising edge is measured, it indicates that the model in Figure 1 is incomplete. In fact, it does not take into account the parasitic inductance \( L \) of the D-dot sensor itself, which has no effect on the measurement of pulse electric field signals with low frequency, but the inductance can not be ignored when the frequency is high, and the effect of the inductance will appear. In this case, the equivalent circuit of the D-dot sensor is shown in figure 2.

![Figure 2. Equivalent circuit of D-dot sensor considering parasitic inductance](image)
This is a second-order RLC system, which can be obtained by equivalent circuits as follows:

$$R \varepsilon_0 A_c \frac{dE}{dr} = C L \frac{d^2 V}{dr^2} + R C \frac{dV}{dr} + V_o$$

(4)

Its characteristic equation is:

$$\lambda^2 + \frac{R}{L} \lambda + \frac{1}{LC} = 0$$

(5)

The two characteristics are as follows:

$$\lambda_{1,2} = -\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

(6)

There are three types of cases[9]:

1. \( R > 2 \sqrt{\frac{L}{C}} \), at that time, the equation has two different negative real roots, which belong to over-damped state. There is no oscillation and no ringing phenomenon in D-dot measurement.

2. \( R = 2 \sqrt{\frac{L}{C}} \), at that time, the equation has two equal negative real roots, which belong to the critical damping state. There is no oscillation and no ringing phenomenon in D-dot measurement.

3. \( R < 2 \sqrt{\frac{L}{C}} \), at that time, two real parts of the equation are negative coincident complex root, and the attenuation oscillation occurs, and the ringing phenomenon appears in D-dot measurement.

In D-dot measurement system, the cable connected to the sensor takes 50 \( \Omega \) as load impedance. For the common monopole antenna used for electromagnetic pulse measurement, \( L \) is nH order, \( C \) is pF order, and generally meets the condition of condition 3.

3. Simulation and Analysis

In this paper, the equivalent capacitance \( C \) and the equivalent area \( A_e \) of the asymptotic conical antenna are analyzed[9]. The contour equation of the asymptotic conical antenna can be expressed as follows:

$$\rho = \Theta_0 \left( z + \sqrt{z^2 + \rho^2} \right) \sqrt{z_0 - z + \sqrt{(z_0 - z)^2 + \rho^2}} \sqrt{z_0 + z + \sqrt{(z_0 + z)^2 + \rho^2}}$$

(7)

Among them, \((\rho, z)\) is the contour coordinate under the column coordinates, and \((\Theta_0, z_0)\) is the constant related to the shape of the antenna, the equivalent capacitance and the equivalent area of the antenna can be expressed as follows:

$$A_e = \frac{\pi \varepsilon_0 z_0^2}{\ln(\Theta_0^{-1})}$$

$$C = \frac{2\pi \varepsilon_0 z_0}{\ln(\Theta_0^{-1})}$$

(8)

If \( \Theta_0 = 0.3 \) mm and \( z_0 = 1 \) mm, then \( A_e = 2.61 \times 10^{-4} \) m² and \( C = 4.61 \times 10^{-13} \) F are obtained by fomular (8), and an asymptotic conical antenna simulation model shown in figure3 is established by using CST microwave studio. The antenna tip is connected with the inner conductor of coaxial cable and is connected to the ground by the central resistance of 50 \( \Omega \). The voltage drop on the resistance is equivalent to the output voltage \( V_o \) of the actual sensor on the 50 \( \Omega \) transmission cable. The excitation source uses the electric field plane wave perpendicular to the ground, the field strength 1V/ m, the waveform is the square wave with the rising edge and descending edge of 0.1 ns and the flat top duration of 2ns.
The simulated result of load voltage $V_o$ is shown in figure 4.

If the first-order $RC$ equivalent circuit model is used in figure 1, the electric field waveform can be calculated by the formula (3), as shown in figure 5.

As can be seen from figure 5, the electric field waveform obtained by first-order $RC$ model has a serious overshoot compared with the incident wave shape. The maximum overshoot reaches 27%. In this case, the circuit model of figure 1 will cause a large error to the measurement result. Therefore, we must consider the influence of the parasitic inductance $L$ on the measurement results. The circuit
model of figure 2 can get more accurate results, but it is difficult to get the parasitic inductance $L$ by analytical or numerical method.

In this paper, we use the method of Pspice parameter scanning to obtain value of $L$: establish the pspice model of the circuit shown in figure 2, obtain the analytical result of capacitance, select the same source waveform as above CST simulation, monitor the load output waveform when the parasitic inductance $L$ changes (see figure 6). The $L$ value when the load output waveform is consistent with the CST simulation result is the desired result.

![Figure 6. Load output waveform with inductance $L$ variation](image)

The results show that pspice agrees well with CST simulation results when the inductance is 2 nH, therefore, the inductance value of the circuit model in figure 2 is 2 nH, and figure 7 shows the comparison of the $V_o$ normalization results between pspice and CST in this case.

![Figure 7. The load output waveform obtained by pspice and CST simulation when inductor $L$ is 2 nH](image)

After the value of inductance $L$ is obtained, the waveforms of the field to be measured can be calculated by means of formula (4), and the electric waveforms calculated by $V_o$ of load output are given by figure 8.
Figure 8. Electric field waveform calculated by $V_o$ using the formula (4)

Figure 8 shows that after using the second-order model of formula (4), the waveform overshoot of the measured electric field calculated by the antenna output has been improved obviously, and the overshoot rate has decreased from 27% to 5%, which shows that the equivalent circuit model of Figure 2 is more accurate than figure 1.

In addition, for a determined D-dot sensor, the overshoot size is related to the signal rising edge. Usually the faster the rising edge of the measured signal, the greater the overshoot of the measured signal. The simulation model in Figure 3 is still used. The excitation source is the square wave with different rising edge and the square wave is taken up to 5 ns at flat top. The load voltage under square wave with different rising edge is obtained. The electric field waveform is calculated by using the first-order and second-order circuit models respectively.

![Figure 9](image)

(a) Result of first-order model  (b) Result of second-order model

Figure 9. The electric field waveform calculated by different front-edge square wave excitation

The results in figure 9 show that when the rising edge of square wave is less than 1ns, the overshoot of the waveform calculated by the first-order circuit model is greater than 2.4%, while the waveform calculated by the second-order circuit is less than 2.4% in the range of 0.2 ns-2ns of square wave rising edge. It also shows that the first-order model is only suitable for the measurement of electric field signals with slow rising edge, and the second-order model is suitable for signals with both fast and the slow rising edge.

4. Conclusion

In this paper, the cause of the overshoot of D-dot sensor is analyzed. It is pointed out that the first-order RC equivalent circuit model can not explain the cause of overshoot, and the second-order RLC equivalent circuit model can be used. The parasitic inductance $L$ of the model is determined by using Pspice parameter scanning combined with CST simulation results. The second-order model is used to push back the measured electric field waveform from the output of D-dot antenna, and the overshoot of the measured results is greatly improved. The results obtained by the second-order model are more accurate.
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