Study on electromagnetic field distribution of impulse current wave

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Abstract. The 10/350 μs impulse current wave which is generated by impulse current generator in the laboratory is simulated by Heidler function current model. Based on dipole theory, electromagnetic field equations are calculated. Combined with Heidler function current model, electromagnetic field time-space distribution of 10/350 μs impulse current wave is simulated. The results of simulations show that with an increase in the length of the current element, the electromagnetic field intensity, caused by the current element, increases correspondingly. The electromagnetic field caused by the same current element decreases gradually with an increase in the distance. Based on the above conclusions, some electromagnetic protection measures of the laboratory are presented, which have specific meaning to the shield design of the lab and the health of workers in the lab.

1. Introduction
With the fast development of information industry, electronic devices are becoming highly integrated, highly accurate and low energy-consuming. Meanwhile, lighting electromagnetic pulse (LEMP) following lightning discharge has caused more and more hazards to these electronic devices. According to protection against lightning standard of GB/T 21714 and IEC 62305, 10/350 μs impulse current waveform is chosen to simulate the first lighting stroke. The 10/350 μs impulse current generator running in the laboratory can generate an impulse current of 100 kA. This powerful impulse current must cause very intensive electromagnetic field. As a result, studying the electromagnetic pulse of impulse current in the laboratory is of vital importance for the electromagnetic pulse shielding of electronic devices in the lab, the shield design of a lab and the health of people working in the lab.

2. Theoretical Calculation
The output terminal of the impulse current generator is located in the sample case, which is composed of a high voltage terminal and low voltage terminal as is shown in figure 1. Ideally, when a sample is put in the case, set the conductor with a length of L between the two terminals as current element i(t)L. According to the Maxwell equations, the electric field $E(R, t)$ and the magnetic field $B(R, t)$ in any position can be determined. The Maxwell equations of differential form are as follows:

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Figure 1. Sample case of the impulse current generator.

\[ \nabla \times \mathbf{B} = \mu \mathbf{J} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} \]  \hspace{1cm} (1) \\
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]  \hspace{1cm} (2) \\
\[ \nabla \cdot \mathbf{B} = 0 \]  \hspace{1cm} (3) \\
\[ \varepsilon_0 \nabla \cdot \mathbf{E} = \rho \]  \hspace{1cm} (4)

Figure 2. Calculation for the electromagnetic field generated by current element at the zero point.

When current element is located at the zero point and is in free space, the electromagnetic component, which includes magnetic field component \( H_\varphi \), electric field radial component \( E_r \) and electric field axial component \( E_z \) can be determined by solving the Maxwell equations:

\[ H_\varphi (r, \varphi, z, t) = \frac{L}{4\pi R^2} \left[ \frac{r}{c} \frac{\partial i(t-R/c)}{\partial t} + \frac{r}{R} i(t-R/c) \right] \]  \hspace{1cm} (5) \\
\[ E_r (r, \varphi, z, t) = \frac{Lr}{4\pi R^2} \left[ \frac{3}{R^2} \int_0^\tau \frac{i(t-R/c)}{R} d\tau \frac{1}{c^2} \frac{\partial i(t-R/c)}{\partial t} + \frac{3}{cR} i(t-R/c) \right] \]  \hspace{1cm} (6)
\[ E_z(r, \varphi, z, t) = \frac{L}{4\pi\varepsilon_0 R^3} \left[ \frac{2z^2 - r^2}{R^2} \int_0^t \frac{i(t-R/c) d\tau}{c(R/c)} + \frac{2z^2 - r^2}{cR} i(t-R/c) \pi \tau \right] \] (7)

Where: \( \varepsilon_0 \) (the free-space dielectric constant) is \( 0.854 \times 10^{-12} \text{ F m}^{-1} \); \( \mu_0 \) (the free-space magnetic conductivity) is \( 4\pi \times 10^{-7} \); \( R \) is the distance between current element and observation point.

By applying the Heidler function current model proposed by Heidler, Current element \( i(t) \) can be shown as follows:

\[ i(t) = \frac{I_0}{h} \left( \frac{t}{\tau_1} \right)^n e^{-t/\tau_1} \] (8)

Where: \( I_0 \) is the peak current, \( h \) is the coefficient of correction for the peak current, \( \tau_1 \) is the time constant of the wave head, \( \tau_2 \) is the time constant of the wave tail. The derivative about time of the Heidler function can be described as follows:

\[ \frac{\partial i(t)}{\partial t} = \frac{I_0}{h} \left( \frac{t}{\tau_1} \right)^n e^{-t/\tau_1} \frac{n}{\tau_2} \left( \frac{1}{t(1+t/\tau_1)} - \frac{1}{\tau_2} \right) \] (9)

3. Calculation and simulation

3.1. Simulation for the 10/350 \( \mu \text{s} \) impulse current

![Figure 3](image)

**Figure 3.** The comparison between two impulse currents separately simulated by Heidler function and generated by the impulse current generator in the lab.

The Heidler function is applied to simulate the 10/350 \( \mu \text{s} \) impulse current wave, and this current wave is compared with the impulse current generated by the impulse current generator in the lab, as is shown in figure 3, in which the waveform parameter \( I_0 \) (the peak current) is 10 kA and \( \tau_1 \) (the time constant of the wave head) is 10 \( \mu \text{s} \) and \( \tau_2 \) (the time constant of the wave tail) is 350 \( \mu \text{s} \). As can be seen from the comparison result, the only difference between the simulated and the generated impulse current waveform is located at the wane tail, while in other locations such as the wave head and the peak, the two forms match very well. As a result, it can be reasonable to apply the Heidler function to
simulate the impulse current generated by the impulse current generator in the lab, and calculate the electromagnetic field caused by this impulse current.

3.2. Simulation for the electromagnetic field distribution of the impulse current
As the distance between the two terminals of the impulse current generator output terminal is very short, it can be supposed that a current element with the length of $L$ is caused between the two terminals. In this paper, the electromagnetic field distribution of the impulse current is simulated by combining the Heidler function and the current element electromagnetic field equations.

![Figure 4](image1.png)  ![Figure 5](image2.png)

Figure 4. The electric-field intensity generated by different current elements at a radial distance ($r=50$ m).  
Figure 5. The magnetic induction intensity generated by different current elements at a radial distance ($r=50$ m).

![Figure 6](image3.png)  ![Figure 7](image4.png)

Figure 6. The electric-field intensity generated by the same current element at different distances.  
Figure 7. The magnetic induction intensity generated by the same current element at different distances.

Figure 4 and figure 5 separately shows the electric field and magnetic field generated by different current elements at a radial distance ($r=50$ m). As can be seen from figure 4 and figure 5, as the increase of the current element, the electric-field intensity and the magnetic induction intensity increase at the same time, and the relationship between the current element and field intensity is linear. The electric-field intensity increases fast at first and slow after that. While the magnetic induction intensity increases very fast to a peak value at first and then decreases fast and later gradually decreases to zero.
Figure 6 and figure 7 separately show the electric field and magnetic field generated by the same current element at different distances. As the distance goes further, the electric-field intensity and the magnetic induction intensity decrease gradually.

4. Conclusions
Based on the dipole theory and combing the Heidler function current model, the electromagnetic field of the 10/350 μs impulse current, generated by the impulse current generator, is calculated in this paper. By analyzing and comparing the simulation results, some conclusions and suggestions are proposed as follows:

- With an increase in the length of the current element, the electromagnetic field intensity, caused by the current element, increases correspondingly. Under the condition of meeting the experimental demands, the distance between the high voltage terminal and the low voltage terminal should be decreased as short as possible.
- The electromagnetic field caused by the same current element decreases gradually with an increase in the distance. So it’s noticeable to keep an enough long distance between the impulse current generator and other electric devices and workers in the lab during the construction of the lab.
- Because the electromagnetic field intensity generated by the 10/350 impulse current is very powerful, it’s very essential to improve the electromagnetic shielding in the lab, and set apart the experiment area and the working area.

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