Four Order Electrostatic Discharge Circuit Model and its Simulation

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Abstract

According to the international electrotechnical commission issued IEC61000-4-2 test standard, through the electrostatic discharge current waveform characteristics analysis and numerical experiment method, and construct a new ESD current expression. Using Laplasse transform, established the ESD system mathematical model. According to the mathematical model, construction of passive four orders ESD system circuit model and active four order ESD system circuit model, and simulation. The simulation results meet the IEC61000-4-2 standard, and verify the consistency of the ESD current expression, the mathematical model and the circuit model.

Keywords: ESD, IEC61000-4-2, circuit model, simulation, spectrum

1. Introduction

During electrostatic discharge (ESD), the rate of discharge current change is large, and often accompanied by strong electromagnetic radiation. Coupled by electronic systems distribution parameter, this strong electromagnetic radiation produce transient induced voltage or pulse current in circuit wires and device pins, which interference of circuits and devices work properly. Especially on micro-electronic systems, certain intensity electromagnetic pulse can not only make significant serious interference of electronic equipment, may also cause damage to the device and formation of potential failure. Because this potential failure has strong concealment, it is dangerous. As microelectronic devices are widely used in various fields, electrostatic discharge hazards are more and more attention. Internationally, the electrostatic discharge immunity test of electronic products has been treated as an important part of electromagnetic compatibility for electronic products (EMC) testing and certification, and sets detailed equipment requirements of electrostatic discharge immunity test.

The first edition of IEC61000-4-2 electrostatic discharge immunity test standard was promulgated of the International Electrotechnical Commission in 1995. Following by it, in 1998 and 2001, respectively, it has issued a IEC61000-4-2 version 1.1 and version 1.2. 2nd Edition [1], the latest version of IEC61000-4-2, was introduced in 2008. Among IEC61000-4-2 standards, human metal model (HMM) electrostatic discharge is regarded as a typical discharge current waveform, as shown in Figure 1.

<table>
<thead>
<tr>
<th>V(kV)</th>
<th>I_{max}(A)±10%</th>
<th>t&lt;sub&gt;r&lt;/sub&gt;(ns)</th>
<th>I_{z0}(A)±30%</th>
<th>I_{z2}(A)±30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>7.50</td>
<td>0.7-1</td>
<td>4.00</td>
<td>2.00</td>
</tr>
<tr>
<td>4</td>
<td>15.00</td>
<td>0.7-1</td>
<td>8.00</td>
<td>4.00</td>
</tr>
<tr>
<td>6</td>
<td>22.50</td>
<td>0.7-1</td>
<td>12.00</td>
<td>6.0</td>
</tr>
<tr>
<td>8</td>
<td>30.00</td>
<td>0.7-1</td>
<td>16.00</td>
<td>8.00</td>
</tr>
</tbody>
</table>

Figure 1. IEC61000-4-2 provides ESD current waveform
According to the IEC61000-4-2 standards, ESD simulator should meet the following two main performance parameters:

Produce electrostatic discharge current waveform, as shown in Figure 1, and meet waveform parameters specified in Table 1 requirements. In the discharge circuit of ESD simulator, the sum of the distributed capacitance $C_d$ and energy-storage capacitor $C_s$ is $(150 \pm 10\%)$pF; Discharge circuit resistance $R_d$ is $(330 \pm 10\%)$Ω.

Older IEC61000-4-2 standard gives only four key parameters, the typical waveforms of ESD current and maximum values $I_p$, discharge current value $I_{60}$ at the time of 30 ns, discharge current value $I_{60}$ at the time of 60 ns as well as the rise time $t_r$, which has been brought uncertainly to the user when referencing standards, and has also been brought related difficulties to the theoretical research on ESD. In order to get the mathematical expressions of typical of ESD current waveform, many scholars have explored in it.

2. Mathematical model of HMM-ESD system

2.1. Four kinds of HMM-ESD current expression

In 1991, the Keenan-Rosi built a four-index of ESD current mathematical expressions [2]:

$$i(t) = i_1 \cdot \left( e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}} \right) + i_2 \cdot \left( e^{-\frac{t}{\tau_3}} - e^{-\frac{t}{\tau_4}} \right) \tag{1}$$

In 1998, the Berghe-Zutter built the ESD current mathematical expressions based on Gaussian function [3]:

$$i(t) = A \cdot e^{-\frac{(t-\tau_1)^2}{\sigma_1^2}} + B \cdot t \cdot e^{-\frac{(t-\tau_2)^2}{\sigma_2^2}} \tag{2}$$

In 2003, Sheng Songlin built the ESD current mathematical expressions based on pulse function [4]:

$$i(t) = i_1 \cdot \left( 1 - e^{-\frac{t}{\tau_1}} \right)^p e^{-\frac{t}{\tau_2}} + i_2 \cdot \left( 1 - e^{-\frac{t}{\tau_3}} \right)^q e^{-\frac{t}{\tau_4}} \tag{3}$$

Wang Kai built the ESD current mathematical expressions based on Heidler lightning current equation [5, 6]:

$$i(t) = \frac{i_1}{k_1} \cdot \frac{(\frac{t}{\tau_1})^n}{1 + (\frac{t}{\tau_1})^n} \cdot e^{-\frac{t}{\tau_2}} + i_2 \cdot \frac{(\frac{t}{\tau_3})^n}{1 + (\frac{t}{\tau_3})^n} \cdot e^{-\frac{t}{\tau_4}} \tag{4}$$

In which:

$$k_1 = e^{-\frac{\tau_1}{\tau_2}}, k_2 = e^{-\frac{\tau_3}{\tau_4}}$$

Four expressions of ESD current waveforms can match the waveform shown in Figure 1 to some degree, and meet four key parameters in Table 1. Obviously, ESD current expression is not unique. In the latest version of the IEC61000-4-2 standard, ESD current expression (4) waveform built by Wang Kai is regard as an idealized waveform. In the expression (4), when $\tau_1=1.1\text{ns}$, $\tau_2=2.0\text{ns}$, $\tau_3=12\text{ns}$, $\tau_4=37\text{ns}$, $i_1=16.6\text{A}$ (at 4kV), $i_2=9.3\text{A}$ (at 4kV), $n=1.8$, the ESD standard current waveform as shown in Figure 2.
2.2. New HMM-ESD current expression

Although ESD waveform and the current expression of the construct measured waveform built by Wang Kai can better match, and when \( t=0 \), first derivative equals to 0 at all times, but the mathematical forms is complex, and solve time integration is difficult, so it is difficult to build the circuit model.

The Figure 3 can know, ESD standard waveform are two pulse waveform superposed results. Based on the characteristics of ESD current waveform, and the numerical experiment, HMM-ESD current in this article got a new expression:

\[
i(t) = I_1 e^{-\frac{\tau_1}{t}} + I_2 e^{-\frac{\tau_2}{t}}
\]  

(5)

In the expression (5), when the human body electrostatic voltage is 4kV, take \( I_1=1/0.95 \times 10^9 \), \( I_2=1/0.0262 \times 10^9 \), \( \tau_1=10^{-9} \), \( \tau_2=21.8 \times 10^{-9} \), then:

\[
i(t) = 38.1679 \times 10^9 e^{-10^{-9}t} + 1.0526 \times 10^9 e^{-0.0459 \times 10^{-9}t}
\]  

(6)

Take the normalized time factor, then:

\[
i(t) = 38.1679 e^{-t} + 1.0526 e^{-0.0459t}
\]  

(7)

The new waveform of the current expression is shown in Figure 4. The new current expression waveform and standard waveform comparison are shown in Figure 5. The four key parameters are shown in Table 2. Obviously, the new ESD current expression can better meet the IEC61000-4-2 standards.
2.3. The mathematical model of the HMM-ESD system

In order to get the mathematical model of the HMM-ESD system, expressions (6) for the Laplace transform:

\[
I(s) = \frac{38.1679}{(s+1)^2} + \frac{1.0526}{(s+0.0459)^2}
\]

\[
I(s) = \frac{38.1679}{s^2 + 2s + 1} + \frac{1.0526}{s^2 + 0.0918s + 0.0021}
\]

\[
I(s) = \frac{39.2205s^2 + 5.6090s + 1.1328}{s^4 + 2.0918s^3 + 1.1857s^2 + 0.0960s + 0.0021}
\]

If regarding a step signal \( e(t) = Eu(t) \) as a system of incentives, set \( E = 4000 \text{V} \), the system function of the system is:

\[
H(s) = \frac{I(s)}{E(s)} = \frac{9.8051 \times 10^{-3} s^3 + 1.4023 \times 10^{-3} s^2 + 0.2832 \times 10^{-3} s}{s^4 + 2.0918s^3 + 1.1857s^2 + 0.0960s + 0.0021}
\]

As a result, the mathematical model of HMM-ESD is:

\[
\frac{d^4 i}{dt^4} + 2.0918 \frac{d^3 i}{dt^3} + 1.1857 \frac{d^2 i}{dt^2} + 0.0960 \frac{di}{dt} + 0.002 i = 9.8051 \times 10^{-3} \frac{d^3 e}{dt^3} + 1.4023 \times 10^{-3} \frac{d^2 e}{dt^2} + 0.2832 \times 10^{-3} \frac{de}{dt}
\]

3. HMM-ESD Circuit model and simulation

In IEC61000-4-2 standard, the International Electrotechnical Commission sets detailed equipment requirements of electrostatic discharge immunity test, and the ESD simulator becomes critical equipment in the test. Due to the distribution parameters formed by the structure of ESD simulator discharge circuit have a great impact on the device, and the design of discharge circuit to a certain degree is difficult. Therefore, the IEC in IEC61000-4-2 standard is given only simply electrostatic discharge generators, shown in Figure 6.

![Figure 6. ESD generator diagram](image)
3.1 Passive four order circuit model and simulation

From expression (7), HMM-ESD current is actually made up of two parts, one part is the hand and metal electric discharge current formed by \( i_1(t) \)

\[ i_1(t) = 38.1679e^{-t} \]  \hspace{1cm} (11)

The other is the body electric discharge forming current \( i_2(t) \)

\[ i_2(t) = 1.0526te^{-0.0459t} \]  \hspace{1cm} (12)

Their Laplace transforms respectively correspond to expression (8) in the first and second part. From the point of signals and systems, HMM-ESD systems can be considered to be a four order system made up of two parallel subsystems of second-order. The complex frequency domain circuit model of second-order subsystem is shown in Figure 7.

![Figure 7. Circuit model of second-order subsystem](image)

Obviously, its current is

\[ I(s) = \frac{1}{\frac{L}{E} s^2 + \frac{R}{E} s + \frac{1}{EC}} \]  \hspace{1cm} (13)

If will the hand and metal objects parts regarded as second-order subsystem, its capacitor, inductance and resistance respectively for \( C_1, L_1, R_1 \), in electrostatic discharge produced of current is \( i_1(t) \); body parts regarded as another second-order subsystem, its capacitor, inductance and resistance respectively for \( C_2, L_2 \) and \( R_2 \), in electrostatic discharge produced of current is \( i_2(t) \), then

\[ I_1(s) = \frac{1}{\frac{L_1}{4000} s^2 + \frac{R_1}{4000} s + \frac{1}{4000C_1}} \]  \hspace{1cm} (14)

\[ I_2(s) = \frac{1}{\frac{L_2}{4000} s^2 + \frac{R_2}{4000} s + \frac{1}{4000C_2}} \]  \hspace{1cm} (15)

Comparing expression (14) with the first part of expression (8) and expression (15) with the second part of expression (8), it is noted that the normalization factor, the result is \( C_1 = 9.6 \text{pF}, L_1 = 105 \text{nH}, R_1 = 210 \Omega, C_2 = 125 \text{pF}, L_2 = 3.8 \mu\text{H}, R_2 = 349 \Omega \), its circuit model is shown in Figure 8. \( R_0 \) is sampled resistance, using Multisim for circuit simulation, shown in Figure 8. The oscilloscope waveform simulation results are shown in Figure 9, consistent with Figure 4 wave.
3.2. ESD active four order circuit model and simulation

According to the mathematical model (10) of HMM-ESD system, it can use differentiator, scalar multiplication and adder to implement a HMM-ESD system and it can also be based on the system function (9), using integrator, scalar multiplication and adder to implement a HMM-ESD system.
By expression (8), the HMM-ESD active model of four-order circuit is shown in Figure 7. Using MATLAB to HMM-ESD active four-order circuit model for simulation, oscilloscope output is shown in Figure 8. The results clearly proved the correctness of the HMM-ESD active four-order circuit model.

4. Conclusion

Proposed ESD current expression, the waveform conform to the Electrostatic Discharge Immunity Test waveform characteristics requirements. Because of ESD current expression form simple, so can make use of it to establish ESD system mathematical model and circuit model. Use Multisim and MATLAB respectively on ESD passive four order circuit model and active four order circuit model, and simulation results meet the IEC61000-4-2 test standard, indicating that ESD circuit model in practice can be used as ESD simulator use. Through the ESD system function $H(S)$ analysis, we can get the conclusion: Less than four order dynamic circuit may not meet IEC61000-4-2 requirements.

References


