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Numerical Modeling of ESD-Simulators

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Abstract

ESD generators are widely used for testing the robustness of electronic equipment against human electrostatic discharge via small metal pieces (e.g. key). Presently the IEC 61000-4-2 ESD standard is hotly discussed to improve test result reproducibility. This paper numerically analyzes an ESD simulator and relates its construction parameters to discharge current and field parameters. It uses FDTD method and models the relay (contact mode discharge) as a material with time dependent conductivity. The process is broken down into a charging phase and a stabilization phase until the electrostatic conditions are reached. Then the conductivity of the relay is changed and the discharge process is simulated. A self-developed code is used to simulate the model. The simulation discharge current, measured ESD simulator's current and IEC reference discharge current are compared. Some design choices of the generator are simulated

Keywords

ESD, ESD-Simulator, FDTD, Numerical modeling.

INTRODUCTION

Robustness towards Electrostatic Discharge (ESD) is tested using ESD simulators. Most simulators are built in accordance to the specifications spelled out in IEC 61000-4-2. Insufficient specifications contribute to problems in reproducing test results if a different brand ESD simulator is used. For that reason the IEC TC77b is hotly discussing changes to these specifications [1].

ESD can disturb systems by its current and the associated fields. While the current is somewhat specified there is no specification for the fields. It had been assumed that a specification for the current at the point of injection would sufficiently define the transient fields. The currents and fields are determined by the lumped elements of the ESD simulator and all structural elements that carry current or scatter the fields. Presently, the design of ESD simulators is mostly done by try and error while monitoring the discharge current. As there are no field specifications, fields vary a lot from simulator brand to simulator brand although the currents are somewhat similar [2].

There are two discharge methods for ESD simulator, air discharge mode and contact discharge mode. In Air Discharge mode a spark is formed between the tip and ground. The mostly linear simulator response and the non-linear arc are determining the current. In this case, the simulator current can be modeled using the impedance as seen from the ground plane into the discharge tip. This impedance can be transformed in the time domain and convoluted with the non-linear arc [3,4]. This yields the discharge current. Fully modeling the arc via differential equations in a time stepping algorithm is in principle possible, but may require additional measures to avoid divergence, as the ionization equations are highly sensitive to errors in the electric field across the gap [6]. Other approaches are given in [7].

Most ESD testing is done in contact mode. As the discharge is initiated by a relay and as the impedances as seen from the relay contacts are neither known, nor easy to measure, a different simulation approach needs to be used.

It is not a straightforward task to simulate contact mode discharge, although the system can be regarded as linear (provided the relay switches more or less like an ideal switch). In contact mode a capacitor and some elements of the simulator are pre-charged. To initiate the discharge a relay is closed.

This paper numerically simulates the discharge current of a modified commercial simulator in contact mode and shows how design changes influence the discharge current.

ESD simulator and the discharge pulse waveform.

ESD generators try to reproduce the discharge stress of a typical human-metal ESD. Historically, a peak value of 3.75 A/kV and 0.7-1ns rise time have been defined as a typical human-metal ESD. Analyzing data from measured human-metal ESD at 5 kV shows that discharges having 0.8 mm arc length will be close to the peak current and rise time values defined as typical. This allows defining the total waveform. A reference waveform has been chosen that approximates 5 kV, 0.8 mm arc length human-metal ESD. The reference waveform is given by:

This reference waveform is still under discussion (May 2002). Presently it has been set to:

$$i(t) = \frac{i_1}{k_1}\cdot\frac{\left(\frac{t}{\tau_1}\right)^n}{1+\left(\frac{t}{\tau_1}\right)^n}\cdot\exp\left(\frac{-t}{\tau_2}\right) + \frac{i_2}{k_2}\cdot\frac{\left(\frac{t}{\tau_3}\right)^n}{1+\left(\frac{t}{\tau_3}\right)^n}\cdot\exp\left(\frac{-t}{\tau_4}\right)$$

with the following constants

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$$k_1 = \exp\left(-\frac{\tau_1}{\tau_2}\left(\frac{n\tau_2}{\tau_1}\right)^{1/n}\right)$$

$$k2 = \exp\left(-\frac{\tau_3}{\tau_4}\left(\frac{n\tau_4}{\tau_3}\right)^{1/n}\right)$$

And the following parameter values

I_1 = 21.9 Amp	T1 = 1.3 ns	T3 = 6 ns	N = 3
I_2 = 10.1 Amp	T2 = 1.7 ns	T4 = 58 ns	

In contrast to double or quadruple exponential waveforms this waveform provides a physical current derivative: The current rises smoothly after t=0.

A comparison of the reference waveform and human-metal ESD at 5 kV and 0.8 mm arc length is shown in figure 1. Note that due to the size of the human volunteer his total capacitance was only about 100 pF.

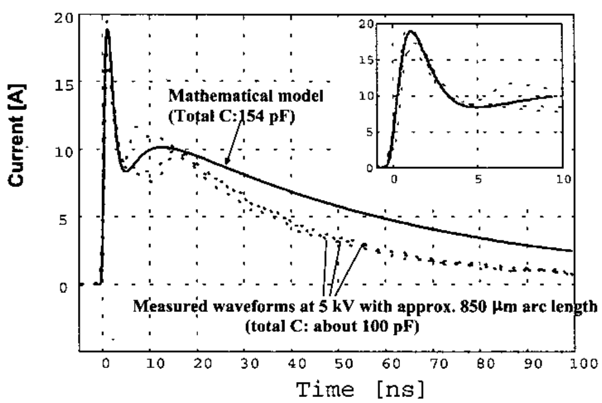

Figure 1: Reference waveform compared to measured human-metal ESD waveforms.

In figure 1, the measured waveforms have been selected from the set of 20 waveforms such that their rise time is between 0.7 ns and 1 ns. The reference waveform parameters have been set such that the waveform is similar to the human-metal ESD. The total injected charge equals a capacitance of about 154 pF. This value was chosen for consistency with the present IEC 61000-4-2 standard. Such a discharge is typical for moderate humidity and typical speed of approaches at 5 kV.

We selected a modified commercial ESD simulator to verify our numerical modeling techniques. The simulator had been modified such that its discharge waveform is similar to the reference waveform.

Figure 2 depicts the modified ESD simulator. The newly designed discharge head is composed of the discharge tip, a pulse forming filter, a high voltage relay, two copper rings and a 330 Ohms resistor and a 110 pF capacitor.

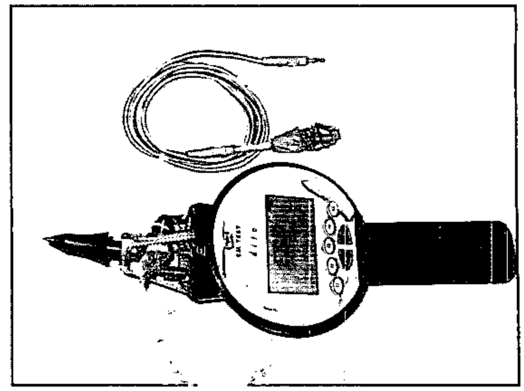

Figure 2: ESD simulator with modified discharge head

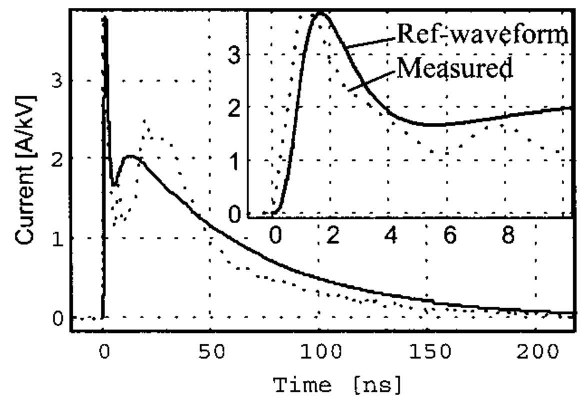

Figure 3: Comparison of the reference waveform with the measured discharge current of the modified simulator

The measured discharge current of the modified ESD simulator and the reference waveform are shown in Figure 3. An equivalent circuit of the simulator is shown in Figure 4. Although it does not allow predicting the current in detail, it aids in understanding the main physical processes.

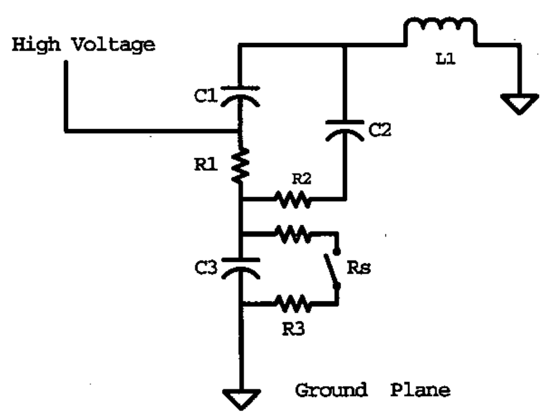

Figure 4: An equivalent circuit of the simulator

Its components can be grouped into 3 groups. Each group is associated with one part of the discharge waveform. The value of each component is shown in Table1.

Table 1: The component value in the equivalent circuit

	Component	Value	Function
Group 1	C3	10 pF	Pulse forming filter.
	R3	36 Ohms	
Group 2	C2	A few pF	Influences the width of the initial pulse
	R2	120 Ohms	
Group 3	C1	110 pF	Determines the tail of the waveform. L1 is associated with the ground strap loop.
	R1	330 ohms	
	L1		

Group 1 determines the rise time. Group 2 is associated with the outer metal structure of the discharge head. It helps increase the pulse width of the initial pulse. Group 3 is composed of lumped elements (a 110 pF capacitor and a 330 Ohms resistor). It is associated with long time decay term in the discharge waveform.

FDTD model of the ESD simulator

FDTD method is used in the modeling, although other approaches have shown to be successful [5]. The advantage this approach over the work presented in [5] is that it can predict currents and does not need currents measured at the discharge point to obtain the current in the relay and from there on, the structural currents and the fields. As disadvantage the need for gridding the complete domain needs to be mentioned. For reasons of calculation time there is a lower limit in the amount of detail that can be modeled.

An internal FDTD software package of University of Missouri-Rolla, EZ-FDTD is used. The model of the FDTD reflects the physical geometry the simulator. The structure of ESD simulator (including the relay, pulse forming filter, ground strap and other main parts) is modeled The cell size in FDTD is 3mm and the domain size is 184cm x 24cm x 64 cm. PML boundary conditions are utilized.

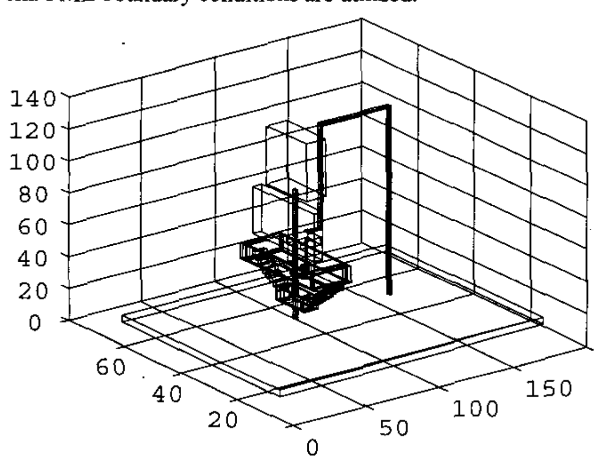

Figure 5: 3D view of the simulator model having a short ground strap.

The 3D view and cross section diagram of the discharge head are depicted in figure 5 and figure 6.

For modeling the resistor, a conductivity is assigned to a cell. The 110 pF capacitor is modeled the same way. As the large permittivity is only assigned to a single cell, no violation of the time stepping criteria will occur. Group 2 is not shown in this diagram.

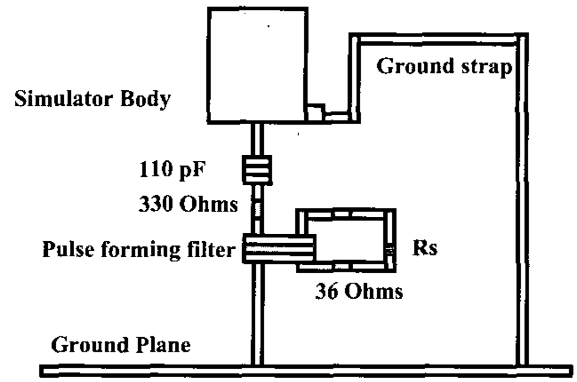

Figure 6: Cross section diagram of the discharge head.

Simulation procedure.

The property time dependent material is introduced into the FDTD code. The EZ-FDTD code is modified such that the material parameters are a function of time. In this way, we can charge the simulator. The system is given some time to stabilize before the discharge is initiated by increasing the conductivity within the relay sown in figure 5. The flowchart of the algorithm is shown in figure 7.

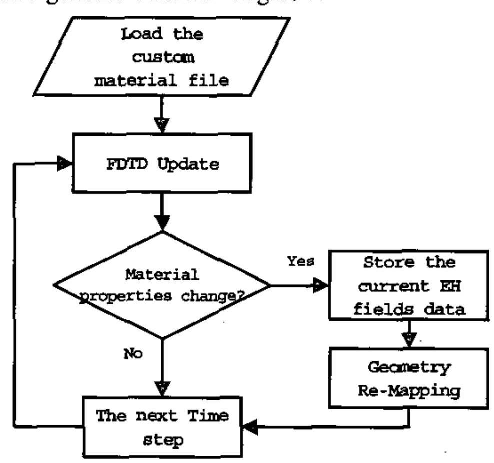

Figure 7: Flow chart of the EZ-FDTD

There are three phases in the simulation. First the 110 pF capacitor is charged to the discharge voltage level. Then the simulator needs some time for stabilization. If the remaining currents in the structure have decreased to about 5 % of the peak discharge value the system is considered to be sufficiently close to the electrostatic solution. The discharge can begin. The conductivity of the switch in the high voltage relay is set to infinite. The discharge phase begins.

Simulation Result

At first, a short ground strap was used. This allows reducing the domain size. In addition, the simulator was hold by Styrofoam during the measurements to avoid influencing the waveform by the human that holds the simulator. The human reduces oscillations as it introduces losses for currents that flow on the structural elements of the simulator.

First, simulation result of the short ground strap model is compared with the measured data in figure 9.

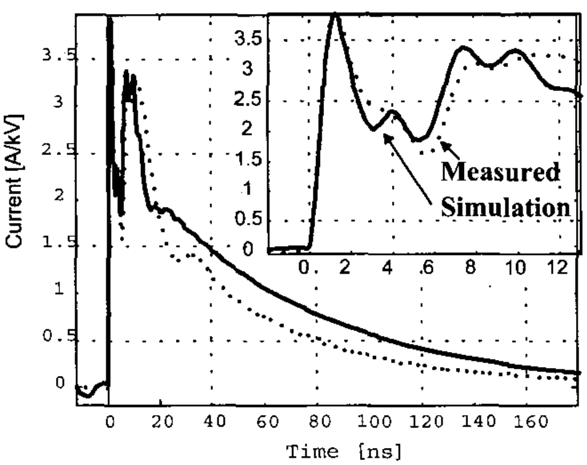

Figure 9: Comparison of discharge currents, simulation result with the measured data

The simulator is operated in contact mode with short ground strap (70cm). The discharge current is normalized to 1KV charge voltage. We use the HP Infinium oscilloscope (1.5 GHz, 8 GS/sec) in the measurement. The result of the simulation is compared with the measured data in table 2. It is low-pass filtered using 2 nd order 1.5 GHz filtering to compare under conditions similar to the measurements.

Table 2: Comparison of the results

	Measured data	Simulation
Rise time	0.8 ns	0.8 ns
1st peak current	3.85 A/KV	3.94 A/KV
2nd peak time	10.5 ns	10 ns
2nd peak current	3.28 A/KV	3.35 A/KV

The spectrum is also compared in figure 10.

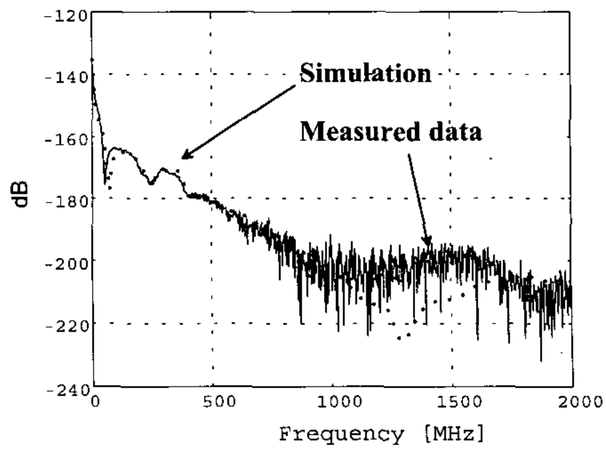

Figure 10: Discharge current spectrum comparison

Due to the grid size, the numerical model only approximates the physical geometry. By slightly modifying the geometry, quite similar rise times and the peak were obtained. The measured current decays faster than the simulated. It was found later that the 110 pF capacitor was set to be about 130 pF in the simulation. The spectral densities of the current are also quite similar, but it needs to be noted that the dynamic range limit of the oscilloscope starts to dominate the measured data above 500 MHz.

The simulation result of the long ground strap is also compared with the measurement in the figure 11 and figure 12.

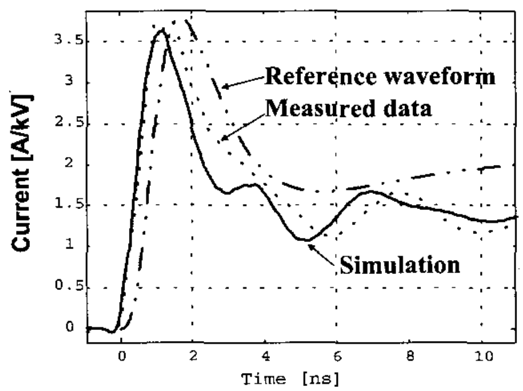

Figure 11: Discharge current, the first 10 ns

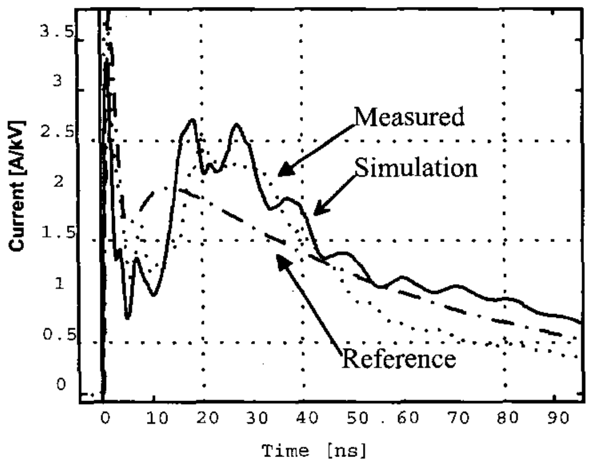

Figure 12: Comparison of discharge currents, simulation result, measured result and the reference form.

As shown in figure 11 and 12, the simulation result agrees with the measured data in the initial pulse peak value, the rise time of the pulse and the second pulse peak value. The discharge pulse in the first 10 ns of the long ground strap setup is compared with the measured data in Figure 11.

Figure 11 shows the discharge current waveform for the first 10 ns. The similarity of the simulation result with the measured data indicates that the model of the discharge head is in general correct. Ground strap current and transient E and H field were also simulated.

Design choice study in building the simulator.

There is a large range of possible design choices for ESD simulators:

1. Rise-time forming can be done either very close to the relay or at the tip. Even if both yield the same discharge current, it is to be expected that the fields differ. If the filtering is done very close to the relay, there will be less very fast rising field components (less than 0.7 ns rise-time) as the very fast rising current is confined to the small space within the relay.
2. The ground strap can be somewhat decoupled from all other parts of the simulator, e.g., by the 330 Ohms resistor. Or parts of the internal structure can be directly connected to some metallic parts inside (local "ground") while they are connected to the capacitor via a 330 Ohms resistor. It is to expect that this design choice influence the amount of "initial peak" current on the ground strap. Any current of the "initial peak" on the ground strap is not desired, as the ground strap is only there to return the discharge current of the lumped capacitor. The ground strap should only carry the "body wave", not the "initial peak" current.
3. Most ESD simulators contain electronics. They may be on HV-potential, i.e., contributing to the distributed capacitance or on a local "ground", connected to the ground strap.
4. The ESD simulator discharge head has a build-in metal cover. This metal cover help to store more energy in the discharge header. It increases the initial current peak value and increases the fall-time of the initial current. We used a double-copper ring structure in the discharge head to investigate its effect. The double-copper ring structure is depicted in Figure 13. The measured data and the simulation result are compared in figure 14.
5. There are no restrictions on the size of an ESD simulator. While it may be possible to realize the correct discharge current using a very small ESD simulator it is to expect that the fields will be fundamentally different.

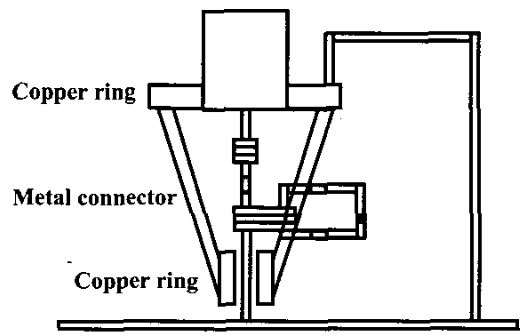

Figure 13: The double-copper ring structure. Both copper rings are connected to the high voltage side of the pulse forming capacitor. Thus they form a capacitance to the body of the simulator (it is on local ground via the ground strap) and they form a capacitor to the ground plane.

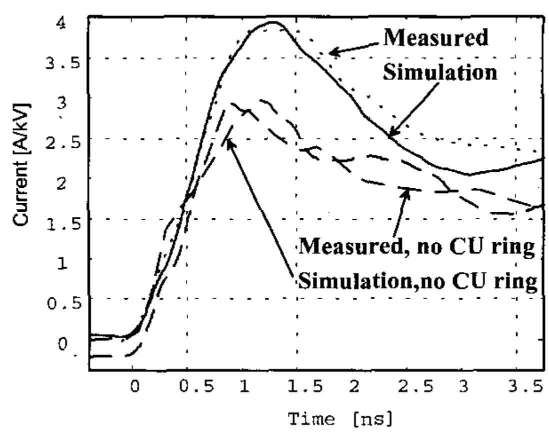

Figure 14: Simulator design choices comparison, Simulator with copper-ring structure compared with that without copper ring.

As shown in figure 14, the copper ring structure helps to store energy in the discharge head, the simulation without the copper ring structure has the same initial current peak value and the same width of the pulse compared with the measurement.

Conclusion

An ESD generator was numerically investigated. Time parameters dependent materials were introduced into the FDTD code. Conductivity of certain material is changed to simulate the relay function. Discharge current and fields are simulated and compared with the measured result.

The simulator is modeled in as much detail as possible according to its dimension and the inner structure. The simulation shows that the model can simulate the discharge current correctly. It can be used to predict the effect of design changes on the current and fields. This is especially handy for the fields and the ground strap current, as their measurement is somewhat tricky.

Future work is implementing the model on FDTD using none-uniform grid and investigating numerical convergence and the effect of boundary conditions in larger detail.

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