Numerical Modeling of ESD Events Including Both Charging and Discharging Processes with FDTD-SPICE Direct Linking Solver

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Abstract—This paper presents numerical modeling of electrostatic discharge (ESD) events with a FDTD-SPICE direct linking solver, which simultaneously solves a full-wave model for structures of analytical objects and SPICE equivalent circuit models including nonlinear lumped elements based on spark resistance formulae. This work focuses on treatment of transition from charging to discharging processes of an ESD in the FDTD-SPICE direct linking solver. A system consisting of full-wave and circuit models to deal with the transition is proposed. An application example of air-discharge occurred in two metal spheres is demonstrated. Our approach is compared with a specialized FDTD solver based on the Rompe-Weizel spark resistance formula.

Keywords—electrostatic discharge(ESD); air discharge; FDTD; SPICE; direct linking method; fullwave simulation

I. INTRODUCTION

Electrostatic discharge (ESD) events are one of the most important issues [1] to be considered in recent designs of electronic equipment. Accurate understanding of transient electromagnetic (EM) fields caused by ESD has precise prediction of ESD-induced noise currents are required in order to improve the ESD immunity of an electronic system. Up to now, the following three numerical approaches were proposed for the simulation of EM fields caused by an ESD:

- Equivalent circuit analysis [2]
- Full-wave analysis [3]-[9]
- Sequential linking analysis [13]

The equivalent circuit analysis [2] is performed by Simulation Program with Integrated Circuit Emphasis (SPICE). In this analysis, discharge current is calculated from an equivalent circuit of discharging objects combined with a nonlinear spark model, and transient EM fields in far region are then estimated by using a current dipole model having the obtained discharge current as a source. The conventional finite-difference time-domain (FDTD) method [10] has been successfully applied to full-wave simulations of an ESD generator in the contact-discharge mode [3]-[6] and also to system-level contact-mode ESD simulations [7]. Full-wave schemes [8],[9] specialized for the Rompe-Weizel nonlinear spark resistance formula [11] were presented for transient analysis of EM fields due to air-discharge ESD. However, pure full-wave scheme specialized for other resistance formulae (e.g. Toepler’s formula [12]) is not yet published. Recently, a sequential linking analysis [13] was presented using both full-wave and circuit models as an extension of the equivalent circuit approach [2]. Although full-wave simulations of air-discharge mode of the ESD generator discharging into a small product are demonstrated in [13], this approach requires complicated procedures: extraction of impedance at the position of a spark channel placed in a full-wave model, reimport of discharge current obtained in SPICE simulation and so on.

In order to overcome the drawbacks of the existing approaches mentioned above, we have been working on the development of the ESD-induced EM field analysis based on a FDTD-SPICE direct linking method [10],[14]. This method has several advantages in the ESD analysis [15]: accurate modeling of arbitrary structures, flexible treatment of various spark resistance equations such as Rompe-Weizel’s and Toepler’s formulae and no extraction of impedance for the full-wave model. In [15] we have applied it into some canonical air-discharge ESD problems of simple metallic objects such as spheres and spheroids. Very good agreements of this direct linking method with the existing approaches have been demonstrated. However, treatment of charging and discharging processes in the method are not in detail described in [15].

The main purpose of this paper is to describe treatment of charging and discharging processes in our approach for the simulation of transient EM fields caused by air-discharge.

II. METHODOLOGY

In order to describe the dynamics of EM fields caused by air-discharge, an analytical model is separated into three models: a linear full-wave model including the ESD generator and the electronic equipment (e.g., printed circuit board with passive circuit elements and the enclosure parts), a nonlinear spark model and an complicated circuit model of nonlinear lumped network such as varistor and the LSI circuit. A FDTD-based full-wave solver computes the linear full-wave model and a SPICE-like solver calculates complicated or nonlinear circuit elements. The nonlinear spark model is then expressed.
as an equivalent circuit within the SPICE netlist. All of the above models can be simultaneously simulated in time domain using the FDTD-SPICE direct linking method [14]. The used scheme is briefly introduced here.

In this work, most of the simulation results are obtained with Fujitsu’s commercial software Poynting for Microwave [16] including a solver based on the FDTD-SPICE direct linking method.

A. FDTD-SPICE Direct Linking Method

A numerical scheme of the FDTD-SPICE direct linking method is illustrated in Fig.1. The two-terminal port of an embedded circuit model is allocated on the edge (length Δz) of a single Yee cell in the discrete space as shown in the left-upper side of Fig.1. In the standard leapfrog scheme, the electric and magnetic field components (E, H) are computed alternately at every half time step on the time axis. One cycle procedure from magnetic field updating to electric field updating is explained below.

In this work, coupling of SPICE with FDTD is based on the use of the integral form of Ampere’s law as follows:

$$\frac{\partial}{\partial t} \int \mathbf{E} \cdot dA + \int \mathbf{J}(\mathbf{E}) \cdot dA = \int \mathbf{H} \cdot d\Gamma$$  \hspace{1cm} (1)

where the contour $d\Gamma$ bounds the cross section $A$ of the cell where the port is embedded. In order to solve (1) in a SPICE solver, (1) can be rewritten in a simpler description as

$$C_0 \frac{\partial V}{\partial t} + I(V) = I_N,$$  \hspace{1cm} (2)

where $C_0 = A/\Delta z$ is the so-called FDTD cell capacitance, $V$ is the voltage calculated from the line integral of $E$ on the cell edge, the second term $I(V)$ in the left-hand side of (2) represents the current flowing through the embedded circuit model and the right-hand side can be calculated from

$$I_N(t) = \int \mathbf{H} \cdot d\Gamma.$$  

Note that (2) can be illustrated as in the left-lower side of Fig.1 and the entire circuit model can be solved by the SPICE.

The numerical procedure is summarized in the following:
First, all magnetic field components in the computational domain are calculated using the conventional FDTD scheme. Then, the current $I_N(t)$ flowing on the objective circuit model is calculated from the four adjacent magnetic field components which loop around the electric field component $E$ on the edge. The FDTD-calculated current $I_N(t)$ is set up as a current source connecting with the cell capacitance and the circuit model. Next, a circuit simulation is performed and the electric field value $E$ allocated on the cell edge is calculated from the obtained terminal voltage $V$ divided by the edge length $\Delta z$. Finally, all other components of electric field in the domain are calculated according to the conventional FDTD scheme.

B. Modelling of Spark Channel

In order to avoid the detailed analysis of the physical process of air-discharge and to characterize the relation between discharge voltage and current, the spark channel is modelled by nonlinear time-varying resistor. This can be regarded as a phenomenological model.

Many spark resistance formulae derived theoretically or experimentally have been proposed [17]. For example, Toeppler’s (TP) and Rompe-Weizel’s (RW) formulae for the spark resistance are often used in a lot of numerical modelling [8]-[9],[13] and experimental studies [18]-[20] of ESD events. The Rompe-Weizel’s formula is expressed as follows:

$$r_{RW}(t) = \frac{l}{\sqrt{(2\alpha R/p) \int_{-\infty}^{t} i^2(v)dv}},$$  \hspace{1cm} (3)

where $r(t)$ is the spark resistance at time $t$, $l$ is the spark length, $\alpha_R$ is a parameter derived from basic ionization processes, $i$ is the spark current and $p$ is the gas pressure. The Toeppler’s formula is expressed as

$$r_{TP}(t) = \frac{K_T l}{\int_{-\infty}^{t} i^2(v)dv},$$  \hspace{1cm} (4)

where $K_T$ is the Toeppler’s constant.

Note that (3) and (4) can be properly expressed as an equivalent lumped element consisting of voltage-controlled current source, integrator, current-controlled current source and

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**Fig. 1.** FDTD−SPICE direct linking method

**Fig. 2.** Overview of a system of full-wave and circuit models for transition from charging to discharging processes
so on. Therefore, for full-wave simulation of transient EM fields caused by air-discharge, the FDTD-SPICE direct linking method allows us to treat many kinds of spark resistance formulae as equivalent circuits. In [15], we have demonstrated application examples of (3) and (4) with the direct linking method.

The applicability of our approach can be at least limited by the validity of a spark resistance formula used in a considered EM problem because of the phenomenological treatment of spark channel. Since the spark resistance formulas are usually derived from specific test conditions and physical assumptions of spark, it may be a limiting factor for our approach. For example, as reported in [17], the RW formula (3) was tested under the condition \( l \leq 0.035 \text{m} \). If the validity of each resistance formula is unclear for a problem of interest, it will have to be verified as in [20].

C. Charging and Discharging Processes

After setting up the linear and nonlinear models, we can run a time domain simulation of the ESD-induced EM field due to air-discharge. In our approach, the time domain simulation is separated into charging and discharging processes. The aim of the charging process is to know the electrostatic field distribution in the computational domain as initial condition [8,9] of discharging process. Fig.2 shows an overview for a system of full-wave and circuit models for simulating transition from the charging to discharging processes. First, the full-wave model is slowly charged by a current pulse \( (I_{\text{charge}}) \) in the charging process. Next, after the charging is stopped, the transition from the charging to the discharging process is made by a switching element (SW). Finally, the discharging process is computed as the main part of this simulation.

III. NUMERICAL EXAMPLES

In order to validate our simulation model for the transition as in Fig.2, we show an application example for air-discharge ESD. Our approach is compared with an FDTD scheme [8] specialized for the Rompe-Weizel spark resistance formula (3). Note that a spark channel with the same physical properties as (3) is treated with the two different numerical approaches.

Here we consider the air-discharge occurred in two metal spheres of perfect conductor as shown in the right side of Fig.3. A spark channel \( (l=2 \text{ mm}, \Delta x=1.1 \times 10^{-7} \text{ atm} \cdot \text{m}^2/\text{V}^2, p=1 \text{ atm}) \) is built between the two metal spheres of radius \( R=25 \text{ mm} \). The FDTD computational region is discretized with \( 350 \times 200 \times 201 \) cubic cells of \( \Delta x=\Delta y=\Delta z=2 \text{ mm} \). The time step size \( \Delta t \) is 3.774633 ps. The perfectly matched layer absorbing boundary condition (with 16 layers) is used for simulating an open scattering problem. In this model, a system of two metal spheres is charged by a Gaussian pulse with about 6ns width. The discharging process starts at 10ns.

Fig.3 shows several numerical results for spark voltage, current and magnetic fields. We can find very good agreement between the voltages and the currents computed with our approach and the specialized FDTD over both charging and discharging processes in Fig.3 (a) and (b). Moreover, in the discharging process the spark current itself and its electromagnetic interaction with two metal spheres generates rapidly varying electromagnetic fields. So we compare results of transient magnetic field at two observation points of near and far distances from the spheres. In Fig.3 (c) and (d), we can see good agreement between our approach and the specialized FDTD method.

IV. CONCLUSION

Numerical modeling of ESD events including both charging and discharging processes with the FDTD-SPICE direct linking solver has been presented. In order to deal with transition from charging and discharging process in the direct linking solver, a system consisting of full-wave and circuit models coupled with a switching element has been proposed. The presented approach has been compared with the specialized FDTD one in a simplified model consisting of two metal spheres. Good agreements between numerical results computed with the two different solvers have been obtained over both charging and discharging processes.

REFERENCES


Fig. 3. Comparison of two different methods for computed results of air-discharge ESD event with transition from charging to discharging processes for two metal spheres.

EMC’14/Tokyo
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