# Coupling into 3D interconnection structures with nonlinear loads – an application of the method of partial elements

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## ABSTRACT

The partial element equivalent circuit (PEEC) method is a suitable tool for analysis of interconnection systems with non-linear loads in the time and frequency domain. The paper studies the application of the PEEC method to calculation of currents and voltages in an interconnection structure being exited by a lumped voltage source or by an external electromagnetic field. The influence of the non-linear load at transients is discussed. The results obtained in the frequency domain are compared with the method of moments (MoM).

## INTRODUCTION

Passive interconnection structures gain an increasing importance on both the functional design and the EMC analysis of electronic components and systems. Main reasons for this are increasing operational frequencies, high changing rates of currents and voltages, high packaging densities of electronic devices and components, and an enormously increasing density of electromagnetic noise sources. Quite often the interconnection structures are loaded with nonlinear elements. From the point of view of EMC, tools for analyzing interconnection structures should take into account 3D geometrical structures, radiation effects, skin effect, incident field excitation and nonlinear loads.

The conventional transmission line theory [1] with its assumptions allows to create very effective numerical procedures on the basis of the Bergeron method or the method of equivalent circuits [2], however, the disadvantage is the limitation to 2D field problems (quasi TEM mode) and as consequence the inability to treat radiation effects. Therefore, there are many works about the extension of the transmission line theory and different approaches on the basis of the electric field integral equation (EFIE).

One of them was presented in [3]. There the EFIE was transformed into telegrapher-like equations with additional terms considering the radiation phenomenon. This method has all advantages of transmission line models and allows to consider the losses for radiation, but only for a limited frequency range. If the characteristic wavelength of the incident field is comparable with the size of the interconnection system, the approach shows bad results.

Another method is created in [4]. The Maxwell equations are transformed into a form of generalized telegrapher equations looking like ordinary telegrapher equations with parameters dependent on frequency and coordinates. Thus, a full-wave model of a non-uniform 3D interconnection system is invented.

The method of moments (MoM) and the singularity expansion method [1] give the opportunity for creating full-wave models for interconnection structures in the frequency and the time domain.

The partial element equivalent circuit method developed by A. Ruehli [5] is a fitting tool for modeling and analyzing problems mentioned above. It is a numerical method based on the EFIE and using the Galerkin method that permits the development of 3D-full-wave models of interconnection structures in both the frequency and the time domain. A program for wire system simulation with distributed or lumped excitation in the time and the frequency domain is created using the wide spread program code SPICE in a modified version for treating PEEC models [6].

The possibilities of the PEEC method are shown by the example taken from the benchmark catalogue for EMC problems of the German IEEE EMC Chapter [7] in particular and also modified by a non-linear load.

## FUNDAMENTALS OF THE PEEC METHOD

The fundamental idea of the PEEC method is the discretization of conductors in volume and surface cells (fig. 1) in one, two or three dimensions. After interpretation of each equation, obtained from the Galerkin method like Kirchoff's voltage law and of each discretized continuity equation like Kirchoff's current law, we get the PEEC circuit (fig. 2) and the equations for the calculation of the partial elements (resistances, inductances, potential coefficients)

$$L_{km} = \frac{\mu_0}{4\pi a_k a_m}\cos\varphi_{km}\int\limits_{a_k}\int\limits_{a'_m}\int\limits_{l_k}\int\limits_{l'_m}\frac{da_k\,da'_m\,dl_k\cdot dl'_m}{\left|\vec{r}-\vec{r}\,'\right|}\qquad p_{ki} = \frac{1}{4\pi S_i S_k \varepsilon_0}\int\limits_{S_k}\int\limits_{S'_i}\frac{dS_k\,dS'_i}{\left|\vec{r}-\vec{r}\,'\right|} \qquad (1)$$

where $L_{km}$ is a partial inductance between volume cells $k$ and $m$, $p_{ki}$ is potential coefficient between surface cells $k$ and $i$,

$\cos\varphi_{km} = \vec{e}_k \cdot \vec{e}_m$, where $\vec{e}_k, \vec{e}_m$ are unit vectors of the cell directions, $a_k$ and $a_m$ are cross-section areas of cells, $S_i$ and $S_j$ are surface areas, $l_k$, $l_k$ are cell lengths.

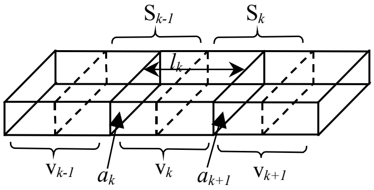

Fig. 1 Volume and surface cells of the conductor discretization.

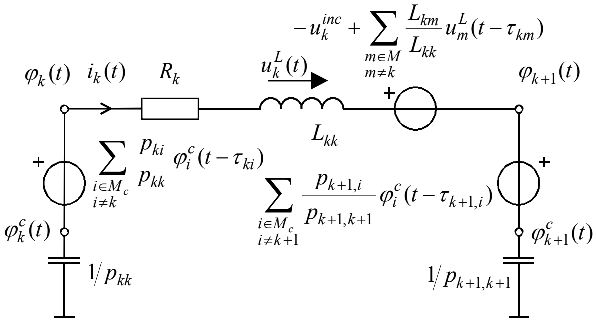

Fig. 2 Equivalent circuit model of the cell

The electromagnetic interaction between the cells is modeled by controlled voltage sources including the retardation of signals in the case of full-wave models. In fig. 2, $M_L$ is the set of all volume cells and $M_c$ is the set of all surface cells, $d_{km}$ is the mean distance between cells. Transients in the PEEC can be calculated by circuit simulation codes. In particular the inclusion of nonlinear loads is possible in the time domain.

There are two steps to solve the problem. The first one is the discretization of the structure. The maximal length of PEEC cells can be approximately chosen on the basis of the minimal leading edge of the exiting pulse as $l_k \le \tau_e/(10\cdot c)$, where $c$ is the light speed in the free space and $\tau_e$ is the minimal leading edge time. Further, the parameters of the PEEC model are to be defined. The second step is the calculation of currents and voltages of the created PEEC model in the time or frequency domain by a circuit simulator. The SPICE program is modified for this aim. The PEEC model of an arbitrary three-dimensional wire structure is included there.

## RESULTS

As an example of an interconnection system a monopole antenna situated close to a transmission line over a perfectly conducting ground is investigated (fig. 3). All wires are lossless. This is a modified task from the benchmark catalogue for EMC problems of the German IEEE EMC- Chapter [7]. The first calculation was realized in the frequency domain with the assumption that the antenna is exited by a lumped sinusoidal voltage source with magnitude $\hat{V}^{src} = \sqrt{2}$ V at all frequencies. The transmission line is loaded with the resistor $R$=1kΩ. All currents in the interconnection system were calculated by the PEEC method and the Method of Moments. The magnitude of the load current $I_3$ in the frequency range from 1 MHz up to 30 MHz is presented in fig. 4. The results obtained by both methods show a good agreement over the whole frequency range. Because the coupling from antenna to the transmission line causes the current $I_3$, the agreement of the obtained results allows to conclude that the PEEC method has the same precision as the MoM for modeling in the frequency domain.

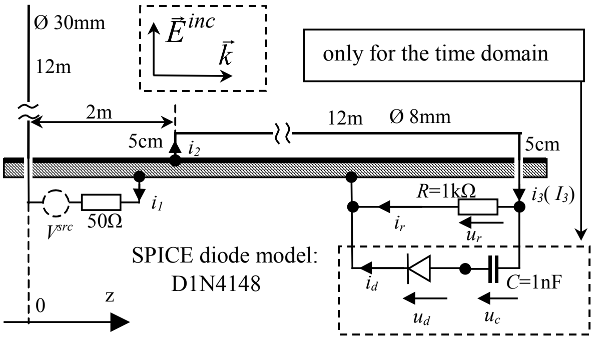

Fig. 3. Interconnection system geometry

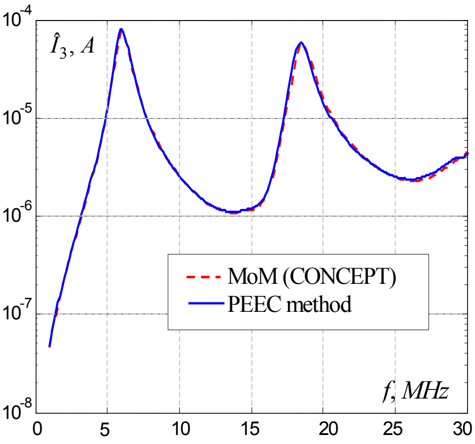

Fig. 4. The magnitude of the load current calculated in the frequency domain

The PEEC method is applicable for transient simulation in interconnection systems with nonlinear loads. Let us consider a coupling from the antenna to the transmission line if the antenna is exited by a 6 MHz sinusoidal switched on source and the line is loaded by an additional branch with diode (fig. 3). The SPICE model of the commercial diode D1N4148 is used. The voltages and currents in the transmission line coupled in from the antenna are calculated by the PEEC method in the time domain. The resistor and capacitor voltages are shown in fig. 5 together with the resistor voltage calculated without the diode branch. The capacitor voltage looks like stairs because of the series connection with the diode. It is the characteristic capacitor charging in this case. The voltage on the resistor has usual distortions caused by the diode and no distortion without diode.

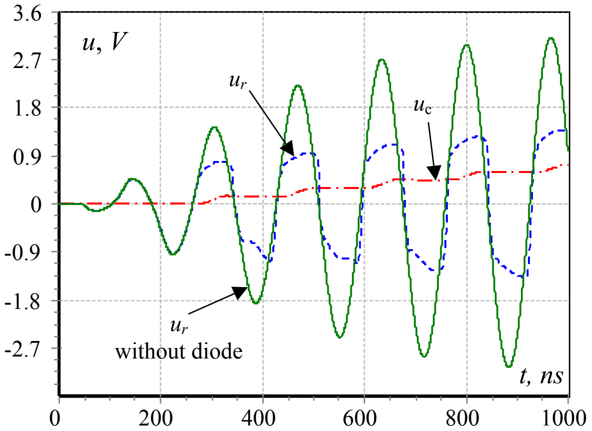

Fig. 5. Voltages on the load of the wire system exited by a lumped source

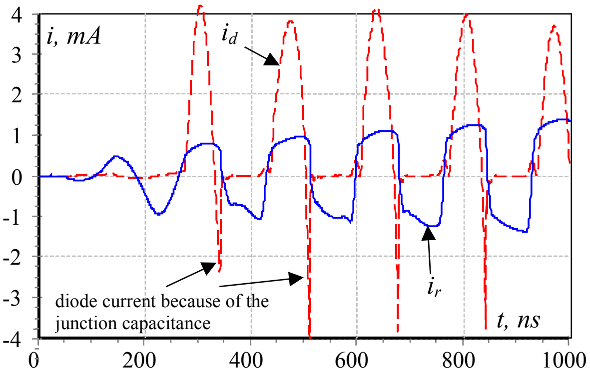

Fig. 6. The current of the diode in the case of a lumped source excitation.

The curve of the diode current presented in fig.6 has a characteristic shape. There is only a little diode current in the first 250 ns because the diode voltage is much less than the junction potential. The diode first time opens at about 250 ns when the voltage at the resistor increases over the forward voltage of the diode. Then, when the diode is closing there is a negative diode current for a short time because of the diode junction capacitance taken into account in the diode model.

In the following we investigated the interconnection system in fig. 3 for an excitation by an external pulse field. In this example the voltage source $V^{src}$ is equal to zero and the wire system is under influence of a plane wave moving horizontally parallel with the transmission line. The electromagnetic wave is vertically polarized as it is shown in fig. 3. The amplitude of the electric field intensity is the following surge function $\hat{E}^{inc} = 1 \cdot (e^{-t/\tau_1} - e^{-t/\tau_2})$ kV/m, where $\tau_1$=30ns and $\tau_2$=25ns.

In the example considered the pulse incident field is modeled by pulse voltage sources (see $u_k^{inc}$ in fig. 2) in each PEEC cell of the vertical elements of the wire structure. The plane wave starts to travel at time 0 ns from the point $z$=-0.5m (see fig. 3).

The voltages (fig. 7) and currents (fig. 8) in the load elements are calculated by the PEEC method.

The external plane wave reaches the left vertical element of the transmission line when the time is about 8 ns. Further the external wave travels along the line to the right load with diode. A current is induced in the left vertical element of the transmission line. It can be traced as the load current $i_2$ in fig. 8. The current and voltage waves travel from the left end of the transmission line to the right one. The speed of traveling is equal the light speed in the free space because the wires are lossless. The external plane wave reaches the right end at the same time as the wave traveling from the left end of the transmission line. Both waves produce currents of opposite directions in the right load. The superposition of both effects causes the load voltage and current, when the time is about 45-50 ns.

When the diode voltage becomes high enough for its opening (see fig. 7) the capacitor begins charging through the diode. Then, the diode closes and a negative peak in the diode current at about 150 ns (see fig. 8) occurs for a short time. This phenomenon can be good explained with discharging of the capacitor C through the junction capacitance of the diode. The junction capacitance of the diode is assumed $C_j$=2pF in the SPICE model. There is a weak decreasing of $u_c$ in fig. 7.

The presented results demonstrate that PEEC models for interconnection structures validated in the frequency domain (e.g. by MoM) are suitable for calculations in the time domain, also with nonlinear elements as loads. The physical reliability and evidence of the results obtained show the correctness of the model.

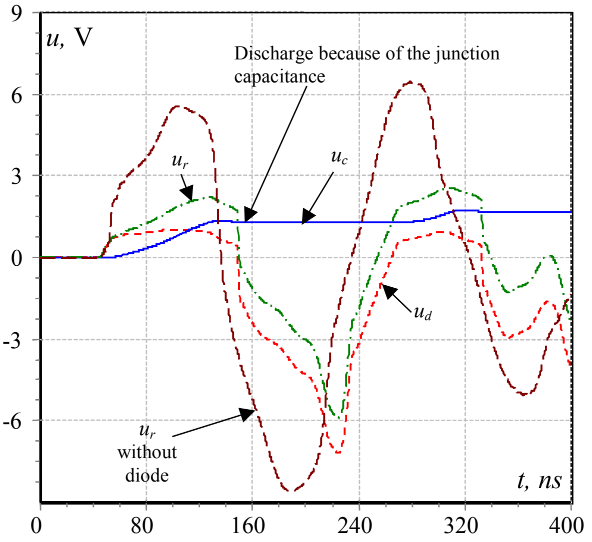

Fig. 7. Voltages on the load of the wire system exited by an incident field

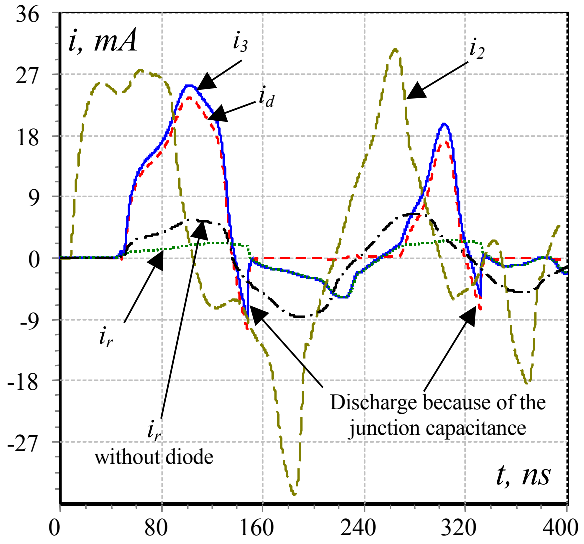

Fig. 8. Currents in loads of the wire system exited by an incident field

## CONCLUSION

The results obtained with PEEC in the frequency domain are compared with the MoM (CONCEPT code) solution as reference. They show a good agreement for the whole frequency range analyzed. It validates the correctness of the PEEC model for the interconnection system with linear loads. Further, the benchmark problem is modified by adding a nonlinear load, using the SPICE model of the commercial diode D1N4148. The modified problem was analyzed in the time domain under the influence of a switched on sinusoidal lumped source of 6 MHz at the antenna mounting and also under the influence of a pulse shaped incident field. The results obtained for both types of excitations are analyzed and discussed.

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