An Asynchronous Co-Simulation Method for Time-Dependent Simulations: Application to a Transmission Line Network

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Abstract

Numerical co-simulation methods are increasingly used to solve complex electromagnetic compatibility problems. For the time-dependent Maxwell-Equations, these approaches may exchange information and simulation results for each temporal iteration. In this paper, we propose an asynchronous temporal co-simulation method. The approach is illustrated on a transmission lines network. The results obtained are validated with the global simulation.

1. Introduction

Co-simulation allows solving a complex problem by breaking it into simpler sub-problems [1]. Generally, the most suitable numerical method is applied to each sub-domain. However, most existing methods are synchronous and share numerical models. For time-domain co-simulation methods, an exchange of results for each temporal iteration is required [2]. We propose in this paper an asynchronous co-simulation method based only on the impulse responses of the sub-domains. The simulations are time-independent and don't require any exchange of numerical models.

2. Formulation

We aim to find the solution to a global linear system after splitting it into sub-problems via one or more exchange interfaces. To demonstrate the principle of the proposed co-simulation method, we consider the transmission line network consisting of 5 uniform lossless lines and two junctions (Fig. 1).

V_s is a Gaussian pulse of amplitude 1V, and we want to evaluate the voltage V_3 across impedance Z_{L3}.

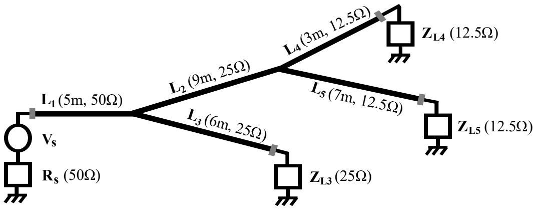

Figure 1: Lengths and characteristic impedances of the network's transmission lines

Based on the FDTD (Finite Difference Time Domain) method [3], the currents and voltages are obtained by solving the telegrapher's equations. In the following, we consider the same method (FDTD) in both sub-domains. However, the proposed approach is independent of the choice of the numerical model for sub-domains.

Let's suppose the global network is split at line L_2 into two sub-networks Y^k, each consisting of three tranmission lines $L_i^k \in \{1, 2, 3\}$ as shown in Fig.2.

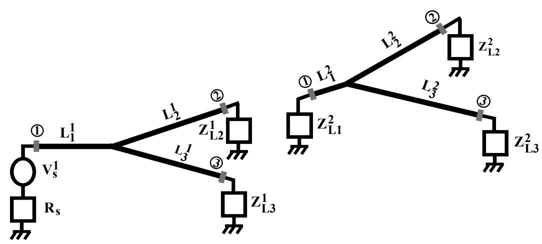

Figure 2: Sub-networks Y^1 and Y^2 after spliting the global network

For a given system, caracterised by its impulse reponse h, the product of convolution in equation (1) allows linking the output V_{out} to the input V_{in} .

$$V_{out} = h \otimes V_{in} \tag{1}$$

In the following, we consider the voltage V_{out} a (m+1)-dimensionnal discret vector evaluated for each discret time $t \in [0, m\Delta t]$, $(m \in \mathbb{N}^*)$, with Δt a discret time step which satisfies the CFL criteria.

The product of convolution in equation (1) is a matrix product, and the impulse reponse h is considered in its matrix form.

Let's define h_{ij}^k the impulse responses h_{ij}^k, for a sub-network Y^k, between the terminal points i and j.

For a sub-network k with p voltage sources V_{si}^k, q exchange interfaces and n terminations, the voltage at a measuring point j, V_j^k, is given by the following equation.

$$V_j^k = \sum_{\{i\}} h_{ij}^k \otimes V_{si}^k + \sum_{\{l\}} h_{lj}^k \otimes V_{\sim l}^k \tag{2}$$

With :

$\{i\} \subseteq \{1, ..., n\}$ a sub-set of p voltage indexes, $p \leqslant n$.

$\{l\} \subseteq \{1, ..., n\}$ a sub-set of q exchange interface indexes, $l \leqslant n$.

By applying the equation (2) to the example of Fig. 2 considering $k = 1$, $j = 3$, $i = 1$ and $l = 2$, we obtain the explicit equation (3).

$$\begin{aligned} V_3^1 &= h_{13}^1 \otimes V_{s1}^1 + h_{23}^1 \otimes V_{\sim 2}^1 \\ &= h_{13}^1 \otimes V_{s1}^1 + h_{23}^1 \otimes (h_{11}^2 \otimes (h_{12}^1 \otimes V_{s1}^1)) \end{aligned} \quad (3)$$

The equation (3) is composed of two terms, the first one translates the contribution of the real source V_{s1}^1 to the measured voltage V_3^1. While the second term, represents the contribution of the equivalent source at the exchange interface.

The term $h_{12}^1 \otimes V_{s1}^1$ represents the incoming voltage at the interface. The product of convolution of this term with h_{11}^2 is the response of the sub-network Y^2.

We compare in Fig. 3 the results obtained considering a unique simulation of the global network and the co-simulation method.

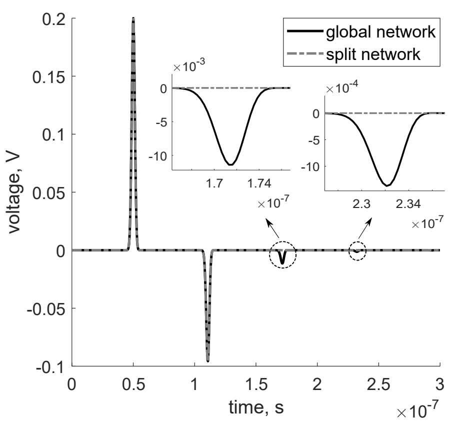

Figure 3: Voltage V_3^1 for a matched network

The first peak corresponds to the direct propagation of the Gaussian signal within lines L_1^1 and L_3^1. The second peak corresponds to the first reflection of the signal in the circuit due to the mismatch at the network's nodes.

For the first two peaks, both results overlapp and validate the equation (3).

However, the multiple Gaussian-pulse reflections along the network are not considered in the equation (3), hence the differences between the results shown in Fig. 3.

By adding an additionnal term to equation (3), we consider these multiple retro-actions between the two sub-networks. Equation (4) allows finding both contributions from each sub-network and their multiple round-trips to the q-th order.

$$V_3^1 = h_{13}^1 \otimes V_s^1 + h_{23}^1 \otimes V_{\sim 2}^1 + \sum_{i=2}^{q} h_{23}^1 \otimes (h_{11}^2 \otimes (h_{22}^1 \otimes V_{\sim 2,i}^1)) \quad (4)$$

$V_{\sim 2,i}^1$ is definied as the i-th order of the equivalent source, and is given by the equation (5).

$$V_{\sim 2,i}^1 = h_{11}^2 \otimes (h_{22}^1 \otimes V_{\sim 2,i-1}^1) \quad (5)$$

Let's consider a mismatched network at line L_2^2 loaded with $Z_{L2}^2 = 10^{10}\Omega$ (open circuit). By applying equation (5) for the order $q = 3$, the results obtained by the co-simulation method and the global simulation superpose, as shown in Fig. 4.

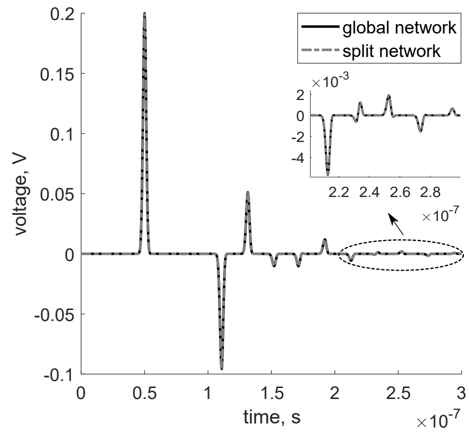

Figure 4: Voltage V_3^1 for a mismatched network

3. Conclusions

This paper presents a temporal co-simulation method applied to a transmission line network. The approach is based on evaluating impulse responses of each sub-domain and therefore preserves the confidentiality of the associated numerical models. Furthermore, the simulations are independent of time (asynchronous) and the choice of the temporal numerical method. The methodology's principle can be generalized for complex systems with multiple exchange interfaces. The proposed approach is general and can be applied for various applications: from low to high frequency, for 1D and 3D computational electromagnetics problems.

References

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