A FULLY INTEGRATED MULTICONDUCTOR MODEL FOR TLM

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Abstract – A fully integrated model of coupling between the electromagnetic field and multiconductor cabling is developed using the transmission line matrix (TLM) method. In this model, the multiconductor cables are represented by multiconductor transmission lines which connect to the general TLM mesh.

1 INTRODUCTION

Very often, particularly in electromagnetic compatibility studies, there is a need to model multiconductor cables which couple with the electromagnetic field. The main difficulty, as far as time-domain transmission line matrix (TLM) and finite-difference time-domain (FD-TD) are concerned, is that it can be prohibitively inefficient to model the fine detail of closely spaced conductors in a large volume of space such as the interior of an equipment cabinet or room. A common technique used to incorporate multiconductor cables into differential time-domain techniques is the so-called separated solution [1], in which the multiconductors are treated separately from the rest of the problem, allowing for field coupling to the wires by introducing equivalent sources derived from a knowledge of the incident field. Although this method is simple, it involves several restrictions, the most important being that any electromagnetic interaction of the wires with the rest of the structure must be negligibly small.

Recently, an integrated solution, allowing for two-way coupling between the field and single thin wires, has been introduced in TLM [2, 3]. Here, the propagation of signals along the wire is modelled by using special wire networks constructed by additional TLM link and stub lines which also model the excess of capacitance and inductance introduced by the wire presence. Such wire networks are interfaced with the ordinary three-dimensional condensed TLM nodes during the usual time-stepping procedure.

In this paper, we extend the TLM integrated thin wire model to allow for modelling of multiconductor cables. We choose to regard the multiconductor transmission lines used in the TLM model as *vector lines*, i.e. lines which carry a signal which is an n-*dimensional vector* rather than a scalar function of time. This terminology is concise and helps to distinguish the TLM multiconductor transmission lines from the multiconductor cables being modelled. We consider the possible network connections (shunt and series) between vector lines and between vector and scalar lines, before presenting the integrated TLM multiconductor cable model.

2 THEORY

A general multiconductor line consists of a number of parallel conductors of arbitrary cross-section but uniform in the third dimension. The state of an $n+1$ conductor line (carrying TEM or quasi-TEM modes only, and neglecting the common mode), can be specified by n voltages and n currents at each point along its length. It is convenient to assume that the n voltages chosen to specify the state of the line, are the voltages of n of the conductors, with respect to the $(n+1)$th (reference) conductor, while the currents are the currents on the same n conductors in the direction of propagation. These currents and voltages can be represented by two n component vectors; I and V, while the line can be characterized by per-unit-length capacitance and inductance matrices C and L [4].

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Following the approach used in the TLM model of thin single wire [2], we can assume that one part of the required per-unit-length capacitance and inductance of an n-conductor line is already modelled by the single column of TLM cells through which it passes. This can be accounted for in a TLM model by placing a fictitious cylinder sheath around the multiconductor line, which can be taken as the reference conductor, or $(n+1)$th conductor line. Its diameter is the effective diameter of a column of metal-filled TLM cells, which is, unfortunately, different for capacitance and inductance, with the 'capacitance shell' radius r_C being greater than the 'inductance shell' radius r_L [2]. Notice that common mode currents are, accounted for in this model – the body of the TLM mesh refers any distant return paths to the sheath, while including all the effects of intervening metal or dielectric structures and sources.

The basic parameters, therefore, needed for the TLM model, are C_d, the $n \times n$ distributed-capacitance matrix for the n-conductor cable placed inside the r_C radius reference conductor, and L_d, the $n \times n$ distributed-inductance matrix for the n-conductor cable placed inside the r_L radius reference conductor. Calculation of L_d and C_d requires solution of a two-dimensional electrostatic problem in the cross-section of the multiconductor line. In the general case, this cannot be done analytically, but well-defined numerical techniques are available [4].

To allow modelling of multiconductor cables in TLM, we have to introduce new TLM elements which, as explained in the introduction, we refer to as *vector link lines* and *vector stub lines*. A TLM vector line (link or stub) is characterized by an $n \times n$ impedance matrix Z, (or $n \times n$ admittance matrix $Y = Z^{-1}$), while the state of the line is described by n-element incident and reflected voltage pulse vectors, U and V, respectively.

The shunt connection between m n-vector lines (labelled by $i = 1 \dots m$) can be physically constructed by connecting n corresponding conductors in n junction points and having all vector lines sharing the same reference conductor. The total current in the junction must be zero vector, therefore

$$I_{tot} = \sum_{i=1}^{m} Y_i (U_i - V_i) = 0 \qquad (1)$$

The total voltage at the junction is given as sum of incident and reflected voltages

$$V_{tot} = U_i + V_i \qquad \text{(for all } i\text{)} \qquad (2)$$

Combining (1) and (2) we can describe total voltage vector in terms of incident voltage vectors only as

$$V_{tot} = 2 \left(\sum_{i=1}^{m} Y_i \right)^{-1} \sum_{i=1}^{m} Y_i U_i \qquad (3)$$

and hence calculate reflected voltage pulses as

$$V_i = V_{tot} - U_i \qquad \text{(for all } i\text{)} \qquad (4)$$

The series connection between vector lines is difficult to construct for more than two multiconductors. It is however possible by using n 1:1 transformers at the end of each line (between the reference conductor and the other n conductors), to give n two conductor ports (not sharing the same reference conductor), and then series connecting the corresponding ports of all the lines. In this case the total voltage going around junction is a zero vector, so

$$V_{tot} = \sum_{i=1}^{m} (U_i + V_i) = 0 \qquad (5)$$

while the total current around the junction is

$$I_{tot} = Y_i (U_i - V_i) \qquad \text{(for all } i\text{)} \qquad (6)$$

Combining (5) and (6) we can express total current vector in terms of incident voltage vectors only as

$$I_{tot} = 2 \left(\sum_{i=1}^{m} Z_i \right)^{-1} \sum_{i=1}^{m} U_i \qquad (7)$$

and hence calculate reflected voltage pulses as

$$V_i = U_i - Z_i I_{tot} \qquad \text{(for all } i\text{)} \qquad (8)$$

The principal TLM model of a segment of n-conductor cable is shown in Fig. 1. The cable and enclosing fictitious cylinder sheath form an $(n+1)$-conductor transmission line, which is modelled using a circuit of n-vector lines. This line is coupled to the external environment at the centre of each TLM cell by a break in the sheath. The vector link lines,

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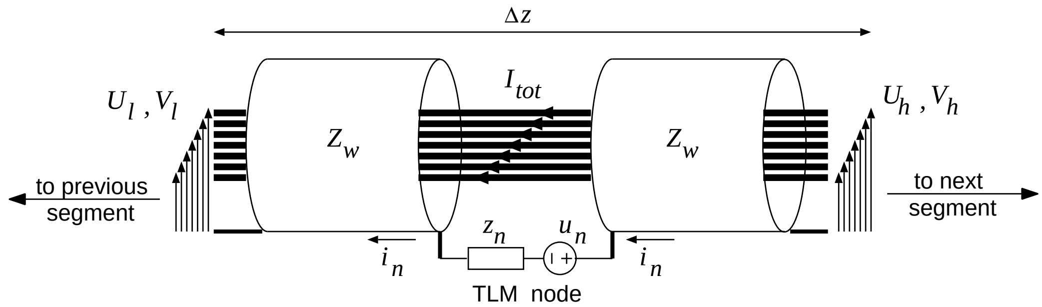

Figure 1: TLM model of a multiconductor segment

of the impedance matrix Z_w, can be chosen to model the total required capacitance of the wire segment of length Δz. By preserving the time-synchronism of the TLM pulses imposed by the time step Δt, we have $C_{tot} = C_d \Delta z = Z_w^{-1} \Delta t$, which gives

$$Z_w = \frac{\Delta t}{\Delta z} C_d^{-1} \quad (9)$$

The inductance modelled by the vector link lines, $Z_w \Delta t$, is normally insufficient [2], and a vector inductance stub of the impedance Z_s, connected in series to vector link lines, is required to make up the required total inductance given by

$$L_{tot} = L_d \Delta z = Z_w \Delta t + Z_s \frac{\Delta t}{2}$$

from where it follows that

$$Z_s = 2(L_d \frac{\Delta z}{\Delta t} - Z_w) \quad (10)$$

The n-vector inductance stub is not shown in the diagram due to the difficulty of drawing multiconductor series connections.

It can be seen from Fig. 1, that the coupling between the multiconductor cable model and the external environment is modelled using a voltage source in the reference line. The voltage source represents the electric field component coupling with the multiconductor line. Its amplitude u_n and the resistance z_n can be calculated from the incident voltage pulses and characteristics admittances of the relevant node's link and stub lines [5].

It is noted that the current in the reference conductor i_n is minus the sum of the currents in the other conductors, i.e. $i_n = -1_h I_{tot}$, where 1_h is the single row matrix $(1, 1, \ldots 1)$ and I_{tot} is current through vector link lines. Similarly, the voltage drop v_t on the reference conductor affects equally all the other lines, which can be described as $V_t = 1_v v_t$. Since $v_t = u_n + z_n i_n$ and $i_n = -1_h I_{tot}$, we write

$$V_t = 1_v u_n - 1_v z_n 1_h I_{tot}$$

which implies that a source in the reference line is equivalent to a vector source of $1_v u_n$ and impedance matrix $1_v z_n 1_h$ connected in series with other vector lines.

Using (7) we can now express I_{tot} in terms of incident voltage pulses as:

$$I_{tot} = 2(2Z_w + Z_s + 1_v z_n 1_h)^{-1}(U_h - U_l - U_s + 1_v u_n)$$

Using (8), voltage pulses reflected to the vector link lines (V_h and V_l) and vector stub lines (V_s) are calculated as

$$V_h = U_h - Z_w I_{tot} \quad (11)$$
$$V_l = U_l + Z_w I_{tot} \quad (12)$$
$$V_s = U_s + Z_s I_{tot} \quad (13)$$

Finally, the current flowing through the reference conductor, $i_n = -1_h I_{tot}$, is used to update voltage pulses on the ordinary node link and stub lines, following the method described in [5].

In many situations, the model of straight multiconductor cables, described here, may not be sufficient – for example, when modelling multiconductor bends, junctions, branching-off, partial terminations, etc. However, by exploiting the fact that in the TLM multiconductor model there is always a common reference conductor (fictitious cylinder) which divides and

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follow every multiconductor branch, one can formulate a generalized model using the shunt connection of vector lines described earlier. Such a general multiconductor junction model has been developed, but its detailed description is beyond the scope of this paper.

3 NUMERICAL EXAMPLE

Two metal cubes representing equipment boxes are placed on a metal ground plate. The first wire passes directly from one equipment box to the other and is terminated at each box. A second wire is terminated on the metal ground plate near one equipment box, travels vertically to the first wire, then follows the path of the first wire for most of the distance to the second equipment box. The wire then drops down to a termination on the metal plate. In each case, the wires are terminated with 50Ω coax feeds.

The wires and metal structure form a coupling mechanism between the four terminations, or ports. By exciting each unique port one at a time, and monitoring the transmitted signal and signal received at each port, a complete 4×4 scattering matrix can be calculated that fully characterizes the electromagnetic coupling between the two wires on the metal structure. For this particular example that has a symmetrical structure, two electromagnetic simulations are sufficient to obtain wide band coupling predictions.

The calculation has been performed using the new multiconductor model, and a very fine TLM mesh in which the wires and coax feeds are formed from solid cylindrical blocks of metal. Results are compared in Figs. 2 and 3. It should be noted that the multiconductor model required 20 times less CPU time than the fine mesh model.

4 CONCLUSION

Vector link lines and vector stub lines have been introduced in the TLM method to assist the development of a multiconductor model, integrated directly into the TLM time-stepping procedure. The method allows for an efficient modelling of coupling between the electromagnetic field and the multiconductors systems, which has been successfully demonstrated.

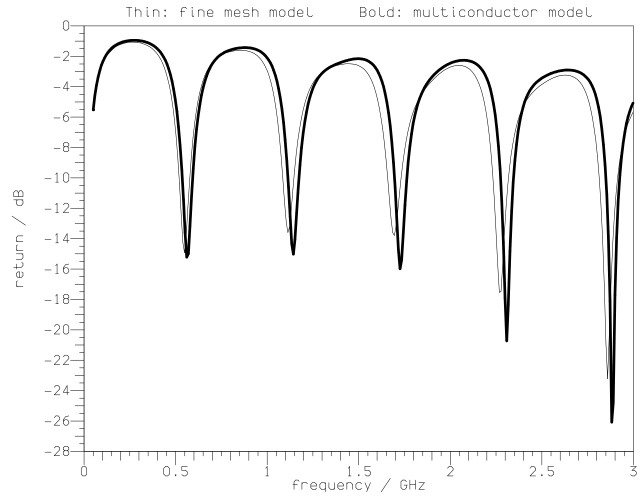

Figure 2: Return at equipment box port

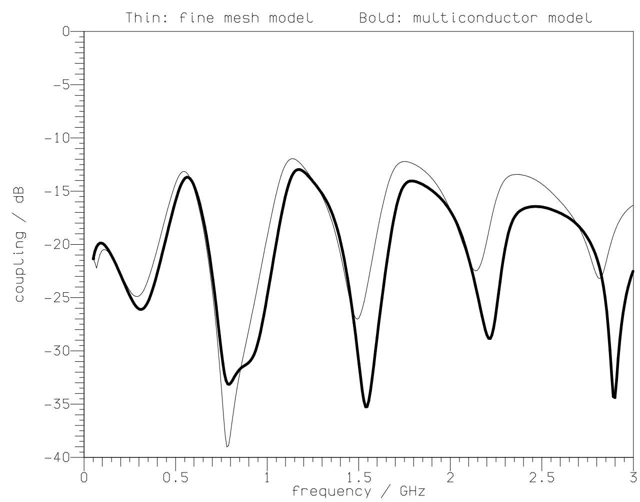

Figure 3: Coupling from port at equipment box to port on metal plate

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