EXTENDED THEVENIN MODELS FOR TRANSIENT ANALYSIS OF NON-UNIFORM DISPERSIVE LOSSY MULTICONDUCTOR TRANSMISSION LINES

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Abstract - In this paper we present a new time-varying equivalent circuit model for transient analysis of uniform and nonuniform multiconductor transmission lines with arbitrary linear and non-linear loads. Calculated or measured scattering parameter data are used to characterize the interconnection structures. Both sides of the transmission line structure are modeled as extended Thevenin equivalents, which consist of constant resistances and time-dependent voltage sources. This new circuit model is compatible with existing simulation programs.

Introduction

Nonuniform transmission lines are quite often used in microwave systems and in high-speed electronics. In chip carriers for example, the interconnections are usually nonuniform because of the high circuit density and the geometrical constraints near the chip. Nonuniform transmission lines are also used as filters, as couplers, as impedance matching sections, as resonators and as pulse transformers. Some nonuniform transmission lines show good transmission responses and they are used to realise specific time domain waveforms in various measurement systems.

Transient analysis of general uniform transmission line structures has been extensively studied by many authors [1]. However, the transient analysis of nonuniform lines is described by fewer authors. These nonuniform interconnection structures, together with linear and non-linear loads, constitute a rather complicated simulation problem.

Originally, these studies were restricted to particular nonuniform transmission lines such as binomial form coupled lines, and exponential or hyperbolic tapered lines. In some specific cases closed-form solutions for the transient response have been found. Sometimes, the nonuniform structures have been simulated as a cascade of lumped elements and ideal lossless transmission lines.

In recent years, the transient analysis of nonuniform lines has been addressed in much more detail. Yang, Kong and Gu [2]-[3] used a time domain perturbational technique for the analysis of a pair of nonuniform coupled transmission lines. This approach is based on many simplifying assumptions. Palusinski and Lee [4] presented a new method based on a spectral method (with Chebyshev polynomials as interpolants). This complicated method is restricted to frequency-independent structures, and its accuracy is limited. Mehalic and Mittra [5] studied the transient responses on tapered multiple microstrip lines. The lines are characterized by modal scattering parameter matrices. The modal decoupling is supposed to be frequency-independent.

New Equivalent Thevenin Model

In this study we present a new elegant time domain approach for transient analysis of uniform and nonuniform dispersive lossy multiconductor transmission lines with arbitrary linear or non-linear loads. The transmission line characteristics are allowed to be frequency-dependent.

Consider a set of N nonuniform transmission lines plus a reference conductor (figure 1). This linear, stationary, passive, reciprocal 2N-port is completely characterized in the frequency domain by its scattering parameter matrix, which can be calculated or measured. Normally, a single reference resistor is associated with each of the 2N ports. We use a different N by N reference resistance matrix $\mathbf{R_p}$ for each side of the interconnection structure (p = 1, 2):

$$\mathbf{R}_p = \lim_{\omega \to \infty} \{\mathbf{Z}_{c_p}(\omega)\} \quad (1)$$

This reference matrix is equal to the local instantaneous characteristic impedance matrix of the structure.

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The frequency domain voltage vector $\mathbf{V_p}$ is equal to the sum of the incident and the reflected voltage wave vectors at side p:

$$\mathbf{V_p}(\omega) = \mathbf{A_p}(\omega) + \mathbf{B_p}(\omega) \tag{2a}$$

while the frequency domain current vector $\mathbf{I_p}$ is equal to the difference of the incident and the reflected voltage wave vectors at port p divided by the local reference impedance matrix:

$$\mathbf{I_p}(\omega) = \mathbf{R_p}(\omega)^{-1} [\, \mathbf{A_p}(\omega) - \mathbf{B_p}(\omega) \,] \tag{2b}$$

The relations between the traveling voltage wave vectors $\mathbf{A_p}$ and $\mathbf{B_p}$ are described in an unambiguous way by the scattering parameters:

$$\begin{pmatrix} \mathbf{B_1}(\omega) \\ \mathbf{B_2}(\omega) \end{pmatrix} = \begin{pmatrix} \mathbf{S_{11}}(\omega) & \mathbf{S_{12}}(\omega) \\ \mathbf{S_{21}}(\omega) & \mathbf{S_{22}}(\omega) \end{pmatrix} \begin{pmatrix} \mathbf{A_1}(\omega) \\ \mathbf{A_2}(\omega) \end{pmatrix} \tag{3}$$

$\mathbf{S_{pp}}(\omega)$ can be seen as a scattering reflection coefficient matrix, while $\mathbf{S_{pq}}(\omega)$ can be seen as a scattering transmission coefficient matrix ($p \neq q$ and $p, q = 1, 2$).
Combining (2.a) and (2.b) learns that the voltages at side p are related to the currents and the reflected voltage waves at the same side:

$$\mathbf{V_p}(\omega) = \mathbf{R_p}\, \mathbf{I_p}(\omega) + 2\, \mathbf{B_p}(\omega) \tag{4}$$

The time domain formulation is found by using the inverse Fast Fourier Transform. A Hamming window is used to transform the frequency domain S-parameters into time domain impulse functions. The instantaneous impulse functions $\mathbf{s_{pp}}(0)$ and $\mathbf{s_{pq}}(0)$ are equal to zero due to the specific choice of the reference impedance matrices and the propagation behaviour of interconnection structures. These impulse functions have a relatively short duration due to the particular choice of the reference matrices.
The transient problem is solved in a time-marching way: after each time step, relevant transmission line parameters are computed by convolving the impulse functions with previous voltage waves. At each point in time, both sides of the transmission line structure are reduced to an extended Thevenin circuit model (see figure 2), described by:

$$\begin{aligned} \mathbf{v_p}(g) &= \mathbf{R_p}\, \mathbf{i_p}(g) + 2 \sum_{q=1}^{2} \sum_{h=1}^{g} \mathbf{s_{pq}}(h)\, \mathbf{a_q}(g-h)\, \Delta t \\ &= \mathbf{v_p}(g\text{-}1) + \mathbf{R_p}\, \mathbf{i_p}(g) \end{aligned} \tag{5a}$$

$$\mathbf{a_q}(g\text{-}h) = 0.5\, [\, \mathbf{v_q}(g\text{-}h) + \mathbf{R_q}\, \mathbf{i_q}(g\text{-}h) \,] \tag{5b}$$

$\mathbf{v_p}$ is a voltage source vector which depends on previous current waves. The simulation algorithm is represented in the flowchart of figure 3.

This new simulation algorithm can be seen as a generalization and an extension of the simulation method for uniform lines proposed in [1]. The frequency dependence of the modal decoupling matrices is explicitly taken into account. The advantage of this method over the other techniques resides in its speed, its computational stability, its flexibility, its simple Thevenin representation and its compatibility with existing circuit simulators such as SPICE. No approximations or model fitting is required.

Numerical example

Consider a tapered microstrip line. The top view and the cross section are shown in figure 4. The scattering parameters of this nonuniform interconnection structure are calculated using HP MDS [6]. In figure 5.a, the network configuration is shown. The voltage source has an internal impedance of 33.4 Ω and generates a pulse of 600 ps with a rise and fall time of 100 ns. The tapered line is terminated in a 65.4 Ω resistor. The simulation time step is 10 ps. The highest relevant frequency involved in the computation of the impulse functions is 50 GHz.
Figure 5.b shows the voltages at the generator A and at the load B. Remark the inductive effect of the taper. Due to the change of width, the current is forced to concentrate in a smaller area, which causes this inductive effect.

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[5] M.A.Mehalic and R.Mittra, "Investigation of Tapered Multiple Microstrip Lines for VLSI Circuits", IEEE MTT, Vol. 38, No 11, pp.1559-1567, November 1990.
[6] HP 85150B Microwave Design System (HP MDS).

Figures

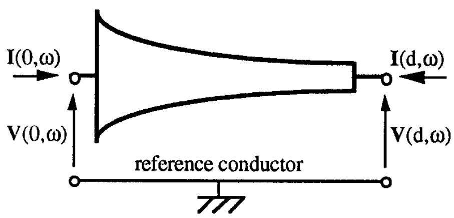

fig.1 : Compact representation of nonuniform transmission line network.

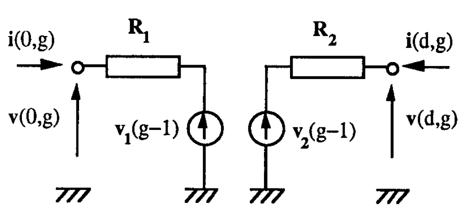

fig.2 : Extended Thevenin equivalent at time gΔt.

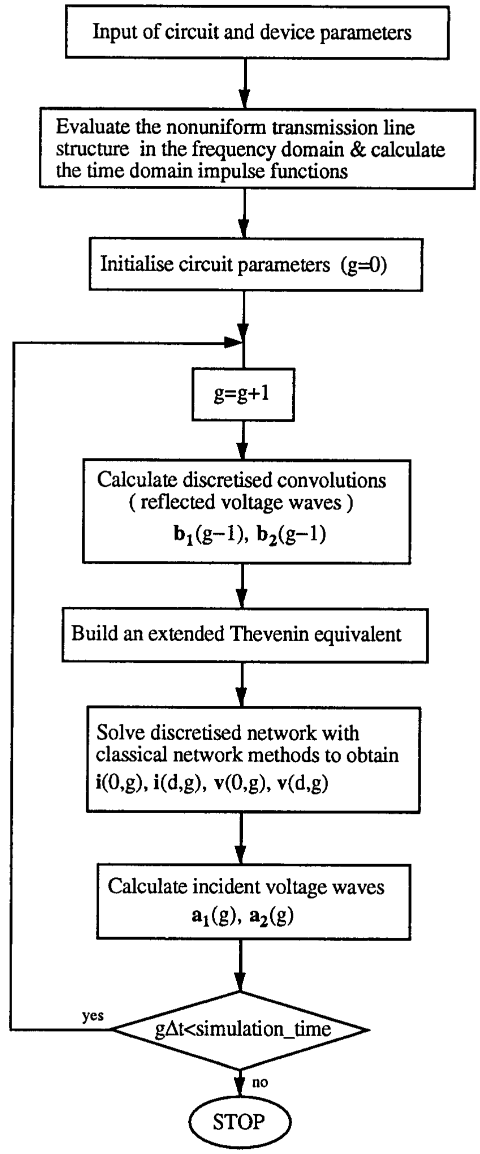

fig.3.: Flow chart of simulation algorithm.

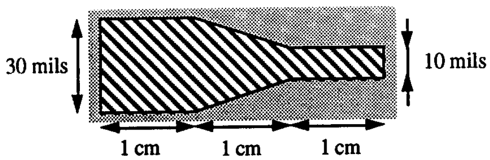

fig. 4.a: Top view of tapered line.

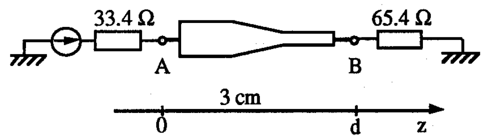

fig. 5.a: Network configuration.

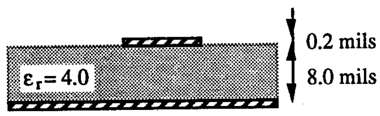

fig. 4.b: Cross section.

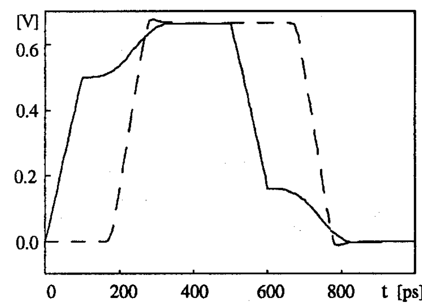

fig. 5.b : Voltages at generator A (——) and at load B (– –).