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Enhancing the frequency-domain calculation of transients in multiconductor power transmission lines

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ABSTRACT

In this paper numerical improvements are proposed to enhance the accuracy and efficiency of frequency-domain transient transmission line modeling. The adopted procedure is based on a robust eigenvector tracking algorithm and an accurate shape-preserving interpolation routine, formulating the highly resonant nodal admittance matrix from a minimal number of frequency data. The proposed method is integrated with the numerical Laplace transform and its performance is demonstrated in a configuration, consisting of an underground cable and an overhead line. Results are validated with the corresponding obtained from a frequency-domain model with regular sampling, revealing the high accuracy of the proposed formulation. The computational efficiency of the proposed numerical improvements is highlighted by comparisons of the execution times in cases of high sampling rates.

1. Introduction

The development of simulation models for the accurate calculation of electromagnetic transients in overhead lines and underground cables has been considerably increased again in recent years. A large number of simplified and advanced models have been proposed, which can be generally classified into two main categories according to the solution method adopted in the calculation routine.

In time-domain modeling the solution is based on a simple rule of integration, mainly exploiting the benefits of the recursive convolution technique [1]. This is significant, since such models can be easily incorporated in EMTP-like programs. These models can be further divided into modal- [2,3] or phase-domain [4], depending on whether the transfer propagation and the characteristic impedance/admittance matrices are expressed and fitted in their diagonalized or full matrix form, respectively.

On the contrary, in frequency-domain models, calculations take place solely in the frequency-domain, while the voltages and currents are converted back to the time–domain with the explicit use of the inverse Fourier or Laplace transform [5–7]. Although frequency-domain models were initially used in linear networks, considerable efforts have been made to include non-linear and time-varying elements, network configuration modifications and non-equidistant sampling schemes [8–15]. This class of models is usually used as stand-alone transient analysis tools or as backup options for the validation of time-domain models in certain cases.

One of the major drawbacks in frequency-domain modeling is the number of samples required to resolve the transient responses [13], which is explicitly determined by the frequency sampling interval. The latter can be extremely small in cases of transmission network simulations, where long observation times and extended frequency ranges are required due to different lengths and resonance frequencies [14]. As a result, an excessive number of samples is required leading to high computational costs in the preparatory calculation stage of the per-unit-length (PUL) parameters and propagation characteristics. The same issues can also occur in repetitive studies [16], such as statistical analysis, where multiple simulations of the examined system are performed by varying specific parameters of interest.

Scope of this paper is to present numerical improvements for the accurate and efficient frequency-domain calculation of transients in multiconductor power transmission lines (TL). More specifically, a backward eigenvector tracking algorithm and a shape-preserving interpolation technique are proposed for the formulation of the highly resonant nodal admittance matrix from a relatively small number of initial frequency data, which is predefined by the user. The proposed numerical improvements, combined with the

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utilization of the numerical Laplace transform (NLT) [6], provide high accuracy in the simulation of any type of transients and great computational efficiency, even in cases requiring high sampling rates or when time-consuming and complex integral forms of earth representation must be used for the calculation of the PUL parameters.

The proposed numerical improvements are applied to a power line configuration, consisting of an underground cable and an overhead line in cascade connection, highlighting the robustness of the eigenvector tracking algorithm and the high precision of the interpolation procedure. The accuracy of the resulting nodal admittance matrix is thoroughly investigated for variable number of initial frequency data. The obtained transient responses are further validated with the corresponding derived from a standard NLT model, where all frequency samples are directly calculated. Finally, the computational costs are compared, revealing the high efficiency of the proposed method, especially in cases where complex representations of the imperfect earth are assumed.

2. Standard NLT transient model

2.1. Overview

In this section the standard NLT model is summarized [6], presenting the steps for the calculation of the time-domain transient responses on an N-conductor power line with length ℓ.

2.1.1. Step 1

Assuming the regular sampling scheme of [6] and P equally spaced samples in time- and frequency-domain, the standard method starts with the derivation of the required angular frequency and time intervals $\Delta\omega$, Δt from the user-defined total observation time T and maximum examined angular frequency Ω.

$$\Delta t = \pi/\Omega \tag{1}$$

$$\Delta\omega = 2\pi/T = 2\Omega/P \tag{2}$$

2.1.2. Step 2

The $N \times N$ PUL series impedance and shunt admittance matrices in frequency–domain, Z' and $\boldsymbol{Y}'$ respectively, are calculated at each frequency defined by the interval $\Delta\omega$. Modal-domain analysis for multiconductor lines is applied to the matrix product $\boldsymbol{Y}'\boldsymbol{Z}'$ at each discrete frequency to calculate the modal propagation characteristics, namely the propagation constant matrix $\boldsymbol{\gamma}$ as well as the corresponding eigenvector matrices $\boldsymbol{T_i}$ and $\boldsymbol{T_v} = [\boldsymbol{T_i}^{-1}]^{\boldsymbol{T}}$ [17]. The complex and frequency-dependent eigenproblem can be solved using the simple and fast-converging QR diagonalization algorithm [18,19]. Any possible numerical eigenvector switchovers are treated in the final formulation of the nodal admittance matrix (Step 3), which is expressed in the phase-domain [20].

2.1.3. Step 3

The power line can be represented by the exact N-phase PI-equivalent circuit of Fig. 1 [15]. The admittance matrix $\boldsymbol{Y_{PI-eq}}$ of (3), connecting the two nodes of Fig. 1 and also including the termination conditions $\boldsymbol{Y_S}$, $\boldsymbol{Y_R}$ at both ends, is first defined.

$$\boldsymbol{Y_{PI-eq}} = \begin{bmatrix} \boldsymbol{Y_{sr}} + \boldsymbol{Y_{sh}} + \boldsymbol{Y_S} & -\boldsymbol{Y_{sr}} \\ -\boldsymbol{Y_{sr}} & \boldsymbol{Y_{sr}} + \boldsymbol{Y_{sh}} + \boldsymbol{Y_R} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} + \boldsymbol{Y_S} & \boldsymbol{B} \\ \boldsymbol{B} & \boldsymbol{A} + \boldsymbol{Y_R} \end{bmatrix} \tag{3}$$

where:

$$\boldsymbol{A} = \boldsymbol{Z}'^{-1} \cdot \boldsymbol{T_v} \cdot \boldsymbol{diag}\{\boldsymbol{\gamma}\} \cdot \boldsymbol{diag}^{-1}\{\tanh(\boldsymbol{\gamma} \cdot \ell)\} \cdot \boldsymbol{T_i^T} \tag{4}$$

$$\boldsymbol{B} = -\boldsymbol{Z}'^{-1} \cdot \boldsymbol{T_v} \cdot \boldsymbol{diag}\{\boldsymbol{\gamma}\} \cdot \boldsymbol{diag}^{-1}\{\sinh(\boldsymbol{\gamma} \cdot \ell)\} \cdot \boldsymbol{T_i^T} \tag{5}$$

Generalizing (3) for topologies with more than two nodes, the nodal admittance matrix $\boldsymbol{Y_{nd}}$ of (6) is formulated by applying the nodal analysis approach. This matrix is calculated at each discrete frequency of the total number P defined by the adopted sampling scheme in (1) and (2), and is of order $L \times L$ with $L = N \times M$, where M is the number of nodes in the PI-equivalent circuit.

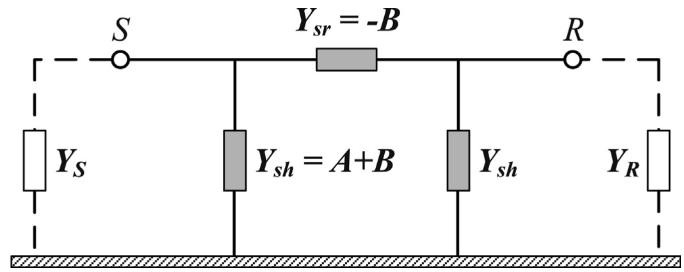

Fig. 1. N-phase PI-equivalent circuit terminated at both ends.

$$\boldsymbol{Y}_{nd} = \begin{bmatrix} \boldsymbol{Y}_{11} & \cdots & \boldsymbol{Y}_{1M} \\ \vdots & \ddots & \vdots \\ \boldsymbol{Y}_{M1} & \cdots & \boldsymbol{Y}_{MM} \end{bmatrix} \tag{6}$$

In (6) the symmetric $\boldsymbol{Y_{ii}}$, of order $N \times N$, represents the self and mutual coupling of the N conductors for node i over the examined frequency range, whereas the symmetric $\boldsymbol{Y_{ij}}$, of the same order, describes the mutual coupling between nodes i and j for all N conductors [15].

2.1.4. Step 4

Utilizing the algorithm of the NLT [6], the voltage and current sources are transformed in the frequency-domain with the same frequency interval used in the nodal formulation of Step 3. Therefore, the node voltages $\boldsymbol{E_{nd}}$ and the injected node currents $\boldsymbol{I_{nd}}$, both of order $L \times 1$, can be related with the generalized nodal admittance matrix $\boldsymbol{Y_{nd}}$, resulting in (7).

$$\boldsymbol{I_{nd}} = \boldsymbol{Y_{nd}} \cdot \boldsymbol{E_{nd}} \tag{7}$$

2.1.5. Step 5

Eq. (7) is reduced by eliminating the rows and columns corresponding to the known nodes. The remaining voltages can be easily calculated by (8) with $\boldsymbol{E_{rd}}$ containing the unknown node voltages, whereas $\boldsymbol{I_{rd}}$ and $\boldsymbol{Y_{rd}}$ are known. Results are finally converted back to the time–domain, implementing the algorithm of inverse numerical Laplace transform (INLT) [6].

$$\boldsymbol{E_{rd}} = \boldsymbol{Y_{rd}^{-1}} \cdot \boldsymbol{I_{rd}} \tag{8}$$

2.2. Sampling scheme considerations

According to the regular sampling scheme adopted in the calculation routine of the standard NLT model, there are several options to determine T, Ω and $\Delta\omega$, Δt. In most cases, once T is selected, $\Delta\omega$ is defined by (2). Next, depending on the type of transient under analysis, Ω is selected according to the required bandwidth that has to be considered. Thus, Δt and P are calculated by (1) and (2), respectively.

From the considered sampling scheme it is evident that in the worst case, i.e. for long simulation times and for wide frequency ranges, a large number of equidistant samples is required [14]. As an example, 10^4 samples (without counting the conjugate symmetric part) are needed for a total simulation time of 10 ms and a frequency range between 0 Hz and 1 MHz, resulting in an equal number of calculations for the PUL parameters and propagation characteristics in Step 2. This increases significantly the computational burden, as it is the most time-consuming process [13], especially when imperfect