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Fast and efficient calculation of lightning-induced voltages in frequency-dependent transmission lines over lossy ground

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ABSTRACT

This paper presents a fast and efficient algorithm for the calculation of electromagnetic fields radiated from lightning return-stroke channel as well as lightning-induced voltages in frequency-dependent transmission lines. The algorithm developed in this paper employs a mixed time-frequency macro-model that is based on tracing the poles and residues of the transfer function of the lightning-transmission-line system. Accurate and fast calculation of electromagnetic field data along the excited transmission line is critical to obtain the source terms (or forcing functions) in field-to-transmission-line coupling equations. Using the proposed method, we are able to obtain a closed form solution for the lumped sources required for the analysis of a two-conductor transmission line exposed to nonuniform electromagnetic fields. The algorithm provides high accuracy as well as significant speed gain for multiconductor transmission lines (MTL) as well. To demonstrate the application of the proposed method, we will compare our results with those obtained using other methods or measurements.

1. Introduction

Lightning-induced voltages on overhead transmission lines have been the subject of many theoretical and experimental investigations. Incorporation of accurate and efficient calculation of over-voltages induced by indirect lightning strikes in power system networks is important in electromagnetic transient (EMT) type simulators. A fundamental difficulty arises in integrating transmission line simulation into an EMT-type simulator. The reason is that network nonlinearities and time-dependant components require a time-domain analysis whereas transmission line characteristics such as conductor loss and dispersion are best described in the frequency domain. The issue of mixed time-frequency domain modeling of lossy coupled multiconductor transmission lines has been studied in both power systems and electronics communities for many years.

There are several models available to analyze transmission lines which can be categorized into *terminal-based* models and *distributed* ones. Terminal-based models [1–7], have access only to the information of the transmission line's terminals. These models are not inherently capable of calculating external-field coupling, such as those induced by indirect lightning strikes, whereas one of the inherent features of distributed models, such as those based on the FDTD method [8–16], is the capability of determining the response of the line to external exciting fields. However, these models are time consuming and need massive memory space which decreases the efficiency of the calculations. A distributed-model procedure for the calculation of lightning-induced voltages on transmission lines has been implemented as a computer code known as LIOV (lightning induced over voltage) [17] where an extension of the Agrawal model [8] for the case of lossy ground has been employed. Improvements to this approach [18], incorporation within EMT-type simulators [19], and consideration of the distribution network topology and terminations [20] have been presented in the literature.

For a terminal-based model, the problem of incident plane-wave electromagnetic field coupling to MTL has already been addressed in the literature, for example, in [21–29]. However, there are few papers that consider the case of non-uniform electromagnetic fields such as [30], where a hybrid FDTD and similarity transformation technique are used to calculate the additional voltage sources due to excitation of lossless transmission line.

In this paper, a fast and efficient macro-model is presented for the calculation of induced voltages by external nonuniform electromagnetic fields in frequency-dependent transmission lines. Radiated electromagnetic fields from indirect lightning strikes that are significant sources of high power electromagnetic radiation in power systems analysis, are studied in this work as the source of nonuniform excitation of the transmission lines.

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2. Problem statement

The Telegrapher's equations for a transmission line in the presence of external electromagnetic radiation, such as those radiated by the lightning return-stroke channel (RSC) as shown in Fig. 1a, are written in the frequency-domain as [10]

$$\frac{dV(z)}{dz} + ZI(z) = V_E(z)$$
$$\frac{dI(z)}{dz} + YV(z) = I_E(z) \quad (1)$$

where in the general case of a lossy frequency-dependent transmission line, Z and Y are the per-unit-length impedance and admittance, respectively. In (1), V_E and I_E are distributed sources that represent external excitation of the transmission line and are determined using a proper coupling model. There are a few alternatively equivalent, commonly used coupling models developed by Taylor et al. [31], Agrawal et al. [8], and Rachidi [32]. In this paper, without the loss of generality, we are using the extended version of the formulation developed by Taylor, Satterwhite, and Harrison. In this model, the distributed excitation sources are described in terms of the vertical and horizontal component of the incident electric field. For a two-conductor transmission line, shown in Fig. 1a, we have [10]

$$V_E(z) = [E_z^{\mathrm{inc}}(h, z) - E_z^{\mathrm{inc}}(0, z)] - \frac{\partial}{\partial z}\int_0^h E_x^{\mathrm{inc}}(x, z)dx$$
$$I_E(z) = -Y\int_0^h E_x^{\mathrm{inc}}(x, z)dx \quad (2)$$

where h is the height of the line, and $E_z^{\mathrm{inc}}(x, z)$ and $E_x^{\mathrm{inc}}(x, z)$ are the horizontal and vertical components of the incident electric field, respectively. The lightning external excitation of the transmission line is represented by distributed voltage and current sources in transmission line circuit model. The effect of these sources can be lumped at the terminals of the transmission line by using two lumped voltage and current sources, as shown in Fig. 1b. The advantage of using lumped sources at the terminal is that the transmission line can be treated as an unexcited transmission line (*i.e.*, zero right-hand side in (1)), and employ any of several already-developed models that are available for the analysis of frequency-dependent transmission lines. With transmission lines as an integrated part of a large network, that includes other components and protection devices, fast and efficient calculation of the lumped sources becomes an important issue. Besides, by using the approach presented in this paper, we are able to incorporate frequency-domain techniques for the calculation of lightning electromagnetic (EM) fields in time-domain circuit/power system simulators. The lumped sources, which replace the distributed sources, are given by [10]

$$V_{FT}(L) = \int_0^L \varphi_{11}(z)[E_z^{\mathrm{inc}}(h, z) - E_z^{\mathrm{inc}}(0, z)]dz + \int_0^h E_x^{\mathrm{inc}}(x, 0)dx - \varphi_{11}(L)\int_0^h E_x^{\mathrm{inc}}(x, L)dx \quad (3)$$

$$I_{FT}(L) = -\int_0^L \varphi_{21}(z)[E_z^{\mathrm{inc}}(h, z) - E_z^{\mathrm{inc}}(0, z)]dz + \varphi_{21}(L)\int_0^h E_x^{\mathrm{inc}}(x, L)dx \quad (4)$$

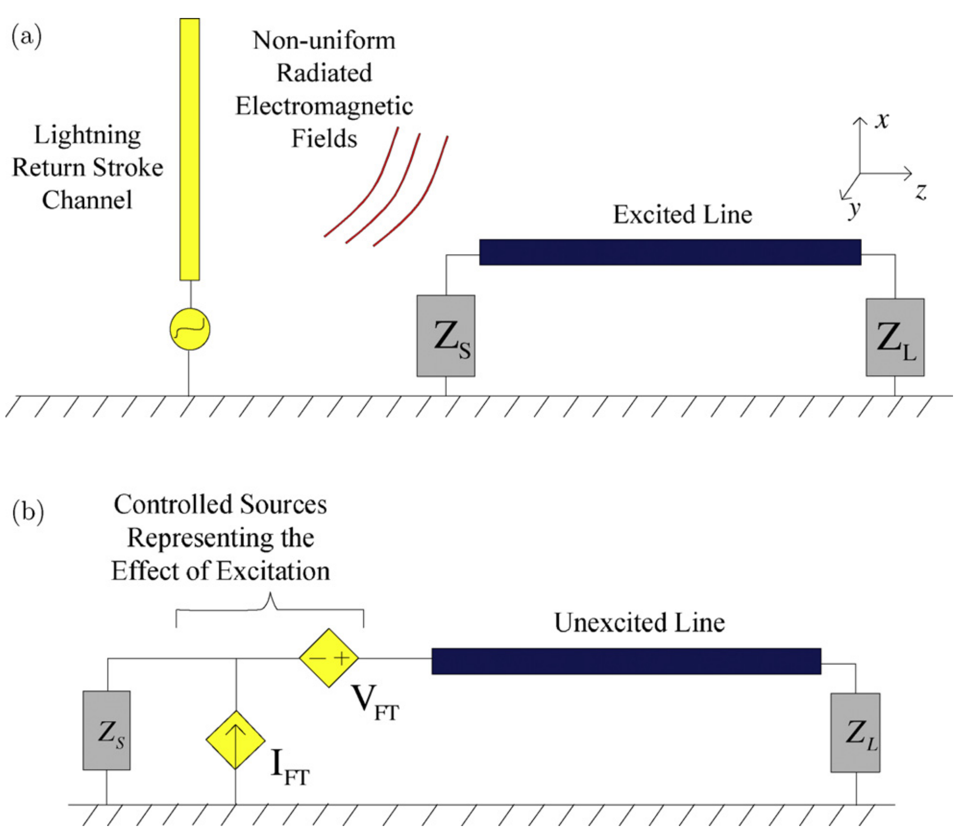

Fig. 1. (a) A two-conductor transmission line excited by lightning RSC EM fields and (b) equivalent circuit representation with controlled sources located at the terminal of unexcited line.