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Frequency domain modeling of nonuniform multiconductor lines excited by indirect lightning

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ABSTRACT

This paper describes a methodology in the frequency domain for the modeling of a multiconductor transmission line excited by a lightning stroke hitting the nearby ground, considering also variations of the line parameters along its length (nonuniform line). Modeling of the line excited by an external field (also known as illuminated line) is based on Taylor's formulation, while the incident electromagnetic field representing the nearby lightning stroke is computed following the expressions defined by Master and Uman. This formulation computes a nonuniform electromagnetic field dependent of the lightning's point of impact with respect to the line. A nodal form is used to completely describe the field excited line, including the effect of the incident field by means of current sources connected at the line ends. From this description, nodal voltages are computed in the frequency domain, using the inverse numerical Laplace transform algorithm to obtain the corresponding time responses. As an initial verification of the method, a comparison with an experimental result previously published is provided. As a second application example, a test case is used to analyze the effect of the point of impact on the magnitude and waveshape of the transient overvoltages obtained, as well as the effect of line's sagging between poles. Finally, it is demonstrated that the inclusion of lightning arresters can be considered in this frequency domain model by means of a combination of a piecewise linear approximation and the superposition principle.

1. Introduction

Lightning induced overvoltages in transmission and distribution lines can be classified, according to the point of impact, in direct and indirect. Taking advantage of modern computational techniques, the study of direct lightning phenomena still attracts a great deal of attention (see for instance [1–3]), bearing in mind that it produces higher transient overvoltages than indirect lightning. However, the incident field excitation from nearby lightning strokes produces traveling waves along the line that can be important for the design of insulation and protection elements, particularly for the voltage level of distribution lines. In addition, it is a much more frequent phenomenon than direct lightning impact.

In a general sense, a transmission line excited by an incident electromagnetic field from any type of source is known as an *illuminated line*. Several researchers have modeled and analyzed this problem for power and electronics applications (see for instance [4–20]). Formulations proposed by Taylor [4], Agrawal [5] and Rachidi [6] are the most commonly applied to this date.

This paper describes a methodology for the modeling of a field-excited multiconductor line in the frequency domain, taking into account variations of the line parameters along its length (nonuniform line case). The modeling is based on Taylor's formulation, which approximates an incident electromagnetic field by means of voltage and current sources distributed along the line's length. In this work, following the procedure described in [11,16], the technique is reduced to lumped current sources connected only at the line ends. This leads to a substantial simplification of the analysis without losing accuracy of the results.

The incident electromagnetic field representing the nearby lightning stroke is computed using the formulation described by Master and Uman [7], which depends on variables related to the point of impact (with respect to the line's location) and the return stroke current. However, the usual integro-differential form of the equations in time domain is replaced in this work by a more convenient algebraic form in the frequency domain. Once the electromagnetic field is obtained, the sources required by the model can be included. Finally, the numerical Laplace transform algorithm is used for the frequency–time transformation required [21].

Performance of the resulting method is initially validated by comparison with experimental results from a reduced-scale model reported in [13]. Then, the effect of the point of impact on the magnitude and waveshape of the transient overvoltages at the line ends is analyzed on a test case. The consequences of considering line nonuniformities and non-linear elements are also discussed.

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The major contribution of this paper is the application and combination of several existing methods and tools, such as modal analysis, the numerical Laplace transform, the cascaded connection of chain matrices, Master and Uman's formulation, among others, to present a methodology in the *frequency domain* for the modeling of a multiconductor line excited by a nearby lightning stroke (which produces a nonuniform electromagnetic field), including also the effect of nonuniformites of the line's electrical parameters. Previous works have shown the capabilities of frequency domain models not only as standalone analysis tools but also for the validation of new time domain models and numerical techniques. As an additional contribution, this paper demonstrates the possibility of including the effect of connecting non-linear elements (specifically surge arresters) in the frequency domain modeling of field-excited lines.

2. Computation of incident electromagnetic field

Fig. 1 shows the geometrical configuration of a transmission line excited by an incident electromagnetic field due to a nearby lightning stroke. Assuming ground as a perfect conductor, Master and Uman defined the components of electric and magnetic field produced by a differential segment of the lightning channel [7]. Since the model used in this work is defined in the frequency domain, these components are as follows:

$$dE_r(r,y,s) = \frac{dy}{4\pi\varepsilon_0} I(y,s) \times \exp(-Rs/c)\left[\frac{3r(h-y)}{R^5 s} + \frac{3r(h-y)}{cR^4} + \frac{r(h-y)s}{c^2R^3}\right] \tag{1a}$$

$$dE_y(r,y,s) = \frac{dy}{4\pi\varepsilon_0} I(y,s) \times \exp(-Rs/c)\left[\frac{2(h-y)^2 - r^2}{R^5 s} + \frac{2(h-y)^2 - r^2}{cR^4} - \frac{r^2 s}{c^2R^3}\right] \tag{1b}$$

$$dB(r,y,s) = \frac{\mu_0 dy}{4\pi} I(y,s)\exp(-Rs/c)\left[\frac{r}{R^3} + \frac{r}{cR^2}\right] \tag{1c}$$

where h is the line's height, r is the horizontal distance between a point of the line along the z axis and the lightning channel and c is the velocity of light in free space. The Laplace domain image of the lightning channel current propagating towards the cloud is defined from the MTLE model as [8]:

$$I(y,s) = \exp(-\alpha y)\exp(-ys/\upsilon)I(0,s) \tag{2}$$

where $I(0,s)$ is the Laplace image of the channel current at ground level (initial current), α is the attenuation constant of the current as it propagates in vertical direction (towards the cloud), and υ is the velocity of the return current. Field components corresponding to the complete lightning channel are obtained by numerical integration of Eq. (1) from H to $-H$, being H the cloud height, as depicted in Fig. 1.

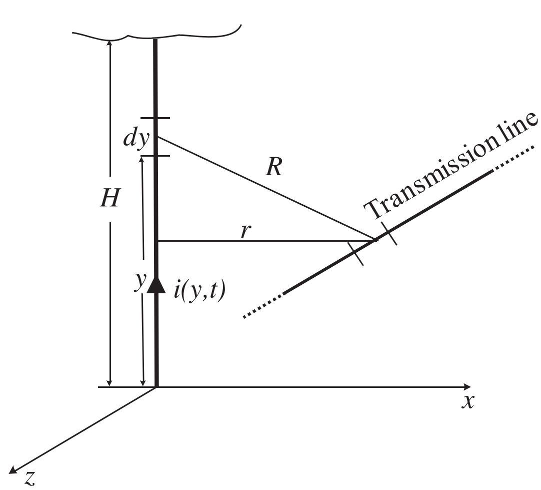

Fig. 1. Geometrical configuration of the transmission line-lightning channel arrangement.

Expressions by Master–Uman consider perfectly conducting ground. In order to take into account the effect of lossy ground (finite conductivity), Cooray and Rubinstein proposed the following correction [25]:

$$\widetilde{E}_r(r,y,s) = E_r(r,y,s) - \frac{cB(r,0,s)}{\sqrt{\varepsilon_{rg} + 1/(\varepsilon_0\rho_g s)}} \tag{3}$$

where $\widetilde{E}_r(r,y,s)$ is the horizontal electric field modified by considering the ground resistivity ρ_g, ε_{rg} is the relative ground permittivity, and $B(r,0,s)$ is the magnetic field at ground level for perfectly conducting ground. Vertical electric field is modified in a similar manner.

3. Modeling of the illuminated transmission line

According to Taylor's formulation [4], a transmission line excited by an incident electromagnetic field (also known as an illuminated line) can be described by means of the inclusion of distributed series voltage sources and shunt current sources along the line's length. For a nonuniform multiconductor line, the Telegrapher equations are defined in Laplace domain as follows [16]:

$$\begin{aligned}\frac{d\mathbf{V}(z,s)}{dz} &= -\mathbf{Z}(z,s)\mathbf{I}(z,s) + \mathbf{V}_F(z,s)\\ \frac{d\mathbf{I}(z,s)}{dz} &= -\mathbf{Y}(z)\mathbf{V}(z,s) + \mathbf{I}_F(z,s)\end{aligned} \tag{4}$$

where s is the Laplace variable; $\mathbf{V}(z,s)$ and $\mathbf{I}(z,s)$ are the vectors of voltages and currents along the propagation axis z; $\mathbf{Z}(z,s)$ and $\mathbf{Y}(z)$ are the matrices of series impedances and shunt conductances per unit length, respectively. Notice that for the nonuniform line case, these matrices are a function of z. Also, due to skin effect in conductors and in ground plane, the impedance matrix is frequency dependent. On the other hand, $\mathbf{V}_F$ and $\mathbf{I}_F$ represent the vectors of distributed sources, which are related to the incident electromagnetic field as [6]

$$\begin{aligned}\mathbf{V}_F(z,s) &= \begin{bmatrix}\vdots\\ s\int_0^{h_i(z)} B_{x,i}(z,s)dy + E_{z,i}(0,s)\\ \vdots\end{bmatrix}\\ \mathbf{I}_F(z,s) &= -\mathbf{Y}(z)\begin{bmatrix}\vdots\\ \int_0^{h_i(z)} E_{y,i}(z,s)dy\\ \vdots\end{bmatrix}\end{aligned} \tag{5}$$

where $h_i(z)$ is the height of the ith conductor; $E_{y,i}(z,s)$ and $B_{x,i}(z,s)$ are the vertical electric and transversal magnetic field components of the ith conductor in the Laplace domain, respectively. These variables are also a function of z for the general case of a nonuniform line. Besides, $E_{z,i}(0,s)$ is the horizontal electric field at ground level, which is due to the finite ground conductivity [6].