

Electromagnetic Transient Analysis of Lightning Strokes in Transmission Tower Including Frequency Dependent Effect

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The modeling of electrical towers is fundamental to the assessment of electromagnetic transients caused by lightning in power systems. In this context, classical tower models without frequency-dependent effects are well studied in the literature. However, there are few studies on frequency-dependent effects, which have recently received a significant attention due to their specific characteristics. Frequency-dependent effects on tower systems are created by ground characteristics. This paper addresses the overvoltage phenomenon resulting from a lightning strike at the top of towers cascade. The analysis is carried out using transmission line theory for modeling the propagation of voltage surges along the power system. The impedance and admittance of the whole system (tower, multi-conductor line and tower grounding system) are approximated by the vector fitting technique. The results obtained show a clear difference in the voltage response in the time domain for the different soil characteristics.

Index Terms—Flashover, Electromagnetic analysis, Lightning protection, Power system modeling, Transmission lines, Vector Fitting.

I. INTRODUCTION

THE Lightning strokes are one of the main causes of voltage surges along the transmission tower structure that may result in insulator failures by Back-Flashover (BF) mechanism, leading to outages. In this context, an accurate modeling of electric transmission tower is extremely crucial for power systems protection against lightning disturbances. Voltage surges caused by lightning depend on several parameters: the tower surge impedance, the waveform of the injected current at tower top and tower-footing grounding impedance. The tower surge impedance can be obtained using different methods [1].

The analysis of the electromagnetic transients in transmission towers during an atmospheric surge is usually achieved based on the transmission line theory or antenna theory. In the full wave electromagnetic fields approach, the towers are modeled based on the numerical analysis by antenna theory [2]. In the transmission line approach [3], currents and voltages are obtained from solving the well-established Telegrapher's equations of transmission lines as a function of the distributed electrical parameters of the tower. Knowing that, the modeling of towers using the antenna approach (full wave) is more accurate than transmission line approach where the transverse electromagnetic (TEM) is assumed to be the only propagation mode. However, the existing models of towers using antenna theory are limited to simplistic geometries, such as cone or cylindrical forms. The results cannot be properly evaluated without an accurate numerical procedure.

In purpose to avoid the complexity of antenna theory, our modeling is based on the transmission line approach. Thus, the transmission tower is represented as a combination of a series of vertical and horizontal short line segments that represent each section and cross-arms of the tower [4]. This paper presents a comprehensive study of the lightning direct impact on complex electric system (cascade of towers equipped with grounding systems). In fact, this approach permits to consider soil resistivity, permittivity, and the geometric characteristics of the grounding system. This new modeling allows to investigate the response of the entire system due to lightning surges. The transient behavior, particularly the Ground Power Rise (GPR), can be studied with high accuracy.

The inclusion of frequency-dependent effects in time-domain simulations presents a big challenge. Our proposed approach resolves this problem directly in time domain through advanced Vector Fitting (VF) technique, which enhance the reliability of power system modeling and providing valuable insights into system behavior during transient events.

II. MODELING OF THE LIGHTNING DISCHARGE AND TOWERS CASCADE

The Geometry of the towers cascade exposed to a direct lightning strike is shown in Fig.1. Note that each electrical tower is equipped with shield wire and grounding system.

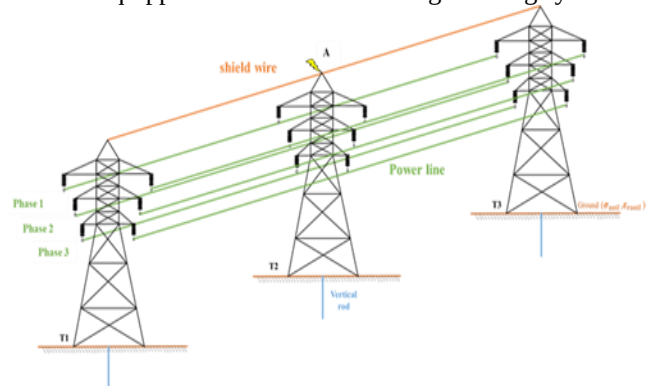


Fig1. Cascade of three towers with grounding system.

The time domain response of this system can be calculated based on multi-conductor transmission line theory. The telegrapher's equations can be written in their standard form as follows:

$$\begin{aligned} \frac{d[u(x, t)]}{dx} + [z'(t)] \otimes [i(x, t)] &= [0] \\ \frac{d[i(x, t)]}{dx} + [y'(t)] \otimes [u(x, t)] &= [0] \end{aligned} \quad (1)$$

$[u(x, t)]$ and $[i(x, t)]$: N-order vectors of phase's voltages and currents at each point of the equivalent tower network.

$[z'(t)]$ and $[y'(t)]$: square N-order matrices of impedance and admittance per unit length in time domain.

Based on the geometry of towers and their grounding systems, when subjected to lightning strikes, we can outline a general matrix system $[A].[X]=[B]$ in the time domain, which can be used to analyze the characteristics of the entire system [5].

Furthermore, the matrix $[A]$ is composed of two parts; the upper sub matrix $[A_1]$ represents the propagation effects that occur on the towers including multi-conductor transmission line and grounding systems. The lower sub matrix $[A_2]$ represents the relationship derived from applying Kirchhoff's laws at each node. Vector $[X]$ contains the unknown currents and voltages at each node, Vector $[B]$ contain the excitation signal.

A. Vector Fitting (VF) method

Vector Fitting performs the fitting by replacing a set of heuristically calculated initial poles with a set of relocated ones through an iterative procedure [6]. The incorporation of frequency dependent effects of the soil characteristics in our work is realized through the impedance $[z'(t)]$ and admittance $[y'(t)]$ matrices. Unfortunately, there is no analytic expression for $[z'(t)]$ and $[y'(t)]$ in time domain. To overcome this difficulty, we use the so-called "Vector Fitting" approach and we express the per unit length impedance $[\bar{Z}(\omega)]$ and the admittance $[\bar{Y}(\omega)]$ matrices by rational function approximation as follows [6]:

$$Z(s) \approx \sum_{r=1}^N \frac{A_r}{s - \alpha_r} + R + sL \quad (2)$$

Where: A_r and α_r are the residues and the poles of the rational function approximation. These poles can be either real or complex conjugate pairs. In the equation above, N is the number of poles for the rational function approximation. The terms R and L are real coefficients and $s=j\omega$ is the complex angular frequency.

By using the decomposition as described in equation (2) for the impedance and similarly for admittance per unit length in equation (1) and after conversion, by invers Laplace transform, in the time domain leads us to the equations (3):

$$\begin{aligned} \frac{d[u(x,t)]}{dx} + [R][i(x,t)] + [L] \frac{d[i(x,t)]}{dt} + \left[\sum_{r=1}^N A_r e^{\alpha_r t} \right] \otimes [i(x,t)] &= [0] \\ \frac{d[i(x,t)]}{dx} + [G][u(x,t)] + [C] \frac{d[u(x,t)]}{dt} + \left[\sum_{r=1}^N B_r e^{\beta_r t} \right] \otimes [u(x,t)] &= [0] \end{aligned} \quad (3)$$

where: $[R]$, $[L]$, $[G]$ and $[C]$, are respectively matrices, longitudinal resistance, longitudinal inductance, conductance to ground, capacitance to ground, defined per unit length. In case of the horizontal segments (towers arms) we propose to use expressions from [4]. On the other hand, the vertical segments parameters are calculated by using expressions described in [4]. For the grounding system (vertical buried rod) we use the expressions mentioned in [7].

B. Numerical results

The lightning strike is represented by a normalized current generator of 10kA, 8/20 μ s.

In our work, the frequency dependent of both soil resistivity and permittivity are considered using Smith-Longmire model. The geometric parameters of electric tower used in simulation are described in [4].

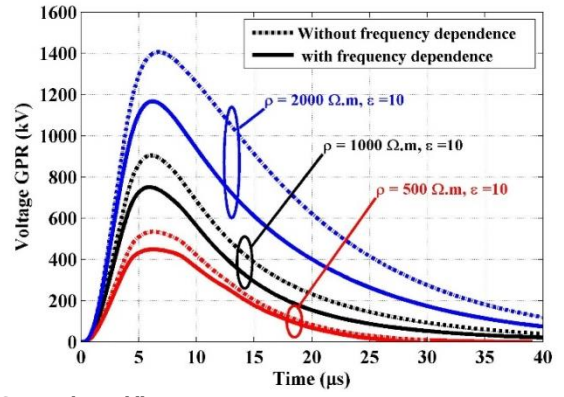


Fig.2. GPR at the middle tower T2.

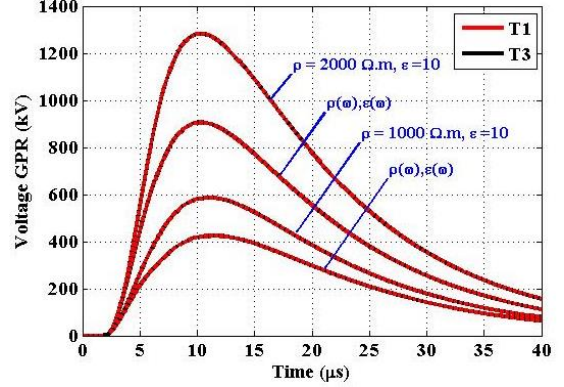


Fig.3. GPR at the extremities towers T1 and T3.

It is shown in Fig. 2 and Fig.3 that the inclusion of frequency dependence in the calculation of tower branches (horizontal and vertical) and the footing grounding impedance play a crucial role in the time-domain electromagnetic transient. Effectively, the peak of the voltage curve without frequency dependent is always higher than the corresponding value with frequency dependent, which can be explained by the effects considered in the analyses, such as skin effect, proximity effect, and frequency dependent of the soil permittivity and conductivity.

Thus we can conclude that the incorporation of frequency dependent soil directly in time domain using the transmission lines and FDTD is well convenient in this work. The proposed model gives accepted results even for complexe systems (electric cascade of towers).

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