# Time-Domain Simulation of Tower with Grounding Device under Lightning Strikes

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***Abstract*—The lightning protection ability of transmission line is greatly determined by the transient impedence of transmission tower and its grounding device. In this paper, a branch current method is developed for the simulation of lightning-caused electromagnetic transients on tower and its grounding device based on the partial element equivalent circuit method. In comparison to the method based on electric-field integral equation, the new method has several attractive features: 1) it has a simple time-domain form; and 2) it is much faster because the inverse of the system matrix only needs to be evaluated once. In comparison to other methods based on partial element equivalent circuit method, the new formulation has few unknown variables and can set up equations easily.**

***Index Terms*—Electromagnetic transients, grounding, lightning protection, time domain analysis**

## I. Introduction

When lightning strikes a transmission tower, great current will flow through the tower and dissipate into the soil from the grounding device. The flashover of transmission line is determined by the transient impedence of both the tower and its grounding device. Understanding the lightning-caused electromagnetic transients on thin-wire structures such as the tower and the grounding device has been a research topic for a long time. Many papers paid attention to the transient performance of grounding device [1]-[4]. Some others paid attention to the performance of tower [5]. However, the tower and the grounding device will interact under lightning strikes. The waveform of the injected current of grounding device may be quite different from the lightning current striking the top of tower. Thus, it is necessary to analyze the transient performance of tower and its grounding device as a whole.

Among numerical methods, electric-field integral-equation (EFIE) method based on moment methods (MoM) has been widely used for the thin-wire structures[2, 5, 6]. However, the EFIE method is always restricted to frequency domain. Finite-difference time-domain (FDTD) method has also been adopted [3], but it is troublesome to build division meshes because the characteristic dimensions of the structure vary in a wide range. Recently, it has been verified that partial element equivalent circuit (PEEC) method is quite effective in the evaluation of electromagnetic transients on thin-wire structures [4]. The method transforms the problem into a circuit which can be solved eithor in frequency domain or in time domain. Based on the PEEC method, paper [7] simulated thin-wire structures above and buried in lossy ground using modified mesh current method, but it is difficult to find independent loops for complex structure. In this paper, a branch current method in time domain is developed based on the PEEC method, which has few unknown variables and can set up equations easily.

## II. Basic Principle

Because the size of the thin-wire structure is much less than the wavelength of the significant frequency of lightning current, static field theory can ensure a satisfactory accuracy. According to the four coupling mechanisms among conductors, namely, capacitive coupling, conductive coupling, inductive coupling, and resistive coupling, the PEEC method transforms the electromagnetic field problem into a circuit domain [4, 7].

The capacitive coupling and the conductive coupling are related to the potential rise of one conductor caused by the current (including displacement and conductive currents) flowing radially out of another conductor. Expressing the two mechanisms in a matrix form gives

$$\begin{bmatrix} \boldsymbol{V}_{n1} \\ \boldsymbol{V}_{n2} \end{bmatrix} = \begin{bmatrix} \boldsymbol{R}_{11} & \boldsymbol{R}_{12} \\ \boldsymbol{R}_{21} & \boldsymbol{R}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{I}_{n1} \\ \boldsymbol{I}_{n2} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} \\ \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{Q}_{n1} \\ \boldsymbol{Q}_{n2} \end{bmatrix}, \quad (1)$$

where $\boldsymbol{V}$ denotes the potentials of conductor segments, $\boldsymbol{Q}_n$ denotes the charges bonded on conductors, and $\boldsymbol{I}_n$ denotes the radially conductive currents flowing out of conductors. $\boldsymbol{P}$ is the potential coefficient matrix, $\boldsymbol{R}$ is the mutual resistance. Subscripts 1 and 2 indicate that the quantity is above and below the ground plane, respectively. Both $\boldsymbol{P}$ and $\boldsymbol{R}$ can be obtained by image method. For the conducotrs in the air, $\boldsymbol{I}_{n1}$ is almost zero, and $\boldsymbol{R}_{11}$, $\boldsymbol{R}_{12}$, and $\boldsymbol{R}_{21}$ approach infinite. While for the conducotrs in the soil, $\boldsymbol{I}_{n2}$ can not be neglected. Thus, in the soil, (1) will become

$$\boldsymbol{R}_{22}\boldsymbol{I}_{n2} = \begin{bmatrix} \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{Q}_{n1} \\ \boldsymbol{Q}_{n2} \end{bmatrix}. \quad (2)$$

The conductive coupling and the inductive coupling are related to the voltage drop on a conductor caused by the current flowing axially in another conductor. Expressing in a matrix form gives

$$\boldsymbol{V}_l = \boldsymbol{R}_l \boldsymbol{I}_l + \boldsymbol{L}\frac{d\boldsymbol{I}_l}{dt}, \quad (3)$$

where $\boldsymbol{R}_l$ and $\boldsymbol{L}$ are the branch resistance and inductance matrices, respectively. $\boldsymbol{R}_l$ only has nonzero elements on its diagonal while $\boldsymbol{L}$ is a full matrix with self-inductance on its diagonal and mutual inductance off its diagonal. $\boldsymbol{V}_l$ is the vector of potential drops along branch, and $\boldsymbol{I}_l$ is the vector of branch currents.

If $\boldsymbol{Q}_n$ and $\boldsymbol{I}_n$ are put around the nodes (intersections of the conductors), and $\boldsymbol{I}_l$ is put along the conductors, as Fig. 1

shows, following equations can be obtained at the nodes according to Kirchhoff's current law:

$$\boldsymbol{A}_1^T \boldsymbol{I}_l - \frac{d\boldsymbol{Q}_{n1}}{dt} = 0 \text{, for the conducotrs in the air} \tag{4}$$

$$\boldsymbol{A}_2^T \boldsymbol{I}_l - \frac{d\boldsymbol{Q}_{n2}}{dt} = \boldsymbol{I}_{n2} \text{, for the conducotrs in the soil} \tag{5}$$

where $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ are the matrices of the connection relationship between nodes and conductors above and below the ground plane respectively, whose entries are:

$$A_{ij} = \begin{cases} 1, \text{if node } j \text{ is connected to the end of conductor } i \\ -1, \text{if node } j \text{ is connected to head end of conductor } i \\ 0, \text{if node } j \text{ is not directly connected to conductor } i \end{cases}.$$

Let $\boldsymbol{A}$=[$\boldsymbol{A}_1$ $\boldsymbol{A}_2$]. Then, the potential drops along the branch and the node voltages will have following relation

$$\boldsymbol{V}_l = -\begin{bmatrix} \boldsymbol{A}_1 & \boldsymbol{A}_2 \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_{n1} \\ \boldsymbol{V}_{n2} \end{bmatrix} \tag{6}$$

Then, the problem under consideration can be solved in time domain with the help of central difference scheme. First, from (2), (4) and (5) we get

$$\begin{cases} \boldsymbol{Q}_{n1}^{t+1} = 2\Delta t\, \boldsymbol{A}_1^T \boldsymbol{I}_l^t + \boldsymbol{Q}_{n1}^{t-1} \\ \boldsymbol{Q}_{n1}^{t+1} = 2\Delta t\, \boldsymbol{A}_1^T \boldsymbol{I}_l^t + \boldsymbol{Q}_{n1}^{t-1} - \boldsymbol{R}_{22}^{-1} \begin{bmatrix} \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{Q}_{n1}^t \\ \boldsymbol{Q}_{n2}^t \end{bmatrix} \end{cases}. \tag{7}$$

Then, by substituting (1) into (6), and then into (3), we get:

$$\boldsymbol{I}_l^{t+1} = \boldsymbol{I}_l^{t-1} - 2\Delta t\, \boldsymbol{L}^{-1} \boldsymbol{R}_l \boldsymbol{I}_l - \boldsymbol{L}^{-1} \boldsymbol{A} \begin{bmatrix} \boldsymbol{P}_{11} & \boldsymbol{P}_{12} \\ \boldsymbol{P}_{21} & \boldsymbol{P}_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{Q}_{n1}^t \\ \boldsymbol{Q}_{n2}^t \end{bmatrix}. \tag{8}$$

If all the values in (7) and (8) before $t$+1 are known, the new values at $t$+1 can be obtained by (7) and (8). And other values can be calculated by (1) and (2). Thus, the transient performance of the tower and the grounding device can be simulated in time domian step by step. The method is much fast because explicit difference scheme is used and the inverse of the system matrix needs to be evaluated only once.

## III. Application

As an application, a 220 kV transmission tower with grounding device as shown in Fig. 2 (a) is analyzed. The height of the tower is 38 m. The span of the legs is 12 m. The grounding device has four radial electrodes, each of them has a length of 19 m and a depth of 0.8 m. Under the tower legs, there are four addational 2-meter-long vertical grounding rods. The soil has a resistivity of 42 Ωm and a relative permittivity of 10. The voltage distribution along the tower when 2.6/50 μs lightning current or 5.2/50 μs one strike the top of the tower is analyzed. Results are shown in Fig. 2 (b) and (c).

It can be seen that in the stage when the lightning current increases very fast, the potential at the top of the tower is much higher than that on the grounding device. The potential is mainly produced by the tower body. Because the peak time of potential is far ahead of that of current, the tower is like an inductance. Due to the reflection of the tower, oscillations appear. When the lightning current varies slowly, the potential at the top of the tower drops quickly. The proportion of the potential on the grounding device begins to rise. The shorter the rise time of the current is, the more obvious above phenomenon becomes.

In the formal paper, a field test on a real tower will be presented to verify the method.

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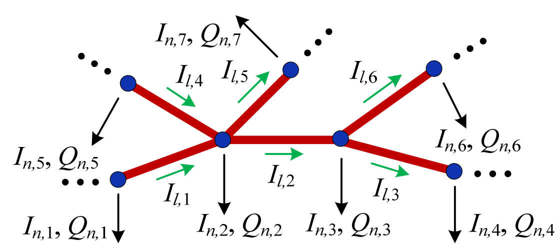
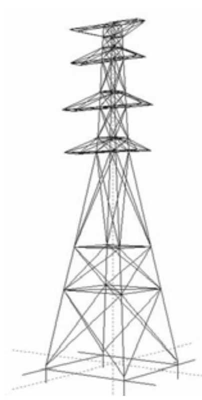
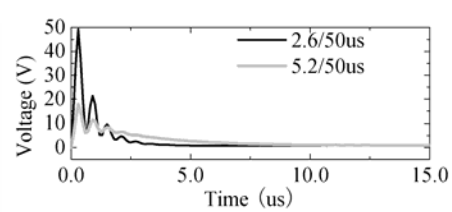


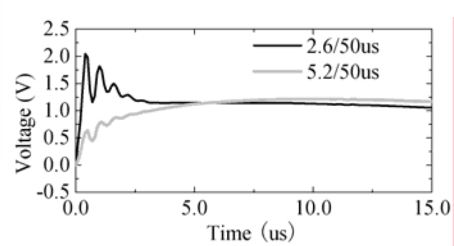

Fig. 1. Current distribution along the thin-wire structure



(a) tower and grounding device




(b) voltage at the top of the tower




(c) ground potential rise of the grounding device

Fig. 2. Transient voltage distribution along the tower