

Analysis of Lightning Transients in the Grounding Circuits of a Wind Farm

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In this paper, we propose the modeling analysis of the transient behavior of the grounding circuits of a wind farm during a direct lightning strike. This modeling, in the time domain, is developed from the transmission line equations, the vector fitting technique, the FDTD numerical method and the electromagnetic topological formalism. This modeling simultaneously considers the dependence on frequency and the ionization of the ground which generally occurs during the injection of a high intensity current. We validate this modeling by measurement and we propose applications on grounding circuits used in wind farms.

Index Terms— Grounding, lightning, modeling, wind farm

I. INTRODUCTION

To protect electrical installations against the direct impact of lightning discharge, engineers use the Lightning Protection System "LPS", whose important element is its Grounding. Experience shows that the lightning protections, when they exist, have often been implemented without proper study on their effectiveness. It seems important to examine the problem carefully, in order to be able to propose suitable and effective solutions.

In order to design protection measures, the consequences of a lightning strike must be assessed, that is to say, the phenomenon must be studied in detail: from the nature of the formation of the lightning discharge, to the effects of the different types of impacts, through the interactions of all the components exposed to the lightning energy.

Designing the ground network of a wind farm, which has the particularity of being complex given the presence of several interconnected grounding systems, is obviously a task that requires special consideration to optimize its role and thus allow lightning currents to flow quickly and avoid a significant increase in the GPR (Ground Potential Rise).

While measurement can sometimes address certain concerns regarding the design and dimensioning of an grounding system, it should be noted that these analyses are often limited to simple grounding systems (horizontal or vertical grounding conductor) or small grounding grids. On-site measurements are costly and sometimes not feasible; to help with the proper design of an grounding circuit for the electrical network, numerical modeling is now often used.

Many models are already published in the literature and are frequency or time. Frequency modeling allows to consider the effect of frequency and that in time has the advantage of allowing the consideration of non-linear effects (ionization of the ground) which occur during the injection of a very high intensity current. In this paper for studying lightning transients in the grounding circuits of wind farms, we use a modeling which allows to consider simultaneously the effect of frequency while taking into account non-linear effects. This new modeling is developed from the theory of transmission lines, the vector fitting technique and the topological electromagnetic formalism.

II. THEORETICAL BACKGROUND

Generally, numerical models of the transient behavior of a grounding developed from the equations of the two-conductor transmission line which are as follows:

$$\frac{du(x,t)}{dx} + Ri(x,t) + L \frac{di(x,t)}{dt} = 0 \quad (1)$$

$$\frac{di(x,t)}{dx} + Gu(x,t) + C \frac{du(x,t)}{dt} = 0 \quad (2)$$

Where $u(x,t)$ and $i(x,t)$ are respectively the voltage and the current for the abscise x at time t .

In these equations the parameters per unit length (R , L , C and G) are constant and calculated for a buried conductor (grounded electrode) using the expressions proposed by E. D. Sunde [1]. However, many studies have shown that the consideration of the effect of frequency on both the parameters of the electrodes (wire conductors) and the electrical characteristics of the soil (electrical resistivity and dielectric permittivity) is mandatory to better understand the transient behavior of grounding systems [2]. To do this in our work, we instead use the equations of frequency transmission lines defined as follows:

$$\frac{d\bar{U}(x, \omega)}{dx} = -\bar{Z}(\omega)\bar{I}(x, \omega) \quad (3)$$

$$\frac{d\bar{I}(x, \omega)}{dx} = -\bar{Y}(\omega)\bar{U}(x, \omega) \quad (4)$$

Where $\bar{Z}(\omega)$ and $\bar{Y}(\omega)$ are respectively the longitudinal impedance and the transversal admittance per unit length.

To consider the dependence with the frequency in the time domain, the two equations (3) and (4) are written by inverse Fourier transform as follows:

$$\frac{du(x,t)}{dx} + z'(t) \otimes i(x,t) = 0 \quad (5)$$

$$\frac{di(x,t)}{dx} + y'(t) \otimes u(x,t) = 0 \quad (6)$$

$z'(t)$ is the inverse Fourier Transform of $\bar{Z}(\omega)$

$y'(t)$ is the inverse Fourier Transform of $\bar{Y}(\omega)$

With $\otimes$ the convolution product.

Unfortunately, analytical expressions for $z'(t)$ and $y'(t)$ do not exist. To overcome this difficulty, we use the vector fitting technique:

$$f(s) \approx \sum_{r=1}^N \frac{b_r}{s - a_r} + D + sE \quad (7)$$

The residues b_r and poles a_r are either real quantities or come in complex conjugate pairs, while D and E are real, and $s = j\omega$.

Which allows us to express the impedance $\bar{Z}(\omega)$ in equation (3) and the admittance $\bar{Y}(\omega)$ in equation (4) which become:

$$\frac{d\bar{U}(x, \omega)}{dx} = -R'\bar{I}(x, \omega) - L's\bar{I}(x, \omega) - \sum_{r=1}^{N'} \frac{b_r'}{s - a_r'} \bar{I}(x, \omega) \quad (8)$$

$$\frac{d\bar{I}(x, \omega)}{dx} = -G'\bar{U}(x, \omega) - C's\bar{U}(x, \omega) - \sum_{r=1}^{N''} \frac{b_r''}{s - a_r''} \bar{U}(x, \omega) \quad (9)$$

The conversion, by Fourier transform, of equations (8) and (9) in the time domain leads us to the two equations (10) and (11).

$$\frac{du(x, t)}{dx} + R'i(x, t) + L'\frac{di(x, t)}{dt} + \sum_{r=1}^{N'} b_r' e^{a_r' t} \otimes i(x, t) = 0 \quad (10)$$

$$\frac{di(x, t)}{dx} + G'u(x, t) + C'\frac{du(x, t)}{dt} + \sum_{r=1}^{N''} b_r'' e^{a_r'' t} \otimes u(x, t) = 0 \quad (11)$$

In this work, a complex geometry grounding composed of wire conductors is analyzed as a network of two-conductor transmission lines interconnected at junction nodes. Using a 1D spatial mesh of this network, the numerical method called FDTD to replace the partial derivatives in equations (10) and (11), an algorithm for calculating recursive convolutions and the topological electromagnetic formalism, we deduce a matrix equation in time domain [3]:

$$[M][X] = [E] \quad (12)$$

which translates the resolution of a set of equations of electric wave propagation in a network of transmission lines considering the nodal electrical relations.

[M]: Matrix which translates the propagation on the transmission lines and the electrical relationships on the nodes; [E]: Excitation vector.

[X]: Unknown vector, whose elements are the currents and voltages on all the nodes of the network.

To consider the variation with frequency of the electrical resistivity and dielectric permittivity of the soil, we use the analytical expressions adopted by CIGRE [2]. The ionization of the soil is considered through the nonlinear resistance model also adopted by CIGRE [4].

III. VALIDATION

For this validation, we compare our results with those calculated by D. Cavka [5] which uses an electromagnetic model (numerical resolution of an integral equation in electric field). The geometric configuration of the grounding is that in figure 1. The wind turbine grounding is buried in a soil with the electrical conductivity $\rho_s = 1200\Omega.m$ and electrical permittivity $\epsilon_r = 5$.

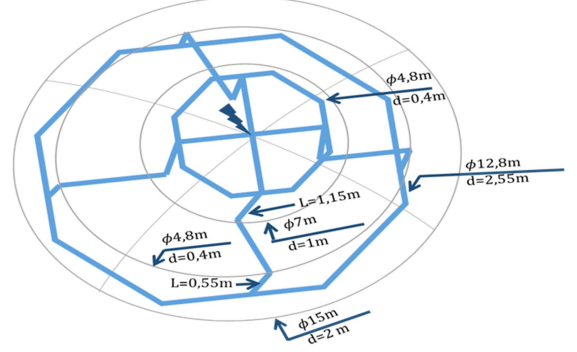


Fig. 1. Geometry of the WT grounding grid.

For this application we consider a current injection successively by first and subsequent return stroke (see Fig. 2).

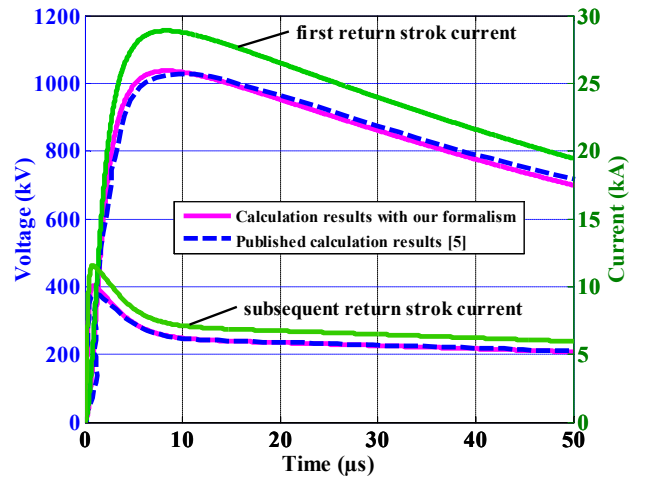


Fig. 2. GPR at injection point with first and subsequent lightning strike.

The analysis of the results of figure 2 shows that the modeling that we propose, developed from the concept of transmission lines with frequency-dependent parameters and the topological electromagnetic formalism, leads to results in perfect agreement with the very rigorous electromagnetic formalism (antenna theory) used by D. Cavka [5] for his simulations. Let us remember that, the modeling we propose allows us to analyze lightning transients in the ground circuit of a wind farm which is generally composed of several grounding systems shown in figure 2 interconnected between them by buried bare bars.

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