

## ON THE INFLUENCE OF CORONA ON LIGHTNING-INDUCED OVERVOLTAGES

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### ABSTRACT

An experimentally inferred charge-voltage (Q-V) diagram used to macroscopically model the corona phenomenon is adopted for the calculation of the lightning-induced transients in presence of corona.

The paper aim at presenting the calculation procedure as well as the analysis of the corona Q-V diagram on the lightning-induced surges.

### 1 INTRODUCTION

The availability of accurate models for the calculation of overvoltages originated by lightning electromagnetic pulses (LEMPs), with the aim of analyzing the response of realistic lines, has been already discussed in the literature (e.g. [1]). In this respect, the evaluation of the influence of corona on lightning-originated surges has been treated both for the case of direct strokes to high voltage transmission lines (e.g. [2-7]) as well as for the case of indirect lightning-induced voltages in medium voltage distribution lines [8,9]. As known, this non-linear phenomenon is one of the responsible in the travelling waves surge distortion and its effects for lightning-induced overvoltages are as important as those associated to the finite ground conductivity.

Following the approach proposed in [9], based on the integration of the dynamic capacitance concept into the field-to-transmission line coupling equations of the Agrawal model [10], the paper presents some calculations obtained using an experimentally inferred charge-voltage (Q-V) diagram used to macroscopically model corona. In this paper, for the representation of the corona dynamic capacitance use is made of the Q-V expression proposed in [11].

The paper is structured as follows; Section 2 illustrates the details about the calculation of lightning-induced overvoltages along an overhead line above a lossy soil in presence of corona and with particular reference to the adopted dynamic capacitance model; the section also illustrates the integration of such a model into the LEMP-to-transmission line coupling model; Section 3 illustrate the simulation results and Section 4 concludes the paper with the final remarks and future developments.

### 2 CALCULATION OF INDIRECT LIGHTNING

### INDUCED OVERVOLTAGES IN PRESENCE OF CORONA

#### 2.1 LEMP Calculation

The lightning return-stroke electromagnetic field change is calculated at a number of points along the line employing a lightning return-stroke model, namely a model that describes the spatial and temporal distribution of the return stroke current along the channel. To this end, the return stroke channel is generally considered as a straight, vertical antenna (see Fig. 1).

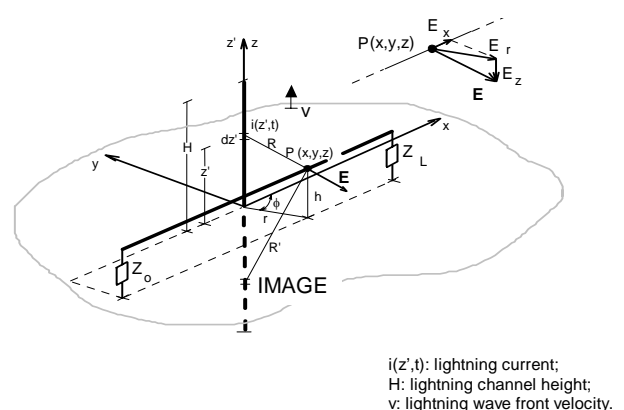


Figure 1. Geometry of the problem.

The LEMP calculation, which requires the specification of the lightning return-stroke current along the channel [12,13] can be performed in either the time or the frequency domain. However, a direct solution in the time domain is sometimes preferable because it allows the handling, in a straightforward manner, of non-linear phenomena such as corona.

The approach adopted in the paper for the LEMP calculation is based on the so-called dipole technique [14]. In particular, by referring to the geometry shown in Fig. 1, expressions for the electromagnetic field radiated by a vertical dipole of length  $dz'$  at a height  $z'$  along the lightning channel, assumed as a vertical antenna over a perfectly conducting plane, can be derived by solving Maxwell's equations in terms of retarded scalar and vector potentials (e.g. [15, 16]).

For distances not exceeding few kilometers, the assumption of a perfectly conducting ground can be considered as reasonable for the calculation of the vertical component,  $E_z^e$ , of the electric field and for the horizontal component of the magnetic field [17]. On the other hand, the horizontal component of the electric field,  $E_x^e$ , is appreciably affected by the finite conductivity of the ground. In this paper we make use of the simplified expression proposed independently by Cooray and Rubinstein [18,19] discussed by Wait in [20] and improved by Cooray in [21].

## 2.2 Field-to-transmission line coupling equations extended to the case of corona

The approach adopted in the paper for the calculation of the field-to-transmission line coupling in presence of corona is the same illustrated in [9]. It is based on the extension of the field-to-transmission line coupling equations of Agrawal et al. [10] in order to take into account both the presence of a finite conductive ground and corona. The model is described by the following equations:

$$\frac{\partial v^s(x,t)}{\partial x} + L \frac{\partial i(x,t)}{\partial t} + \int_0^t \zeta'_g(t-\tau) \frac{\partial i(x,\tau)}{\partial \tau} d\tau = E_x^s(x,h,t) \quad (1)$$

$$\frac{\partial i(x,t)}{\partial x} + C'_{dyn} \frac{\partial v^s(x,t)}{\partial t} = 0 \quad (2)$$

being:

- $v^s(x,t)$  the scattered voltage at coordinate  $x$  along the line and at time instant  $t$ ;
- $E_x^s(x,h,t)$  the horizontal component of the incident electric field along the  $x$  axis at conductor height  $h$ ;
- $i(x,t)$  the current induced along the line;
- $L$  the line inductance (external) per unit length;
- $\zeta'_g$  the inverse Fourier Transform of the per-unit-length ground impedance  $[\zeta'_{gij}] = F^{-1} \left\{ \frac{Z'_{gij}}{j\omega} \right\}$  [22];
- $C'_{dyn}$  the dynamic capacitance per-unit-length associated to corona.

Equations (1) and (2) are written in terms of scattered voltage associated to the total voltage by adding the so-called incident voltage:

$$v(x,t) = v^s(x,t) + v^i(x,t) = v^s(x,t) - \int_0^h E_z^s(x,z,t) dz \quad (3)$$

Note that, in (1) and (2), we have neglected the terms corresponding to the wire impedance and the so-called ground admittance. Indeed, for typical overhead lines and for the typical frequency range of interest (below 10 MHz), disregarding these parameters is a reasonable approximation.

Concerning the calculation of the term  $\zeta'_g$ , the general expression for the ground impedance in the frequency

domain does not have an analytical inverse Fourier transform. Thus, the elements of the transient ground resistance in time domain are to be, in general, determined using a numerical inverse Fourier transform algorithm. However, analytical expressions have been shown to be reasonable approximations to the numerical values obtained using an inverse FFT, and, in this paper, use is made of the expression developed in [23].

It is worth noting that a different coupling model that takes into account the presence of corona has been proposed by Cooray and Theethayi in [24].

Concerning the numerical solution of equations (1) and (2), we have used the Finite-Difference Time-Domain (FDTD) technique, one of the most popular approaches to solve the transmission line coupling equations in the time domain (e.g. [25]). Such a technique was used already by Agrawal et al. in [10] when presenting the field-to-transmission line coupling equations. In [10], partial time and space derivatives were approximated using a 1st order FDTD scheme. In [26], instead, the use of a 2<sup>nd</sup> order FDTD scheme based on the Lax-Wendroff algorithm [27, 28] was proposed. The 2<sup>nd</sup> order FDTD scheme shows much better stability compared to its 1<sup>st</sup> order counterpart, especially when analyzing complex systems involving nonlinearities (e.g. surge arresters and corona) [26, 29] and for this reason this approach has been adopted in this paper.

## 3 CORONA MODEL DYNAMIC EXPRESSION

As mentioned above, the presence of corona in the field-to-transmission line coupling model is taken into account in the term  $C'_{dyn}$ . In particular, from a macroscopic point of view, corona can be described by a charge-voltage diagram [2,3] in which, after a linear increase of the line charge with the voltage, a sudden change of the derivative of charge with respect to the voltage takes place by exceeding a threshold voltage ( $v_{th}$ ). This derivative defines the voltage-dependent dynamic capacitance  $C'_{dyn}$  that clearly becomes a function of time and space  $C'_{dyn}(x,t)$ . By means of such a formulation when the total voltage, defined by (3),  $v(x,t) < v_{th}$  then  $C'_{dyn}(x,t) = C'$  and can be calculated, for the case of single conductor line, by means of the well known expression:

$$C' = \frac{2\pi\epsilon_0}{\ln\left(\frac{2h}{r}\right)} \quad (4)$$

being  $r$  the conductor radius.

The threshold voltage,  $v_{th}$ , is calculated by means of the Peek's formula<sup>2</sup> (e.g. [30]):

<sup>1</sup> In the term  $C'_{dyn}$  the transverse conductance has been considered negligible.

<sup>2</sup> Note that in the Peek's formula both threshold voltage,  $v_{th}$ , and the critical electric field,  $E_{th}$ , the conductor radius is expressed in cm.

$$v_{th} = \frac{2\pi\epsilon_s r}{C_0} E_{th} \quad (5)$$

being  $E_{th}$ , in kV/cm, the critical electric field given by:

$$E_{th} = m_s \cdot 31 \left( 1 + \frac{0.308}{\sqrt{r}} \right) \quad (6)$$

In (6) the coefficient  $m_s$  is proportional to the surface irregularity.

In the paper, we have made reference to the case of a single-conductor line. However, it is worth noting that more complex models that deal with the case of multi-conductor lines have been presented (e.g. [8]).

The dynamic capacitance expression adopted in the paper to represent corona, is the one proposed in [11] and is described by the following equations:

$$C'_{dyn}(x,t) = B \cdot C' \left( \frac{v(x,t)}{v_{th}} \right)^{B-1} \quad (\text{for } v(x,t) \geq v_{th}) \quad (7)$$

$$C'_{dyn}(x,t) = C' \quad (\text{for } v(x,t) < v_{th})$$

where:

$$\begin{aligned} B &= 2.63(2r)^{0.153} & (\text{for } v(x,t) \geq 0) \\ B &= 1.121 + 3.4(2r) & (\text{for } v(x,t) < 0) \end{aligned} \quad (8)$$

#### 4 SIMULATION RESULTS

The line configuration used in this study is the one adopted in [9]. In particular, it is composed by a 1-km long, 7.5-m high, single-conductor overhead line (see Fig. 2). Two stroke locations, namely A (equidistant from the line terminations) and B (unsymmetrical) have been adopted.

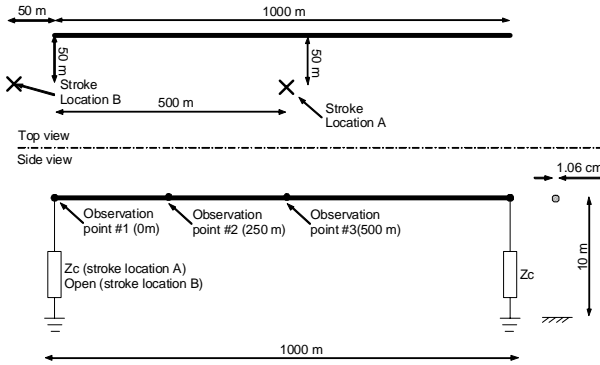


Figure 2. Adopted line configuration.

For each stroke location different lightning currents have been chosen. In particular, the amplitude of both currents has been selected in order to satisfy two conditions: i) obtain large enough induced overvoltages capable of exceeding the  $v_{th}$  value and ii) avoid to result into a direct strike to the line.

For stroke location A the channel-base current is characterized by a peak value of 35 kA and a maximum

time derivative of 42 kA/ $\mu$ s; for stroke location B the peak value is of 55 kA and the maximum time derivative of 66kA/ $\mu$ s. Both lightning current waveshapes and relevant time derivatives are shown in Fig. 3.

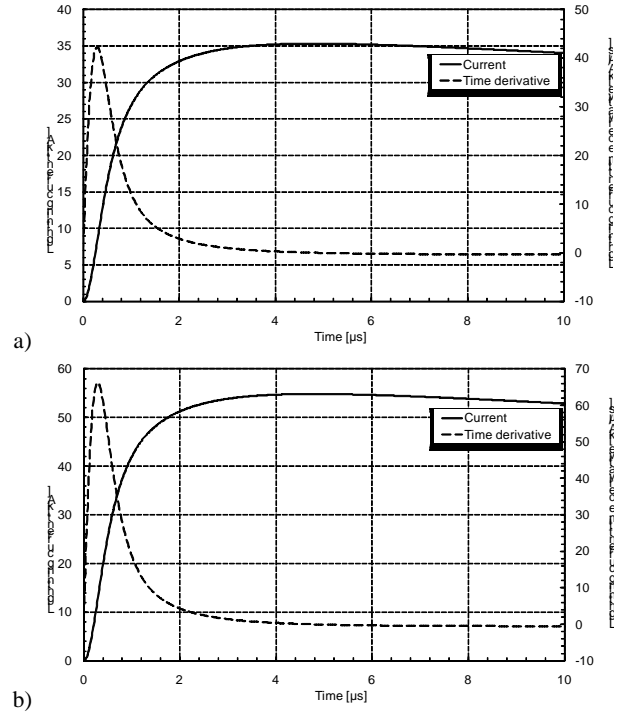


Figure 3. Adopted lightning current waveshapes: a) stroke location A of Fig. 2, b) stroke location B of Fig. 2.

Concerning the line termination, the line is matched at both ends for the case of stroke location A whilst, for stroke location B, the line is assumed open circuited at the left end in order to simulate, in first approximation, the presence of a power transformer, and matched at the right end.

Fig. 4 shows the Q-V curve that results from equations (7),(8).

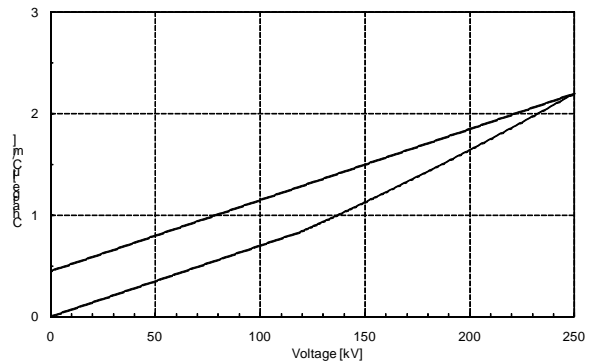


Figure 4. Corona Q-V curve that results from equations (7),(8).

For the case of ideal ground, Fig. 5 shows the comparison between lightning-induced overvoltages calculated with and without corona in correspondence of the three observation points along the line and for both stroke locations A and B (see Fig. 2).

For the lossy ground case the finite conductivity has been considered in both field calculation and coupling model. The ground conductivity has been chosen equal to 0.001 S/m.

As for the ideal ground case, Fig. 6 shows the comparison between lightning-induced overvoltages calculated with and without corona in correspondence of the three observation points along the line for both stroke locations A and B.

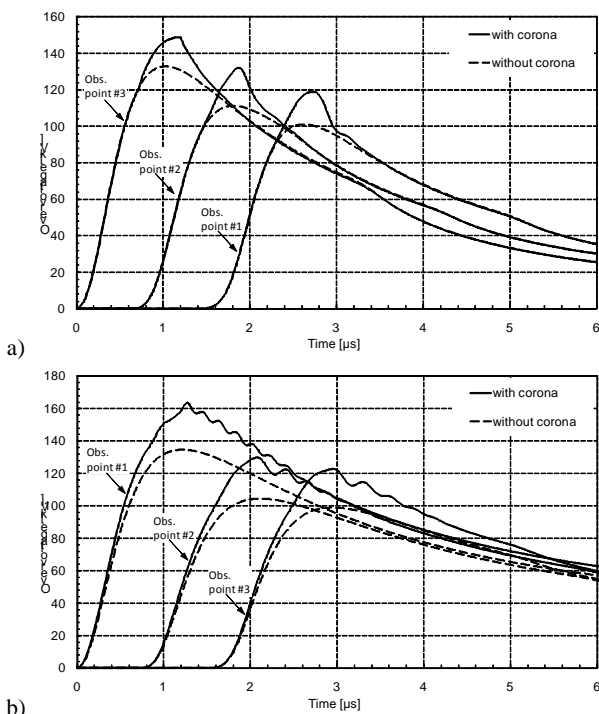
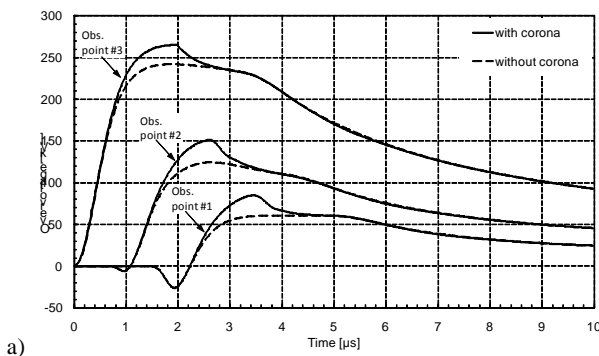
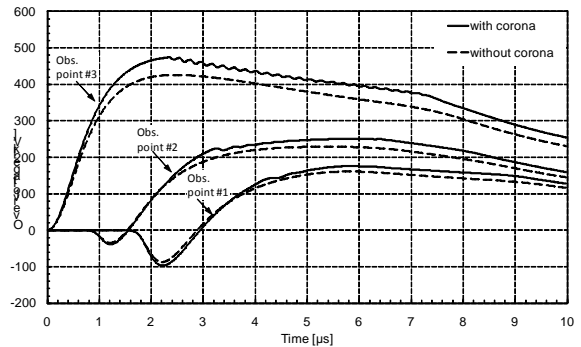


Figure 5. Lightning induced overvoltages in presence of corona for the case of ideal ground: a) stroke location A of Fig. 2, b) stroke location B of Fig. 2.



a)



b)

Figure 6. Lightning induced overvoltages in presence of corona for the case of finite conductive ground (0.001 S/m): a) stroke location A of Fig. 2, b) stroke location B of Fig. 2.

## 5 CONCLUSIONS

As expected the results reported in the paper do not differ qualitatively from those presented in [8,9], namely, the corona phenomenon acts in enhancing the amplitude of lightning-induced voltages. The explanations for such a somewhat unexpected behaviour have been given in [9]. With respect to [9], the present contribution provides results that are based on the adoption of an experimentally determined Q-V diagram and that, overall, reproduce a less pronounced increase of the induced overvoltages amplitude.

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