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Close electric fields and lightning-induced voltages predicted by a return-stroke model including corona and nonlinear channel resistance

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A B S T R A C T

In this paper, a return-stroke model based on nonuniform transmission line theory that includes non-linear losses and corona is used for calculating close electric fields and lightning-induced voltages on an overhead line. A study is performed to identify the influence of return-stroke corona on close electric fields and line overvoltages considering different model assumptions. It is shown that the consideration of corona affects the attenuation and distortion of the return-stroke current. Close vertical electric fields predicted by the model present waveforms, peak values, and decay with distance that are in agreement with measured data. A simpler case in which the return-stroke speed is artificially set to a prescribed value by controlling the inductance and capacitance of the channel is shown to lead to results that are in agreement with the complete return-stroke model considering nonlinear losses and corona. Similar conclusions apply to popular engineering return-stroke models typically used in lightning-induced voltage calculations provided the return-stroke speed is suitably adjusted. It is also shown that lightning-induced voltages calculated with the considered model are in good agreement with experimental data.

1. Introduction

The calculation of lightning-induced voltages on overhead transmission lines requires, as a first step, the determination of the spatial and temporal distribution of the return-stroke current in the lightning channel [1,2]. For their simplicity, ease of implementation and fast computation, engineering return-stroke models [3–5] are usually preferred for this task, even though the physical processes in the lightning channel are somewhat downplayed in their formulation.

A more rigorous representation of lightning return-stroke channels to evaluate the interaction between lightning electromagnetic fields and overhead transmission lines is obtained with return-stroke models based on electromagnetic field theory [e.g., 6–9]. Such models are able to account for aspects that are usually neglected in engineering return-stroke models, such as the non-transverse-electromagnetic (non-TEM) field structure associated with the propagation of the return-stroke current, the presence of losses, and the typically asymmetrical channel geometry. However, models based on electromagnetic field theory are usually time consuming and not straightforward to implement, which poses difficulties to their widespread use in lightning-induced voltage calculations.

A compromise between the rigorous approach provided by models based on electromagnetic field theory and the practical aspects of the engineering return-stroke models can be found in models based on transmission line theory [10], also called distributed-circuit models [11]. In such models, the lightning channel is represented as a non-uniform transmission line that can include nonlinear or time-varying parameters in a straightforward way [12–17]. Different models pertaining to this class have been proposed in recent years to represent the nonlinear decay of the channel resistance from a high value at early times (corresponding to the leader channel) to a low value at later times (corresponding to the return-stroke channel) [15–17]. One of these models was used in [18] to identify the influence of a nonlinear channel resistance on lightning-induced voltages on overhead lines. More recently, this model was improved with the inclusion of a corona model [19], which has led to more consistent predictions in terms of current profiles, return-stroke speeds, and remote electromagnetic fields. However, the implications of this improved model on lightning-induced voltage calculations remain to be evaluated.

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In this paper, the return-stroke model of [19] is used to calculate lightning-induced voltages on overhead lines considering both corona and nonlinear losses in the return-stroke channel representation. The analysis is aimed at identifying to what extent the inclusion of corona in the return-stroke channel is able to modify the resulting lightning-induced voltages compared to simpler channel representations.

2. Modeling details

2.1. Return-stroke model

The return-stroke model used in this paper is described in detail in [19]. It is a nonuniform transmission line model in which the lightning channel is represented as a straight, vertical wire located above a perfectly conducting ground. The lightning current is injected at the channel base by an ideal current source. The line inductance and capacitance per unit length are calculated as $L = c^{-1}Z_c$ and $C = c^{-1}{Z_c}^{-1}$, respectively, where $Z_c = 60\ln(2z/r)$, c is the speed of light, r is the core radius, and z is the vertical coordinate representing the distance from each point of the channel to the ground surface. The expression for Z_c is derived under the assumption that a vertical wire of finite radius located above a perfectly conducting ground plane can be viewed as a conical antenna whose cone angle is very small [20]. In [21], a nonuniform transmission line model using this expression is shown to reproduce with good accuracy the current pulse attenuation and distortion predicted by a rigorous electromagnetic model.

At each channel section, the core radius is assumed to expand as $r = \left(k\int_0^t i^{2/3}\,dt + r_i^2\right)^{0.5}$ [17], where r_i is the initial channel radius and $k = (0.25\sigma\xi\rho_0\pi^2)^{-1/3}$ is a constant depending on the channel conductivity, σ, on the ambient atmospheric density, ρ_0, on the parameter ξ that controls the rate of radial channel expansion, and on the current i at the n-th channel segment. By neglecting skin effect, the channel resistance per unit length is calculated as $R = \sigma^{-1}\pi^{-1}r^{-2}$, which decays nonlinearly with time due to the channel expansion. The resulting variation of R bridges the gap between the initial stage in which the channel is lossy (leader channel) to the final stage in which channel losses are low (return-stroke channel) [22,23]. This same pair of equations was used in [18] to evaluate the influence of a nonlinear channel resistance on lightning-induced voltages.

To calculate the deposition of corona space charges around the channel, the corona model proposed by Cooray [24] is used as described in detail in [19]. According to this model, if the radial electric field E exceeds the breakdown electric field E_b at the surface of the channel core, the corona sheath radius r_c and the deposited corona charges q_c at a given channel section can be obtained from the simultaneous solution of equations relating voltage, charge, the critical electric field for the stable propagation of streamers, E_c, and the inner (r_a) and outer (r_b) radii of the coaxial structure assumed in the corona model. Once the corona charges q_c are determined at each time step, the corona current i_c associated with each channel segment is obtained as the time-derivative of q_c.

For simulating the current propagation in a nonuniform transmission line with nonlinear (time-varying) parameters, the first order FDTD method described in [25] is used to solve $\partial v/\partial z + Ri + L\partial i/\partial t = 0$ and $\partial i/\partial z + C\partial v/\partial t = -i_c$, which are the modified telegrapher's equations proposed in [26] to include corona in the propagation of surges along a horizontal conductor above ground, with the addition of the loss term. Here, this equation is extended to the vertical conductor case with the calculation of L and C as discussed above. In the solution method, the voltages and currents are calculated iteratively at each time step considering the effects of corona and nonlinear losses at each voltage and current node [19].

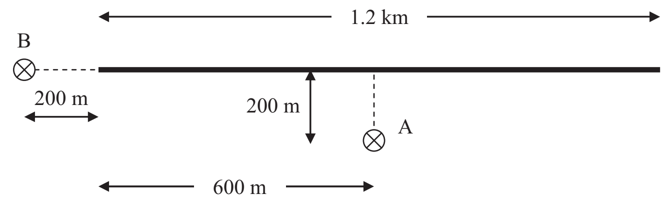

Fig. 1. Upper view of the simulated case. The stroke locations are indicated by the letters A and B.

2.2. Model for lightning-induced voltage calculations

For investigating the simultaneous effect of return-stroke corona and nonlinear channel losses on lightning-induced voltages on an overhead transmission line, the topology shown Fig. 1 is considered. It consists of an overhead wire with length of 1.2 km, height of 10 m, and radius of 5 mm, matched at both ends. Two different stroke locations were considered, one 200 m far from the midpoint of the line (point A) and the other 200 m far from the left end of the line (point B).

In the lightning-induced voltage calculations, the model of Section 2.1 was used for estimating the spatial and temporal distribution of the return-stroke current. The assumed channel-base current, which was synthesized as the sum of two Heidler functions as shown in [27], reproduces the median parameters of subsequent strokes of downward negative lightning measured at the Morro do Cachimbo Station in Brazil, with a peak value of 16 kA and a maximum time derivative of 29.6 kA/μs. The effect of the finite ground conductivity on the incident fields was taken into account with the Cooray–Rubinstein approximation [28,29]. The field-to-line coupling was performed with the model of Agrawal et al. [30]. The interaction of the incident fields with the overhead lines was implemented in the Alternative Transients Program (ATP) as described in [31]. Different values of ground conductivity, σ_g, and a ground relative permittivity of $\varepsilon_r = 10$ were considered in the field calculations. For simplicity, ground and conductor losses were neglected in the calculation of the line parameters.

3. Predicted currents and electric fields

3.1. Model settings

Agrawal et al.'s coupling model [30] is written in terms of the vertical and horizontal components of the incident electric fields. For this reason, it is useful to investigate the influence of corona on electric fields predicted by the return-stroke model of Section 2.1 before presenting any lightning-induced voltage calculation. For this, a base case is defined in which $r_i = 1$ mm, $\xi = 1$, $\sigma = 2.5 \times 10^4$ S/m, and a minimum value of 0.075 Ω/m are assumed in the channel resistance model. This set of parameters leads to an initial resistance of 12.7 Ω/m that is in line with both measurements and theoretical estimates of the leader channel resistance [22,23]. For the assumed channel-base current, the initial resistance at the current injection point decays nonlinearly with time, reaching 1.42 Ω/m, 0.20 Ω/m and 0.11 Ω/m after 1 μs, 5 μs, and 10 μs, respectively. These values are representative of the return-stroke channel resistance [22].

To include the nonuniform nature of the channel geometry in the corona model, it is assumed that $r_b = 2z$, as proposed by Gorin [13], with $r_a = 1$ cm. This is equivalent to considering a nonuniform coaxial structure for the corona model in which the characteristic