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Evaluation of parameters influencing the lightning performance of communication towers by numerical modeling and experimental tests

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ABSTRACT

This paper analyzes the effective parameters on lightning performance. The effects of tower height, breakdown electric field threshold, the ground slope of installation place, and the effect of the trees around the tower are investigated. A 3-D numerical analysis model is proposed to determine the number of direct lightning strokes to antennas. The communication tower, lightning rod, downward descending leader and upward leaders are modeled by different shapes of charges. Finally, a small-scale communication tower was built and tested in a high voltage laboratory. The experimental tests were consistent with the simulation results verifying the merits of the proposed method.

1. Introduction

Lightning rod is basically responsible for the stroke interception, the most important task in a Lightning Protection System (LPS). Since its invention by Benjamin Franklin, lightning rod has found a very wide application [1–3]. The protective angle recommended for lightning rods varied within a wide range. Originally, these protective angles were based on experience, but later with the availability of high-voltage test facilities, these angles were also determined by tests on small-scale physical models [4].

In order to analyze the lightning performance of equipment and structures such as communication towers, several analytical methods have been proposed. At first, the Electro Geometric Model (EGM), based on the principle of striking distance, was found to be satisfactory. The striking distance is defined as the "distance between the object to be struck and the tip of the downward-moving leader at the instant that the upward leader is initiated from the object" [5–7]. Several researchers have developed the EGM. Eriksson [8,9] improved the model named "the Collection Volume Method (CVM)". The Rolling Sphere Method (RSM) was developed for more complex structures. This method is one of the direct applications of EGM for 3-D geometries.

However, in analytical methods, the expression of striking distance does not show any explicit reference to the field intensification at the structure top and the propagation of the upward leaders is not considered [10,11].

Therefore, Dellera et al. [12,13] and Rizk [14,15] proposed the Leader Progression Model (LPM) as a numerical approach to determine the path of the lightning and the final encounter. Recently, the LPM has been employed and developed by some researchers [19–24].

In present work, a model in a three-dimensional environment is proposed which takes the communication tower and antennas as well as air terminal and the step nature of downward lightning leader into account. In addition, the inception and propagation of multiple upward leaders are considered. The electrical fields are computed using the Charge Simulation Method (CSM) [16–18]. The number of direct lightning strokes to the antennas of communication towers is calculated accurately. Here, a new definition called the density of strokes causing shielding failures per year is provided. Accordingly, the risky areas in the leader-tip starting surface are determined. On the other hand, an area with a high density of strokes causing shielding failures expresses greater probability of its lightning encounter to antennas. The lightning performance analysis is performed for different conditions and the results are evaluated. Finally, in order to validate the simulation results, some laboratory tests were utilized on a small-scale communication tower.

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2. Leader progression and final jump

The leader progression approach is based on the idea that a similarity exists between lightning phenomenon and discharges in long air gaps [12]. Here, the cloud-to-ground lightning flashes are considered and the presence of downward lightning leader is a principle of calculations. The simulation is started with a vertical straight section of the lightning leader propagated up to a level, which is high enough to nullify the influences of the earthed objects. This level is selected higher than twice the highest object [7]. The downward lightning leader develops gradually and to be assured of the leader progression in long air gaps, the propagation is simulated by steps with a length of 10 m. Its direction is towards the maximum potential gradient. During the descent of a downward lightning leader, the upward leaders are initiated from grounded objects and are propagated towards the downward lightning leader. When an upward leader succeeds to intercept the downward lightning leader, a conducting path between the cloud and the ground is created and the return stroke lightning current is drained [25].

The main characteristics used in this model are the direction of the leaders; charge distribution along the downward and upward leaders; inception criteria of the upward leaders; leaders advance speed; and the final jump criterion [26].

2.1. Direction of leader motion

The procedure of calculating the downward and upward leader attachment requires the field calculation in the environment of the study. In each step of lightning leader motion, a hemisphere with a radius of a step length is drawn around the tip of the leader. Therefore, the next jump point of the leader is a point on the hemisphere that the voltage gradient along the line connecting the leader tip to the target point is maximum. The path of downward lightning leader including the tilted channel segments is replaced by vertical and horizontal line charges.

2.2. Inception criteria of the upward leaders

For a reliable assessment of the lightning path and hence an accurate evaluation of the lightning protection performance, it is very essential to appropriately consider the inception and propagation of the upward leaders.

Different criteria have been proposed for calculating the electric field intensity to ensure the stability of the upward leader inception [8,12,28,36]. At this work, the model proposed in Ref. [19] is applied to check the upward leader inception condition. The streamer charge is initially calculated as follows [19]:

$$l_s^0 = \frac{U_0}{E_s - E_b} \tag{1}$$

$$\Delta Q^0 = 0.5 \cdot K_Q \cdot l_s^2 \cdot (E_s - E_b), \tag{2}$$

where U_0 and E_b are the voltage and field on the fitted line of the background electric field and l_s^0 is the initial length of the streamer. E_s and K_Q are the constant streamer electric field and a geometrical factor, respectively.

If the initial streamer charge (ΔQ^0) is more than $1\mu C$, the initial leader length is assumed to be 1 cm, then the streamer length and streamer space charge are calculated for each leader movement step as follows [19]:

$$U_{tip}^i = E_{\inf} \cdot l_l^i + x_0 \cdot E_{\inf} \cdot \ln\left(\frac{E_{init}}{E_{\inf}} - \frac{E_{init} - E_{\inf}}{E_{\inf}} e^{-l_l^i/x_0}\right) \tag{3}$$

$$l_s^i = \frac{U_0 + E_s \cdot l_l^i - U_{tip}^i}{E_s - E_b} \tag{4}$$

$$\Delta Q^i = K_Q \cdot \left(l_s^{i-1} - l_l^i\right) \cdot \left[E_s\left(l_l^i - l_l^{i-1}\right) + U_{tip}^{i-1} - U_{tip}^i\right] \tag{5}$$

$$\Delta l_l^i = \frac{\Delta Q^i}{q_l} \tag{6}$$

$$l_l^{i+1} = l_l^i + \Delta l_l^i, \tag{7}$$

where U_{tip}^i is the leader potential in step i; E_{init} and $E_{\inf}$ are the initial and final values of the leader gradient; and x_0 and q_l are the constants. If the leader length (l_l^{i+1}) increases to a maximum value ($l_{\max}$), equal to 2 m, the stable upward leader will be incepted. The constants of the upward leader model are: $E_s = 450$ kV/m; $E_{init} = 400$ kV/m; $E_s = 450$ kV/m; $x_0 = 0.75$ m; $K_Q = 3.5 \times 10^{-}11$ C/V; $q_l = 50 \times 10^{-}6$ C/m.

When this condition is fulfilled, an upward leader propagates towards the downward lightning leader tip. In order to determine the direction of each upward leader, according to subsection 2-1, the electric field is calculated at fixed distances from the upward leader tip over various directions at each step. The next step is then directed along the line with the field maximum mean. The points with more likelihood of inception and propagation of upward leaders are the top of the lightning rod, the top of the antenna, and the ground surface bellow the lightning tip (Fig. 1).

2.3. Charge distribution along the leaders

In the scientific literature, there are different proposals for the charge distribution along the downward leader such as uniform, linear, and exponential distributions [22,27]. Here, the charge density distribution along the downward leader channel is calculated as follows [33,36],

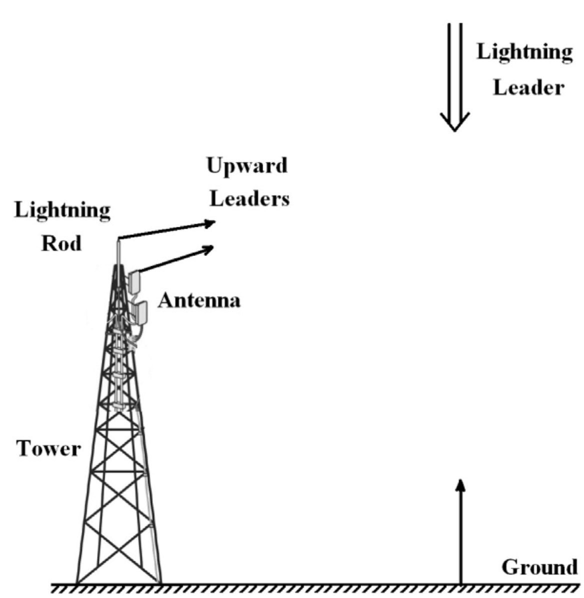

Fig. 1. More likely points to start upward leaders.