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# Attractive radii of vertical and horizontal conductors evaluated using a self consistent leader inception and propagation model—SLIM

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ABSTRACT

A self consistent lightning connecting leader inception and propagation model (SLIM) is utilized to study the attachment of lightning flashes to grounded structures and hence to evaluate the lightning attractive radii of vertical cylindrical structures and horizontal conductors as a function of height of the structure and peak current of the first return stroke. The attractive radius is defined as the maximum lateral distance from where the structure would be able to attract a down-coming stepped leader. The results are compared with the ones that one would obtain using Electro-Geometrical Method (EGM). The results show that for structure heights of the order of 30 m or less the attractive radii obtain from SLIM do not deviate significantly (i.e. the error is less than about 20%) from the EGM values. However, for taller objects SLIM predicts significantly larger attractive radii than EGM and the error increases with increasing height.



## 1. Introduction

An exact evaluation of the point of lightning strike of a grounded structure should take into account the development of streamers from the extremities of the structure, subsequent streamer to leader transition, inception of a stable connecting leader and the final encounter between the upward moving connecting leader and the down coming stepped leader. On the other hand, the current procedure of lightning protection of grounded structures including power transmission and distribution lines is based on the Electro-Geometrical Method (EGM) which neglects most of the physics associated with the attachment process of lightning flashes to structures (Armstrong and Whitehead, 1968). This method assumes that the stepped leader will get attached to the first point on the structure that comes within a critical distance from the tip of the stepped leader. This critical distance is called the striking distance. Several expressions are available in the literature that express the striking distance as a function of return stroke current and structure geometry (Cooray and Becerra, 2009).

The attachment of a stepped leader to a grounded structure takes place through the mediation of a connecting leader that will be issued from the grounded structure due to the intense electric field caused by the down coming stepped leader. The simulation of the attachment process thus requires evaluation of the instant at which a connecting leader is issued from a grounded structure. Several models that can do this have been developed by scientists, but many of these models are based partly on the data gathered from long sparks from laboratory and therefore semi empirical in nature (Eriksson, 1987, Dellera and Garbagnati, 1990a, 1990b, Rizk, 1994, Petrov and Waters, 1995, Akyuz, and Cooray, 2001).

Recently, Lalande (1996) used a model for the leader propagation in long gaps proposed by Goelian et al. (1997) and combined it with the thermo-hydrodynamic model of the leader channel proposed by Gallimberti (1972) in order to compute the leader inception condition. In constructing the model he also assumed that the ratio of the leader velocity to leader current is a constant. Based on this model Lalande (1996) derived the background electric field that is necessary to initiate leaders

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from grounded vertical conductors. However, the theory was not extended to study the propagation of leaders in time varying electric fields generated by stepped leaders. Utilizing the same physics developed by Gallimberti (1972), Becerra and Cooray (2006a, 2006b, 2006c) developed a model that can predict both initiation and subsequent propagation of connecting leaders in the electric field produced by stepped leaders. This model, called Self consistent Leader Inception and propagation Model (SLIM), is utilized here to evaluate the attractive radii of vertical and horizontal conductors. The attractive radius of a conductor is defined here as the maximum lateral distance from where a leader with a given prospective return stroke current is attracted to the conductor.

## 2. Self consistent leader inception and propagation model of Becerra and Cooray—SLIM

The model SLIM, which is introduced by Becerra and Cooray (2006a, 2006b, 2006c) to study lightning attachment to grounded objects, is based on the physics of leader discharges as developed by Gallimberti (1972). The model can be applied to study lightning attachment to grounded structures including conductors and towers of power transmission and distribution lines. The main steps that are included in the model are: (1) Formation of a streamer discharge at the tip of a grounded object (first, second or third streamer bursts). (2) Transformation of the stem of the streamer into thermalized leader channel (unstable leader inception). (3) Extension of the positive leader and its self-sustained propagation (stable leader inception).

In the model, the avalanche to streamer transition, i.e. streamer inception, is evaluated using the well-know streamer inception criterion (Gallimberti, 1972). The transition of the discharge from a streamer to a leader is assumed to take place if the total charge in the second or successive streamer bursts is equal to or larger than about 1 μC (Gallimberti, 1972, Lalande et al., 2002). The procedure utilized by Becerra and Cooray (2006a, 2006b, 2006c) to estimate the charge in the streamer zone is identical to the method originally developed by Goelian et al. (1997). As the background electric field increases, several streamer bursts will be generated by the point under consideration provided that the streamer inception criterion is satisfied. The charge associated with these streamer bursts are calculated as follows using a distance–voltage diagram with the origin at the tip of the grounded structure. The streamer zone is assumed to maintain a constant potential gradient $E_{str}$. In the distance–voltage diagram this is represented by a straight line. On the same diagram the background potential produced by the thundercloud and the down-coming stepped leader at the current time is depicted. If the area between the two curves up to the point where they cross is $A$, the charge in the streamer zone is given by

$$\Delta Q^{(0)} \approx K_Q A \qquad (3)$$

where $K_Q$ is a geometrical factor. If the charge of the second (or third) streamer burst, $\Delta Q^{(0)}$, is lower than 1 μC, unstable leader inception condition is not fulfilled and the analysis is repeated in the next time step.

Once the condition for unstable leader inception is fulfilled, an iterative geometrical analysis of the leader propagation starts with $I=1$ with an initial leader length of $l_L^{(1)}$ equal to $\Delta Q^{(0)}/q_L$. In the previous statement $q_L$ is the charge per unit length necessary to realize the transformation of the streamer stem located in the active region in front of the already formed leader channel into a new leader segment. The extension of the connecting leader and the downward movement of the stepped leader continuously change the potential distribution. The streamer charge generated during the extension of the leader is calculated as before but now including both the leader and its streamer zone in the distance–voltage diagram. This is facilitated by representing the potential at the tip of the leader $U_{tip}^{(i)}$ during the current simulation step i with the semi-empirical equation derived by Rizk (1989):

$$U_{tip}^{(i)} = l_L^{(i)} E_\infty + x_o E_\infty \ln\left[\frac{E_{str}}{E_\infty} - \frac{E_{str} - E_\infty}{E_\infty} e^{-\left\{l_L^{(i)}/x_0\right\}}\right] \qquad (4)$$

In the above equation $l_L^{(i)}$ is the leader length at the current simulation step, $E_\infty$ is the final quasi-stationary leader gradient and $x_0$ is a constant parameter given by the product $v.\theta$, where $v$ is the ascending positive leader speed and θ is the leader time constant. Next, the area between the current background potential and the potential curve that represent the leader and its streamer zone is calculated. The corresponding total charge is calculated using 3. The charge generated in the current time step is obtained by subtracting from this the total charge obtained in the previous time step. From this charge the leader advancement distance $\Delta l_L^{(i)}$ during the current time step is evaluated from

$$\Delta l_L^{(i)} = \frac{\Delta Q^{(i)}}{q_L} \qquad (5)$$

If the charge is greater than about 40 nC the progression of the leader is continued into the next time step. Otherwise, the leader stops and the analysis is repeated again keeping track of the space charge already developed. Once the leader is incepted the condition necessary for its stable propagation is analysed, as described above, by evaluating the charge generated by the streamers ahead of the leader channel. The propagation condition depends on the background electric field as well as the rate of change of the electric field. In the model the stepped leader is assumed to take a straight and vertical path to ground and this path is not affected by the presence of a connecting leader. The direction of the connecting leader, on the other hand, is such that it always seeks the tip of the stepped leader. The final attachment of the two leaders is assumed to takes place when the average potential gradient between the two leader tips is 500 kV/m. The values of the parameters used in Eqs. (3)–(5) are tabulated in Table 1 and a detailed discussion of them can be found in (Becerra and Cooray, 2006a, 2006b, 2006c). The model not only predicts the conditions under which leaders are incepted and finally get attached to each other but it also provides the current and the speed of the upward moving leaders.

## 3. The potential and the charge distribution of the stepped leader channel

In order to evaluate the attractive radii of grounded structures it is necessary to know the potential and the charge distribution along the stepped leader channel. Recently, Cooray et al. (2007) and Cooray and Rakov (2011) (Preliminary results of