Journal of Electrostatics 71 (2013) 577–581

Contents lists available at SciVerse ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

On the attachment of lightning flashes to grounded structures with special attention to the comparison of SLIM with CVM and EGM

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ARTICLE INFO

Article history:
Received 28 August 2012
Accepted 29 November 2012
Available online 13 December 2012

Keywords:
Lightning
Collection Volume Method
CVM
Attractive radii
EGM

ABSTRACT

Lightning attachment to vertical grounded conductors are presented with special attention to the lightning attractive radii of vertical conductors as predicted by self consistent leader inception and propagation model (SLIM), Electro Geometrical Model (EGM) and Collection Volume Method (CVM). Moreover, SLIM was utilized to model the attachment of a slanted stepped leader to a tall tower that resulted in a side flash to a point below the top of the tower. The important conclusions to be drawn from the results obtained are the following: (a) The error (caused by neglect of the connecting leader in EGM) in the predicted attractive radii and the striking distance of EGM increases with increasing structure height. However, for structures whose height is shorter than about 30 m the error associated with using EGM is less than about 20%. (b) The attractive radii predicted by the Collection Volume Method (CVM) are much larger than the ones predicted by SLIM and EGM. Thus, the use of CVM to locate the lightning conductors on a structure may undermine its safety. (c) Slanted stepped leader channels can cause side flashes in tall structures even though long connecting leaders are emitted from the top of the structure.

1. Introduction

The physics of lightning attachment to a grounded structure is very complex and in order to simulate it one has to consider a series of physical processes [1]. Any model that attempts to model the attachment process successfully should include these physical processes. The first model that attempted to model the lightning attachment process was introduced by Eriksson [2]. This model is known in the literature as Collection Volume Method (CVM). Since then Rizk [3] and Dellera and Garbagnati [4] introduced models that can simulate the attachment process with details that were absent in the CVM. More recently Becerra and Cooray [5–7] introduced a model that is based on the physics of the lightning attachment process as developed by Gallimberti [8]. This model is known in the literature as Self Consistent Leader Inception and Propagation Model (SLIM). On the other hand, the standard procedure used today to place lightning terminals on buildings is the Electro Geometrical Model (EGM). In the latter the physics of the attachment process is downplayed in an attempt to create a user friendly engineering model that can be handled easily by protection engineers.

Recently, several lightning protection industries have adopted the CVM to place lightning terminals on buildings to be protected by lightning flashes [9]. This action calls for a thorough investigation of the predictions of CVM and compare them with the predictions of other attachment models. In this paper we will derive and compare the attractive radii of conductors of different heights as predicted by EGM, SLIM, and CVM. Before proceeding further let us summarize the main features of each model.

2. Electro geometrical model (EGM)

According to the EGM of lightning protection, the attachment between the stepped leader and the grounded structure takes place when the tip of the stepped leader reaches a critical distance from the structure. In IEC lightning protection standard this distance is identified as the radius of the sphere used in the *rolling sphere method* of locating lightning conductors on structures. As a consequence EGM does not envisage the presence of a connecting leader. In the current IEC lightning protection standard this critical distance or the striking distance (or the radius of the rolling sphere) as a function of the prospective return stroke current is given by

$$S = 10I_p^{0.65} \tag{1}$$

In the above equation S is the striking distance and I_p is the peak return stroke current (in kA). Observe that according to the above definition the striking distance is independent of the height of the structure.

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http://dx.doi.org/10.1016/j.elstat.2012.11.035

3. Collection Volume Method (CVM)

The following are the main assumptions used in CVM [2].

(1) The downward stepped leader takes a straight and vertical path to ground and is not influenced by the structures at ground level.
(2) The linear charge density on the leader channel decreases linearly upwards. Thus the charge per unit length ρ on the leader channel as a function of height z is given by

$$\rho = \rho_0\left[1-\frac{z}{H}\right] \tag{2}$$

In the above equation H is the height of the lightning channel which is assumed to be 5 km. Thus the total charge on the leader channel is

$$Q = \rho_0 H/2.0 \tag{3}$$

In the above equation ρ_0 is a constant and H is the height of the channel. Eriksson assumed that $H = 5$ km.

(3) In his original treatment Eriksson [2] assumed that the total charge in the leader channel Q (in C) is connected to the return stroke peak current I_p (in kA) by the equation

$$I_p = 29.4Q^{0.7} \tag{4}$$

However, in the recent implementation of the CVM in lightning protection the total charge on the leader channel is assumed to be given by Ref. [10]

$$I_p = 10.6Q^{0.7} \tag{5}$$

Equation (5) in combination with 2 and 3 fix the linear charge distribution on the leader channel. The calculations presented in this paper are based on the Equation (5).

(4) As the stepped leader channel approaches the ground the electric field at the extremities of the structure is evaluated continuously in the model to find the time of the upward leader or connecting leader inception. The critical radius concept is used as the criterion for upward connecting leader inception. In order to apply this concept the tip of the grounded lightning conductor or the extremity of the structure is replaced by a sphere of critical radius (assumed to be 0.38 m) and the leader inception is assumed to take place when the electric field at the surface of this sphere exceeds 3×10^6 V/m. It is assumed that when this condition is reached an upward connecting leader is incepted.
(5) The connecting leader travels in space in such a way that it will find the closest path for the connection with the stepped leader. The final attachment of the two leaders takes place when two tips of the leader channel meet each other.
(6) In order to model the attachment process as described above, it is necessary to have the ratio between the speeds of two leaders. In the model, the ratio between the speed of propagation of the downward stepped leader and the upward moving connecting leader is assumed to be 1.

4. The model SLIM

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). Let us consider these steps in details. The description given below is based on the work published by Becerra and Cooray [5,6].

Assume that the electric field at ground level as a function of time generated by the down coming stepped leader is known. How this is evaluated in the model is described in Section 3.1. The simulation consists of several main steps and let us take them one by one.

(1) The first step is to extract the time or the height of the stepped leader when streamers are incepted from the grounded rod. Since the background electric field produced by the stepped leader is known (or given) the electric field at the tip of the grounded rod can be calculated, for example, by using charge simulation method. This field is used together with the avalanche to streamer transition criterion to investigate whether the electric field at the conductor tip is large enough to convert avalanches to streamers. In the analysis it is assumed that the electron avalanche will be converted to a streamer when the number of positive ions at the head of the avalanche exceeds about 10^8. The simulation continues using the time varying electric field of the stepped leader until the streamer inception criterion is satisfied.
(2) The moment the streamer inception criterion is satisfied a burst of streamers will be generated by the extremity of the object; in our case from the tip of the lightning conductor. The next task is to calculate the charge in this streamer burst. The charge associated with these streamer bursts are calculated using a distance–voltage diagram with the origin at the tip of the grounded conductor as follows. 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

$$Q_o \approx K_Q A \tag{6}$$

where K_Q is a geometrical factor. Becerra and Cooray [5,6] estimated its value to be about 3.5×10^{-11} C/V m.

(3) The next task is to investigate whether this streamer burst is capable of generating a leader. This decision is based on the fact that in order to generate a leader a minimum of 1 μC is required in the charge generated by the streamers [8]. If the charge in the streamer zone is less than this value then the procedure is repeated a small time interval later. Note that with increasing time the electric field generated by the stepped leader increases and, consequently, the charge in the streamer bursts increases.
(4) Assume that at time t, the condition necessary for leader inception is satisfied. The next task is to estimate the length and the radius of this initial leader section. In doing this it is assumed that the amount of charge one needs to create a unit length of positive leader is q_l. Becerra and Cooray [6] evaluated this parameter using the equations given by Gallimberti [8] and it was shown that it is a function of the leader speed. For low leader speeds (around 10^4 m/s) its value is about 65 μC/m. In the analysis the value of q_l is estimated using the relationship between this parameter and the leader speed as published by