Electric Power Systems Research xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Electric Power Systems Research

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

The influence of lightning conductor radii on the attachment of lightning flashes

Vernon Cooray

Department of Engineering Sciences, Uppsala University, Uppsala, Sweden

ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 9 December 2016
Accepted 2 January 2017
Available online xxx

Keywords:
Lightning conductors
Lightning attachment
Blunt and sharp conductors
Glow corona

ABSTRACT

The influence of the tip radius of lightning conductors on their lightning attractive distance as predicted by the self-consistent leader inception and propagation model (SLIM) is presented. The results show that in the absence of any glow corona from the tip of the conductor a smaller tip radius gives rise to a larger attractive radius than a larger radius. It is suggested that the reason for the experimental observations which show that blunt conductors are more efficient lightning receptors than sharp ones is the presence of glow corona at the tip of the sharp ones during the time of lightning strikes. Moreover, in a given background electric field, the probability of the inception of glow corona at the conductor tip increases with increasing conductor height and decreasing conductor radius. Thus, in a given electric field, as the conductor height increases its radius has to be increased to avoid the inception of glow corona at the tip. For this reason, the conductor radius that performs best as a lightning interceptor depends on the height of the conductor and the best performance shift from smaller radii to larger ones with increasing height of the conductor.

1. Introduction

In a classical experiment Moore et al. [1] demonstrated that moderately blunt conductors are more efficient than sharp or extremely blunt conductors. They speculated that the glow corona at the tip of the sharp conductors could be the reason for their inefficiency, in comparison to the blunt ones, in attracting lightning flashes. However, a question that will arise naturally when studying the results of this experiment is the following: What would be the effect of conductor radius on lightning attachment if glow corona is not present at the tip of the conductors? In order to investigate this we will derive and compare the height of attachment and the attractive radii of conductors of different tip radii pertinent to stepped leaders of lightning flashes. The model simulations are conducted using SLIM, a physics based model introduced by Becerra and Cooray [2,3, see also 4 for a detailed description]. Before proceeding further let us summarize the main features of SLIM.

2. 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 a 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 [3,4].

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. The simulation consists of several main steps and let us consider 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 [5]. The simulation continues using the time

E-mail addresses: Vernon.Cooray@angstrom.uu.se, vernon.cooray@hvi.uu.se

http://dx.doi.org/10.1016/j.epsr.2017.01.002
0378-7796/

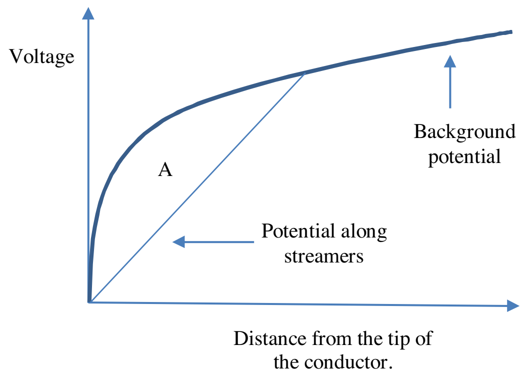

Fig. 1. Distance–Voltage diagram that illustrates how the charge associated with a streamer burst is obtained. The area between the two curves representing the background potential and the streamer potential is marked A.

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 from the extremity of the object; in our case from the tip of the lightning rod. 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 procedure is illustrated in Fig. 1. 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 (see Fig. 1), the charge in the streamer zone is given by

$$Q_o \approx K_Q A \tag{1}$$

where K_Q is a geometrical factor. Becerra and Cooray [3,4] estimated its value to be about 3.5×10^{-11} C/V m. In the analysis we assume $E_{str} = 5 \times 10^5$ V/m [5]. This value of the electric field is valid for streamers propagating in normal atmospheric density. A slight change of this electric field around this value (10%) in the calculations to be presented does not change the conclusions to be reached.

(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 [5]. 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 that is necessary to create a unit length of positive leader is q_l. Becerra and Cooray [3] evaluated this parameter using the equations given by Gallimberti [5] 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 Becerra and Cooray [3]. Based on these considerations, the initial length of the leader section L_1 is given by Q_o/q_l, where Q_o is the charge in the streamer burst that immediately precede the inception of the leader. The initial radius of the leader, $a_{L1}(t)$ is assumed to be 10^{-3} m and the initial potential gradient of the leader section, $E_{L1}(t)$ is assumed to be equal to the potential gradient of the streamer region i.e. 5.0×10^5 V/m. Now we proceed to the next time step, i.e. $t = t + \Delta t$

(5) During the time interval Δt there will be a change in the background potential and we also have a small leader section of length L_1. Now the new charge in the streamer zone generated from the head of the new leader section is calculated as before but now including both the leader and its streamer zone in the distance–voltage diagram. The leader is represented by a line with a potential gradient $E_{L1}(t)$. The charge generated in the current time step is obtained by subtracting from this the total charge obtained in the previous time step. Let the charge obtained thus be Q_1. This charge is used to evaluate the length of the new leader section L_2. Moreover, the flow of this charge through the leader channel changes the potential gradient and the radius of the older leader section L_1. The new potential gradient and the radius of L_1 are given by $E_{L1}(t + \Delta t)$ and $a_{L1}(t + \Delta t)$.

(6) Now let us consider the nth time step. There are n leader sections and they have their respective potential gradients and radii. The radius and the potential gradient of ith leader section are obtained from

$$\pi \cdot a_{Li}^2(t+\Delta t) = \pi \cdot a_{Li}^2(t) + \frac{\gamma - 1}{\gamma \cdot p_0} E_{Li}(t) \cdot I_{Li}(t) \cdot \Delta t \tag{2}$$

$$E_{Li}(t+\Delta t) = \frac{a_{Li}^2(t)}{a_{Li}^2(t+\Delta t)} E_{Li}(t) \tag{3}$$

In the above equation $E_{Li}(t)$ is the internal electric field, $I_{Li}(t)$ is the current of the leader section L_i at time t, p_0 is the standard atmospheric pressure and γ is the ratio between the specific heats at constant volume and constant pressure for air [5]. With these equations it is possible to calculate the time evolution of the internal electric field for each segment and the potential drop along the leader channel (at a given time) as follows:

$$\Delta U_L = \sum_{i=1}^{n} E_{Li}(t) \cdot L_i \tag{4}$$

The steps described above can be used to simulate the inception and propagation of positive leaders. The calculation can be simplified if, instead of calculating the time evolution of leader potential gradient in each segment as above, one uses the expression derived by Rizk [6] for the potential of the tip of the leader channel which is given by

$$U_{tip}^{(i)} = l_L^{(i)} E_\infty + x_o E_\infty \ln \left[\frac{E_{str}}{E_\infty} - \frac{E_{str} - E_\infty}{E_\infty} e^{-\left\{ l_L^{(i)}/x_0 \right\}} \right] \tag{5}$$

In the above equation $l_L^{(i)}$ is the total leader length at the current simulation step, E_∞ is the final quasi-stationary leader gradient and x_0 is a constant parameter given by the product $\upsilon\theta$, where υ is the ascending positive leader speed and θ is the leader time constant.

(7) In the model the negative stepped leader is assumed to travel towards ground without being influenced by the connecting leaders issued from grounded structure unless final jump condition is established with one of them. In the original SLIM, the tip of the connecting leader is assumed to travel, at any given moment, towards the current location of the tip of the down coming stepped leader. In the simulations presented here this assumption is relaxed and the connecting leader is assumed