A new static calculation of the streamer region for long spark gaps

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Different electrostatic approximations have been proposed to calculate the streamer region without going in deep details of the behavior of density of particles under the effect of high electric fields; this kind of approximations have been used in numerical calculations of long spark gaps and lightning attachment. The simplifications of the streamer region are achieved by considering it to be a geometrical region with a constant geometrical shape. Different geometrical shapes have been used, such as cones or several parallel filaments. Afterward, to simplify the procedures, the streamer region was approximated by two constants, one denoted \( K_Q \), called the geometrical constant and in other cases \( K \) named as geometrical factor.

However, when a voltage that varies with time is applied to an arrangement of electrodes (high voltage and grounded electrodes), the background electric field will change with time. Thus, if the background electric field is modified, the streamer zone could cover a larger or smaller area.

With the aim of reducing the number of assumptions required in the calculation of long gap discharges, a new electrostatic model to calculate the streamer region is presented. This model considers a variable streamer zone that changes with the electric field variations. The three-dimensional region that fulfills the minimum electric field to sustain a streamer is identified for each time step, and the charge accumulated in that region is then calculated. The only parameter that is being used in the calculation is the minimum electric field necessary for the propagation of streamers.

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1. Introduction

In the field of high voltage physics, there is still no complete understanding of how a spark traverses a gap between a conductor and a grounded point, plate or rod. Theoretical investigations incorporating the available experimental evidence for long sparks gaps provide a means of complementing our knowledge. The models used to calculate discharges in long spark gaps have used the results from laboratory measurements and to represent the streamer region they make use of different approximations like the models of Bondiou and Gallimberti’s [1], Lalande [2], Goelion et al. [3], Castellani [4], Becerra and Cooray [5].

The assumptions underlying the streamer calculation are different in each model, as described in the following paragraphs:

Bondiou and Gallimberti’s model [1] calculates the charge generated by the streamer formation in terms of estimating the total number of electrons that have left the gap by reaching the high voltage electrode. The calculation takes into account the attachment process. However, as a simplification, the charge is assumed to come from a single filament, therefore the charge for the total streamer area is estimated by multiplying the charge from a single streamer by a branching factor and by the number of filaments. In this procedure, the constants used for the first streamer and all subsequent streamers are the same.

A simplified model for the simulation of the positive spark as developed by Goelian and Lalande’s model [2,3] calculates the charge associated with the advancement of the streamer-leader during a certain time instant by multiplying the area formed by the potential distribution immediately before and after the streamer formation by a geometrical constant. For the calculation, the streamer area is assumed to be comprised of \( N \) parallel streamers of length \( L \), located at a distance \( a_i \) from each other. In their last model Lalande [2] and Goelian [3] introduced a geometrical constant \( K \) which according to them is proportional to the charge accumulated in the streamer region.

The Becerra and Cooray [5–7] streamer approximation assumes that the area covered by the streamer zone required for the simulation process is conical. The charge accumulated is calculated by means of the charge simulation method. In the most recent version, Becerra and Cooray [5] proposed a simplified method in which the...
area accumulated between the potential of two consecutive leader segments is proportional to the streamer charge. The proportional constant to calculate the charge is called the geometrical constant $K_0$.

With the aim of reducing the number of parameters assumed in the calculation of the streamer region in a long spark gap, a three-dimensional identification of the streamer region was made during every time step. The criterion used to identify the region was the minimum static electric field required for the emission of a streamer, proposed by Bondiou and Gallimberti [1,8], i.e., 450 kV/m.

The models mentioned [1–3,5–9,16] have been validated for configurations comprised of a rod and a grounded plane under switching impulses, and the authors claimed that the methodologies developed can be used for sparks crossing long distances over gaps of different configurations [2,5,15,20]. Part of the work reported in these references has been conducted to improve the understanding of the physics of the lightning attachment process, and its applications in the design of lightning protection systems [15]. To determine the effectiveness of this new methodology, the method of Becerra–Cooray [6] and Lalande [2] and the simplified alternatives put forward by these authors [3,5] were implemented and compared with a rod-plane arrangement.

2. Methodology

The model is divided up into several stages: The first of these is the calculation of the background electric field arising from the high voltage source. Second, whether the conditions necessary for the streamer inception is satisfied at the electrode is checked. If the electric field is sufficient to start a new electron in the vicinity of the electrode tip, an applied field is able to start a new avalanche closer to the cathode. Whether or not this process continues until the cathode is reached depends on the electric field inside the streamer channel, is equal to the stabilization field $E_{st}$ [8]. Its characteristic value in ambient air is between 400 and 500 kV/m [1,8]. It has been shown from the theory that the electric field inside the streamer channel, is equal to the stabilization field $E_{st}$ [8,14,15].

Therefore, the volumetric region between the tip of the leader channel or the high voltage electrode and the ground point is divided into several layers. For each layer, the area where the field is equal to or higher than the stabilization electric field (assumed here as 450 kV/m) is identified.

2. Once the avalanche has developed into a space charge cloud of positive ions, the local field may be high enough to start a new avalanche closer to the cathode. Whether or not this process continues until the cathode is reached depends on the applied electric field strength. The lowest value at which stable propagation appears to be possible is called the stability field $E_{st}$ [8]. Its characteristic value in ambient air is between 400 and 500 kV/m [1,8]. It has been shown from the theory that the field inside the streamer channel, is equal to the stability field $E_{st}$ [8,14,15].

3. In this streamer region, it is assumed that the streamers propagate along the electric field lines; the drop in the potential along the electric field line to the boundary of the

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The streamer region is then divided into several layers and the charge is calculated for each layer. This calculation requires that the direction of the electric field vector be taken into consideration, including at the edge of the region, as illustrated in Fig. 2.

Using Gauss’s theorem, the streamer charge located in each layer $Q_i$ is calculated, and the total charge accumulated in the volume for each time step $Q_{total}$ is computed.

$$Q_i = \int \int _s E \cdot dS$$

$$\Delta Q_{total} = \sum_{i=1}^{n} Q_i$$

Once the new charge has been calculated and the source voltage increases, the calculation to identify the new streamer region starts again.

### 3. Validation of the model

To validate the model the charge measurements of a rod–plane set–up were used [16]. The rod-plane air gap is arranged vertically, with a gap length of 1 m; a steel rod with a diameter of 16 mm and a 2 mm-diameter cone shaped tip is used as an electrode. The plane is a square made of 3 mm-thick galvanized iron plate with a size of $4 \times 4$ m. Refer to [16,17] for testing setup.

Measurements of the streamer current and its integration were done in [16] and the integration of the current was used to calculate the streamer electrical charge.

In this paper, the three different methodologies: Becerra–Cooray [5], assuming a conical streamer zone and the charge is calculated using the optimized charge simulation method (CSM) [18–20] as it is explained in section III of Becerra’s paper; Goelian et al. assuming a geometrical $K$ constant as it is clearly explained in annex A [2,3] and the one described in the paper were implemented for comparison purposes.

Fig. 3 presents the results for the streamer charge calculated from the current measurements for different voltage levels and the different models. The results showed that the new proposed methodology is in good agreement with the experimental measurements in the calculation of the streamer charge. The maximum obtained error is less than 25% respect to the measurement values, the average error is of 15% and the tendency of the variation of the charge vs. applied voltage is accurately reproduced.

The other two methods, conical streamer zone of Becerra–Cooray and the linear streamer of Lalande’s and Goelian give magnitudes larger than the experimental measurements; for the results using Becerra and Cooray methodology a lower error of 40% respect to the measurements was found; if the applied voltage
increases the error increases and the maximum error obtained is of 400%. The results using the methodology of Lalande’s are very close to Becerra and Cooray’s model but they give a high difference respect to the experimental results, 52 and 488% are the minimum and maximum percentage error respectively.

3.1. Qualitative comparison

With the aim to compare the results of photographic reports of long gap experiments, Figs. 4–7 show how the streamer zone shape changes at different instants in time when the source a switching impulse is applied. The calculations presented have been carried out for the configuration used by Les Renardieres’ Group [21], assuming a conical tip under a 1850 kV switching voltage impulse (500/10,000 μs), and a gap space of 10 m.

Fig. 4 represents the instant at which the charge started to accumulate in the space gap. As it is possible to observe the geometrical shape of the streamer charge is approximately conical (dashed lines).

However, when the voltage source has increased, the streamer region changes its shape from the conical one to the geometrical one presented in Fig. 5. And in the last stage, when the region is approaching the plane electrode, the results showed that the geometrical shape of the streamer zone becomes more like a cylinder than a cone (see Fig. 6).

The photographic results presented in Figs. 4–6 correspond to a previous paper [22] and the complete process is reproduced in Fig. 7 one can see that they show a similar behavior to that obtained in the simulations. Initially a conical region was observed, then a hyperboloid and, finally, the charge extends the shape in a cylindrical form.

The change in the shape of the streamer region under a switch-like voltage impulse in the simulations is caused by the increment of the applied voltage to the high voltage electrode. When the voltage source is increased, the electric field rises, and the region that will fulfill the criterion for a streamer region grows. Therefore, the frequently made assumption of a constant geometry for the streamer region during an increment in the electric field disagrees with the real physical process of the discharge.

4. The main assumption maid in the study

In calculating the streamer charge using the method proposed in this paper, it is assumed inherently that the outer boundary of the whole streamer region extends out from the central region (i.e., close to the electrode) simultaneously. On the other hand, if the streamer incepted initially travels outwards along high field region before the inception of more streamers in the central region those streamers that penetrated into the gap initially will reduce the electric field in other regions reducing the probability of streamers extending into those regions. In this case, the streamer region will have a different shape than the ones calculated here and the estimated streamer charge would become smaller. However, the agreement of the results obtained with the experiment justify the methodology used.
5. Conclusion

In this paper, a new electrostatic methodology to calculate the streamer region for long gap applications is proposed. The simulations presented here have demonstrated that to reproduce correctly the charge injected in the streamer region, it is necessary to consider the streamer zone to be a variable region because its geometry changes with the change of electric field, i.e., applied voltage.

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