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Glow Corona Discharges and Their Effect on Lightning Attachment: revisited

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***Abstract*— Previous studies in the literature have suggested that glow corona discharges could be potentially used to control the frequency of lightning flashes to grounded objects. Such studies use simplified one-dimensional corona drift models or basic empirical equations derived from high voltage experiments to assess the effect of glow corona on the initiation of both streamers and upward connecting leaders under the influence of a descending lightning leader. In order to revisit the theoretical basis of these studies, a two-dimensional glow corona drift model has been implemented together with a self-consistent upward leader inception and propagation model –SLIM–. A 60 m tall lightning rod is used as a study case. It is found that the shielding effect of the glow corona space charge has been strongly overestimated in the literature. Furthermore, it is shown that streamers under the influence of a descending leader are initiated significantly earlier from the cylindrical body rather than from the corona-emitting area of the rod. Considering the effective shielding potential of glow corona, it is also shown that the presence of glow corona reduces the downward lightning attractiveness of 60 m tall lightning rods by less than 15%. This result shows that the efficiency of lightning rods is not strongly influenced by the generation of glow corona as opposed to the suggestions of previous studies.**

Keywords: lightning attachment; upward leader, glow corona

I. INTRODUCTION

During thunderstorms, glow corona discharges are initiated from the tip of tall slender grounded objects due to the cloud electric field. These discharges can generate positive ions which could shield the geometric electric field and hinder the development of subsequent discharges (e.g. streamers and leaders) prior to a lightning strike. In order to evaluate this effect, several theoretical studies have been reported in the literature [1–9]. These studies assume that the ions generated by glow corona at the tip of tall objects expand radially, holding a semi-hemispherical shape as they drift into the gap. In this way, the analysis of the ion drift can be largely reduced to a single dimension along the axis of symmetry (instead of a 2D or 3D calculation). These studies show that glow corona can delay the inception of streamers and therefore, it later can inhibit the initiation and propagation of upward leader discharges. For this reason, glow corona has been proposed as an efficient mechanism to control lightning strikes to grounded objects [8]. Following a similar one dimensional approach, it has been recently suggested that air terminals can shield themselves due to the generated glow corona [10].

Based on these studies, different non-conventional lightning protection systems based on the generation or suppression of glow corona have been released into the market. Thus, it is claimed that multi-point corona configurations (better known as a dissipation array system) can prevent lighting strikes to objects “protected” with such a system. In addition, lightning rods specially designed to avoid glow corona generation are claimed to be more efficient than conventional sharp or blunt lightning rods. However, there is an ongoing debate in the lightning protection community about the validity of these claims. In order to contribute to the scientific discussion on this issue, an independent study has been performed to revisit the results published in [1–10]. For this, a two-dimensional analysis of the glow corona generation is performed to quantify the electrostatic shielding effect of the generated space charge. Then, the evaluation of this shielding effect on the initiation of streamers and leaders is evaluated with the self-consistent leader inception and propagation model –SLIM– [11–13]. In this way, it is possible to have more realistic estimates of the hindering effect of the generated corona space charge on the streamer initiation.

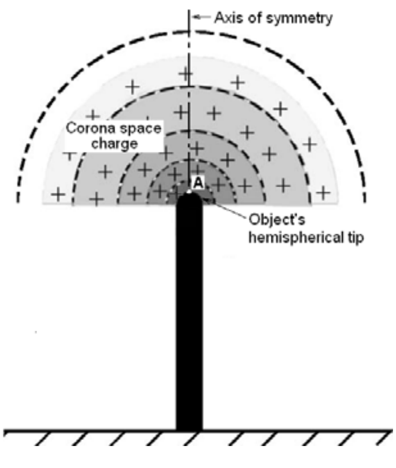

Figure 1. Sketch of the semi-hemispherical expansion of the corona space charge according to the 1D approximation (adapted from [1]).

II. GLOW CORONA ION DRIFT ANALISYS

In order to provide more accurate estimates of the spatial distribution and shielding effect of the space charge generated by glow corona during thunderclouds, a two dimensional drift model have been implemented. Since the space charge emission from a lightning rod in the absence of wind has axial symmetry, the one dimensional model proposed by Aleksandrov et al [1, 2] is extended to two dimensions. Thus, the continuity equations for electrons, small ions and large ions together with the Poisson equation are solved in a two-dimensional, axial symmetric model in a finite element method commercial software. Notice that the ionization zone of glow corona is neglected and the ion generation is set to maintain the corona inception electric field E_{cor} constant according to the Kaptzov assumption. In order to compare directly with the estimations of the 1D approach, an additional model (referred to as the 1D approximation) is implemented such that the space charge drift is forced to expand radially from the rod tip according to [1–10]. The details of the implementation of the drift model are presented in [14].

A. Validation of the model

Even though the estimations published in the literature [1–10] have just been compared with analytical expressions for simplified geometries, a different approach is here used to validate the results. The experimental results of the glow corona generation in a long air gap configurations reported in [15] are used to compare the 1D approximation and the 2D model. The comparison of the measured and calculated corona current for a 1 m tall lightning rod inmmersed in a quasi-uniform DC electric field is shown in Figure 2. It is found that there is a good agreement between the measured currents and the values estimated with the 2D model. However, the corona currents estimated with the 1D approximation are significantly lower than the measured values.

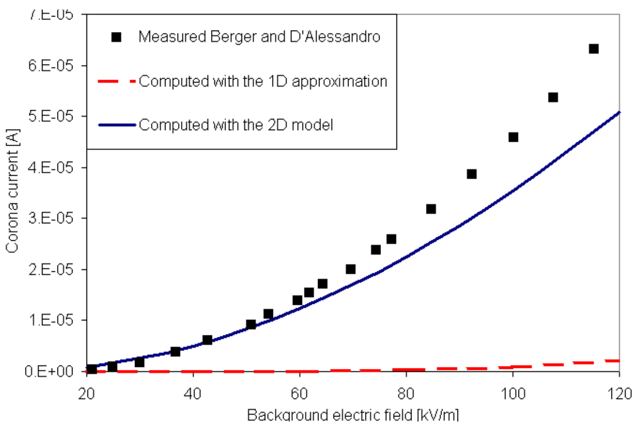

Figure 2. Comparison of the stationary corona current of a 1 m tall pencil-shaped rod computed according to the 1D approximation and with the 2D model. The measured values reported in [15] are also shown.

Careful analysis of the spatial distribution of the corona space charge have shown that the 1D approximation strongly overestimates its shielding effect, causing the large differences with the measured current. For an average background electric field of 80 kV/m, the steady-state charge in the gap computed with the 1D approximation is about six times larger than in the 2D case (56 and 9.7 μC respectively).

It is noteworthy that the generation of glow corona in the laboratory soon reaches a steady-state condition, as opposed to glow corona under thunderstorms where the ions never cover the complete gap. Despite of this fact, the equations to represent the drift of ions in both cases is exactly the same although in a different scale. For this reason, the differences found between the 1D approach and the 2D model in Figure 2 also apply to the case of the glow corona generation from lightning rods under thunderstorms.

B. Glow corona generation from a lightning rod during the thundercloud charging process

The analysis of the generation of glow corona under a thunderstorm is here performed for a 60 m tall lightning rod with a cap radius of 0.02 m. It is first assumed that the thundercloud field increases linearly within 10 s to 20 kV/m (as it is also assumed in [1]). Figure 3 shows the spatial distribution of corona space charge calculated with the 2D model and the 1D approximation when the thundercloud field is 20 kV/m.

As it can be clearly seen, there are clear differences between both calculation approaches. Particularly, notice that the effective generation of glow corona (in the 2D model) does not take place all over the cap surface of the rod as assumed by the 1D approximation. In the case shown in the figure, only 55% of the total cap surface has an electric field high enough to generate glow corona. Furthermore, observe that the space charge in reality does not expand radially as much as assumed by the 1D approximation. This causes that the total space charge injected by glow corona is again overestimated by the 1D approximation (about 40 % larger) compared with the 2D model.

C. Glow corona generation from a lightning rod during the approach of a descending downward leader

Once the thundercloud electric field has reached 20 kV/m, the electric field of an approaching downward leader is also considered in the corona drift evaluation. In this paper, a vertical downward leader with a prospective return stroke current of 20 kA and a velocity of 2 x 10^5 m/s is considered. After following the generation of glow corona as the downward leader rapidly approaches to ground, it is found once more that the shielding effect of the corona space charge is largely overestimated by the 1D approximation. Figure 4 shows the contours of the shielding potential of the injected corona space charge for both calculation approaches when the downward leader tip is 1200 m above ground. Notice that the shielding equipotential contours computed with the 1D approximation cover significantly larger areas compared with the 2D model, especially in the radial direction. For instance, the shielding potential estimated with the 1D approximation at a radial distance of 25 m is about 400 kV. This value is almost double of the shielding potential computed with the 2D model (of about 200 kV).

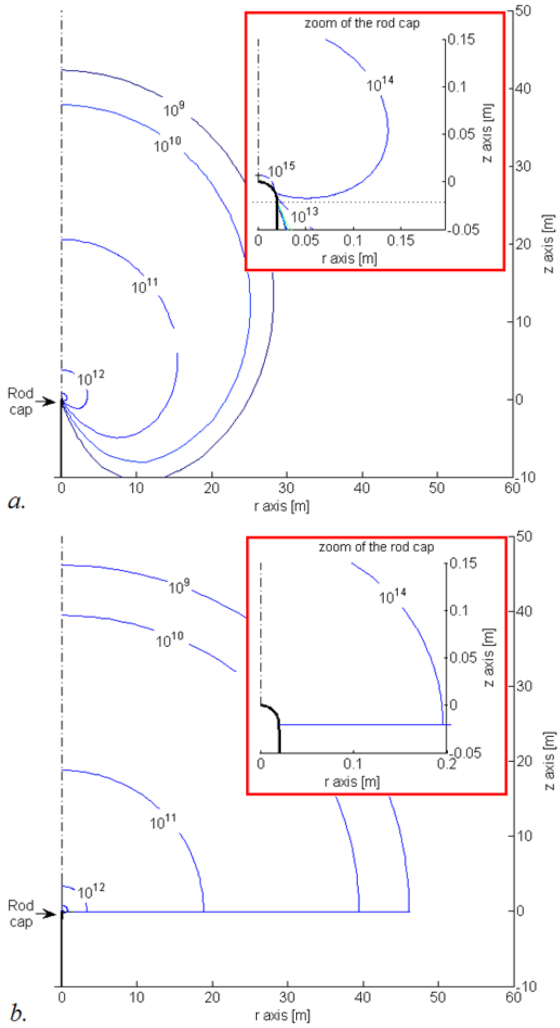

Figure 3. Contour plot of the small ion density produced by corona from a 60 m tall rod computed a) with the 2D model and b) with the 1D approximation. The results correspond to the electric field equal to 20 kV/m.

III. EFFECT OF GLOW CORONA ON THE INITIATION OF STREAMERS

Due to the shielding effect of the injected space charge, it has been suggested in the literature that glow corona can strongly delay the initiation of streamers [1–9]. In order to reassess this effect, the streamer inception is evaluated considering the corona space charge calculated in the previous section. Thus, the transition from glow to streamer is estimated as the condition when the electric field in front of the rod exceeds the corona inception electric field [1]. Under this condition, glow corona generated on the surface of the rod becomes unstable and turns into a streamer as the background electric field due to the descending leader increases.

In contrast to the previous studies, the streamer initiation is not only evaluated along the axis of symmetry (as in [1–9]), but also all over the surface of the cap and the cylindrical body of the rod. Figure 5 shows an example of the electric field along the rod profile at different heights of the downward leader tip Z_{down}. Observe that the electric field on the surface of the rod cap which generates glow corona is maintained at the inception field E_{cor}. However, the electric field on the surface of the rod body (where the space charge shielding is less effective) starts increasing as the downward leader approaches. Assuming that the body of the rod is perfectly cylindrical (i.e. it does not have any protrusion), the electric field can reach values high enough to initiate streamers (according to the well-known streamer criterion) at moderate downward leader heights. For the case considered, the downward leader tip at which streamers are initiated 0.5 m below the rod tip is 1100 m above ground. For a downward leader tip 1000 m above ground, streamers are readily initiated anywhere along the rod cylindrical body between 0.3 and 2 m below the rod tip.

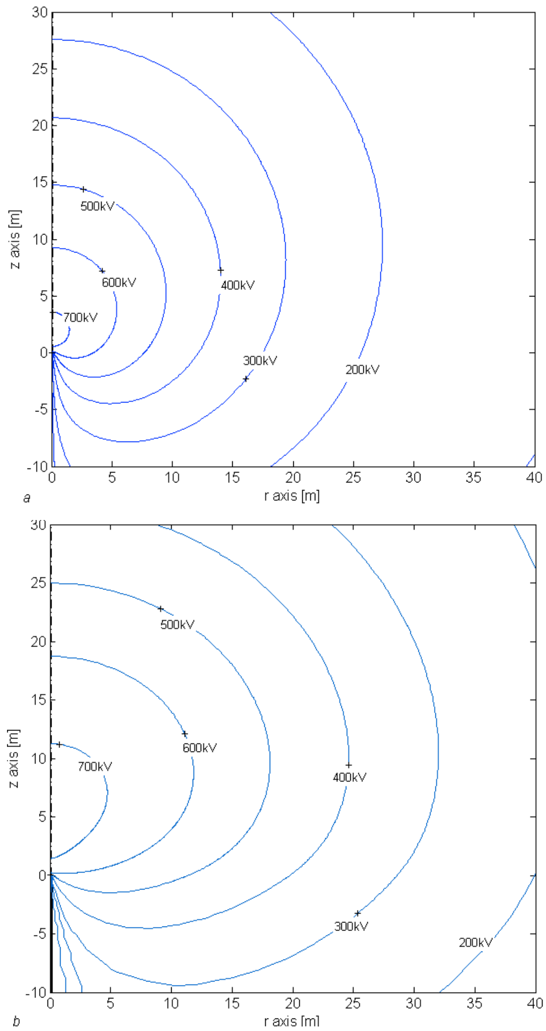

Figure 4. Contour plot of the shielding potential of the generated space charge produced by corona from a 60 m tall rod computed with a) the 2D model and b) the 1D approximation. The figures correspond to the results when the downward leader tip is 1200 m above ground

It is important to mention that the transition from glow to streamer along the axis of symmetry is indeed strongly delayed along the symmetry line as suggested by the previous studies. For the considered case, the inception of streamers in front of the rod tip would take place when the downward leader tip is 420 m above ground. However, streamers are initiated on the rod body much earlier as previously shown. Therefore, the streamer inception criterion used in [1–9] overestimates the shielding effect of glow corona on the streamer initiation. This is caused by the evaluation of the streamer initiation only along the area where the corona space charge shielding is maximum (i.e. along the axis of symmetry). In reality, the shielding effect of the injected ions strongly affects only areas where glow corona is generated (i.e. the rod cap), but it rapidly decays along the body of the rod where streamers can be readily initiated.

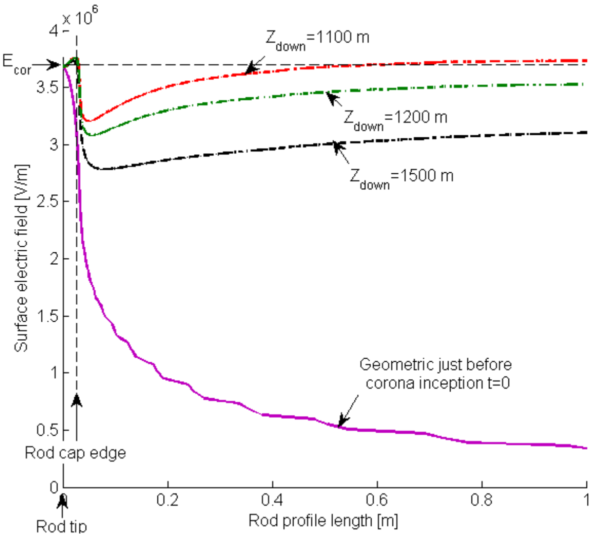

Figure 5. Electric field along the profile of a 60 m tall rod at different height of the downward leader tip.

IV. EFFECT OF GLOW CORONA ON THE INITIATION OF LEADERS

Once the effective streamer inception evaluation is performed, the analysis of the initiation and propagation of upward connecting leaders in the presence of the glow corona is performed with SLIM [11–13]. For the implementation, the model is modified to account also for the shielding potential of the corona space charge as well as the corona-induced delay of the streamer initiation.

It is found that the effective delay of the streamer inception due to glow corona does not influence significantly the lightning attractiveness of tall rods, as opposed to the predictions of the previous publications. Instead, the shielding potential of the generated space charge has a more significant effect on the initiation and propagation of vertical upward connecting leaders. Figure 6 shows an example of the simulated still photograph of the lightning attachment process for a 60 m tall rod neglecting and considering the glow corona space charge. First, notice that the vertical propagation of upward leaders is strongly hindered by the glow corona shielding effect. For this reason, the interception distance I_D of a downward leader overhead the rod is strongly reduced (by 30%) in the presence of corona. Nevertheless, the lateral propagation (along the r axis) of upward leaders is not hindered as much as their vertical displacement. For this reason, the lateral distance L_D of the rod is reduced by less than 15% in the presence of glow corona under a 20 kV/m thundercloud electric field. Since the space charge shielding effect rapidly decrease along the radial axis (as seen in Figure 4), positive leaders trying to connect downward leaders laterally displaced from the rod axis can readily propagate. Observe that this reduction of the lateral distance is significantly smaller than suggested in [1–10]. Further numerical experiments (not presented here) show that the effect of glow corona on the lateral distance is even lower for lower lightning rods. Moreover, it is found that glow corona does not affect significantly the lightning lateral (attractive) distance of lightning rods shorter than 15 m.

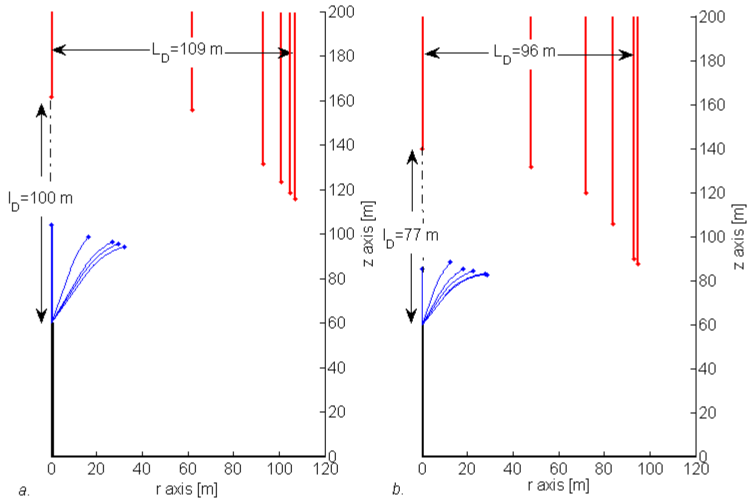

Figure 6. Simulated still photograph of the lightning attachment process for a 60 m tall, 0.02 m radius rod calculated *a*) neglecting and *b*) considering the glow corona space charge.

V. CONCLUSIONS

This study shows that glow corona generated at the tip of grounded objects only reduces slightly the efficiency of (60 m) tall rods, in contrast to the predictions of previous publications [1–10]. In such a case, the lightning attractive distance of the rod is reduced by less than 15% when the glow corona generation is considered. Moreover, it is shown that the shielding effect of the glow corona space charge is overestimated when the drift of ions is performed in one dimension as in [1–9]. In the same way, it has been found that the effective initiation of streamers from tall objects under glow corona requires considerably lower background electric fields during the downward leader descent than those reported before. Since the previous studies have evaluated the streamer inception only along the area with maximum shielding of the corona space charge, they have missed to consider the streamer generation on the cylindrical body of lightning rods. It is also shown that previous studies have neglected the rapid decrease of the corona space charge along the radial direction. For this reason, the lateral displacement of upward connecting leaders is not strongly hindered (as their vertical propagation) in the presence of glow corona.

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