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Laboratory experiments cannot be utilized to justify the action of early streamer emission terminals

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Abstract
The early emission of streamers in laboratory long air gaps under switching impulses has been observed to reduce the time of initiation of leader positive discharges. This fact has been arbitrarily extrapolated by the manufacturers of early streamer emission devices to the case of upward connecting leaders initiated under natural lightning conditions, in support of those non-conventional terminals that claim to perform better than Franklin lightning rods. In order to discuss the physical basis and validity of these claims, a self-consistent model based on the physics of leader discharges is used to simulate the performance of lightning rods in the laboratory and under natural lightning conditions. It is theoretically shown that the initiation of early streamers can indeed lead to the early initiation of self-propagating positive leaders in laboratory long air gaps under switching voltages. However, this is not the case for positive connecting leaders initiated from the same lightning rod under the influence of the electric field produced by a downward moving stepped leader. The time evolution of the development of positive leaders under natural conditions is different from the case in the laboratory, where the leader inception condition is closely dependent upon the initiation of the first streamer burst. Our study shows that the claimed similarity between the performance of lightning rods under switching electric fields applied in the laboratory and under the electric field produced by a descending stepped leader is not justified. Thus, the use of existing laboratory results to validate the performance of the early streamer lightning rods under natural conditions is not justified.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since the middle of the last century, data gathered from laboratory experiments in long air gaps have been utilized in many ways to understand the physical mechanisms of lightning flashes [1]. In the laboratory, it has been observed that in a rod-to-rod configuration under a steep-fronted impulse voltage, a leader discharge develops from the high voltage negative electrode, while a similar discharge also develops from the earthed rod electrode. Thus, the breakdown process occurs when these two discharges meet somewhere in the middle of the gap. Given the similarities between the lightning flash and the electric sparks shown by Benjamin Franklin himself [2], it is possible to relate the final stage in the development of the lightning stroke to the phenomenon observed in the laboratory [3]. Thus, some physical properties of both the negative downward lightning leader which propagates from the cloud towards the ground and the upward connecting positive leaders initiated from grounded objects were first interpreted based on the leaders observed in the laboratory [4–7]. Moreover, the knowledge on the discharge mechanisms and certain basic physical parameters of streamers and leaders gathered from long gap experiments opened the doors to the physical modelling of lightning leaders [8–15].

However, it is believed that laboratory experiments cannot fully simulate the conditions under natural lightning [16]. This is the case since most laboratory leaders are apparently not long enough to become fully 'thermalized'. Therefore, the leaders in the laboratory require larger background electric fields to propagate in comparison with the lightning leaders [17]. Hence there are still doubts on the validity of the procedures in which experimental results obtained from leaders in laboratory long air gaps are utilized and extrapolated to perform calculations pertinent to lightning [18].

Despite this fact, long gap laboratory experiments are nowadays indiscriminately used to simulate the conditions under which upward connecting positive leaders are initiated from lightning rods under natural conditions [19–25]. The continuation of this practice has been fuelled by the recent use of laboratory experiments to assess the efficiency of early streamer emission (ESE) terminals to attract lightning according to some national standards [26, 27]. The manufacturers of these ESE devices claim that their terminals have a larger lightning protection zone than the one offered by a conventional Franklin rod under similar conditions [26–28]. These claims are substantiated by the fact that the earlier initiation of streamers in laboratory air gaps under switching voltages leads to the reduction of the leader initiation time and therefore to a shorter time to breakdown [19–21]. This reduction in the leader initiation in the laboratory has been arbitrarily extrapolated to the natural case by ESE supporters. The main assumption of this extrapolation is that the switching electric fields applied in laboratory 'fairly approximate' the electric fields produced by the descent of a negative downward moving stepped leader [19–21].

The ESE terminals are equipped with a discharge triggering device to increase the probability of streamer initiation upon the approach of a downward lightning leader [26–28]. According to the proponents of ESE terminals, this would reduce the average statistical time related to the upward connecting leader inception, such that there would be a 'time advantage' for the initiation of a continuous upward propagating leader from an ESE terminal. The time advantage would lead to a gain in the length of the upward connecting leader initiated from an ESE terminal compared with an upward leader initiated from a conventional Franklin rod under the same conditions [26–28]. Therefore, the area of lightning protection of an ESE terminal is claimed to be larger above that of a conventional Franklin rod.

However, the discussion on the efficiency of such air terminals has been the subject of much controversy [29, 30]. This is due to the existing doubts on the validity of laboratory experiments to assess the efficiency of air terminals and the procedure used to evaluate the performance of the ESE devices [31]. Even though the best way to evaluate the efficiency of air terminals is to test them in the field under natural conditions, there are several practical limitations that make it difficult to gather conclusive experimental evidence from such tests [30]. Thus, there is a lack of scientific and technical bases either to reject or to accept these devices [30].

Since all the ESE devices have the common characteristic that they enhance ionization of the air in the immediate vicinity of the terminal, a major question that needs to be solved is how this additional ionization acts to enhance the upward connecting leader initiation [30]. This question has to be answered through a careful analysis of the statistical time lag to leader initiation in the laboratory and the time span between the streamer initiation and the connection between the downward and the upward leaders under natural lightning. Due to the limitations of laboratory experiments and the difficulties of field tests, it appears that the theoretical simulation of electrical discharges both in the laboratory and in natural lightning is one of the best tools available to assess the performance of ESE terminals. Unfortunately, the problem of statistical time lags is very complex and it has been avoided in the existing models of leader discharges [30].

In this paper, a recently proposed self-consistent model for the time-dependant evaluation of the inception and propagation of leader discharges [13–15] is used to investigate the above presented question. Hence, the initiation and development of positive leaders is simulated taking into account the time variation of the electric fields applied in the laboratory and those produced by the descent of the downward moving leader. The model also takes into consideration the space charge created by streamers and aborted leaders, so that the influence of the streamer initiation condition on the leader development can be evaluated. Based on the obtained results, the validity of the ESE concept under natural conditions is discussed.

2. Time dependent evaluation of the leader inception and propagation

The development of positive leader discharges from an air terminal under laboratory and natural lightning conditions is simulated with the model described in [14, 15]. This model predicts the initiation and propagation of positive leaders taking into account the time variation of the existing background electric field as well as the space charge created by streamers and aborted leaders. Based on the model, the main physical parameters of the leaders, namely, the charge per unit length, potential gradient, channel radius, injected current and propagation velocity, are self-consistently computed. The model has been successfully applied to estimate the unstable and stable leader inception times [14] as well as the times to breakdown [15] in laboratory long gaps under switching voltage impulses. In addition, the predictions of the model regarding upward connecting lightning leaders have been validated with the results of an altitude rocket triggered lightning experiment [14]. Good agreement between the results of the model and the measured upward leader current, the upward initiation time and the interception point between both leaders was found in [14, 15].

The evaluation of the streamer initiation condition is performed by considering both the minimum electric field required to create a streamer and the statistical distribution of the primary electron that starts the electron avalanche [4]. The former condition, better known as the streamer criterion, is defined by a critical number of electrons in the avalanche head that leads to the formation of a stable streamer [4, 8]. The size of the avalanche head is calculated by integrating the Townsend avalanche equation [4] which considers the electrons created by ionization and lost by attachment before the avalanche reaches the electrode surface. The latter condition is related to the probability of the appearance of the first electron that initiates the avalanche [4,5]. It is computed by considering the critical volume around the tip of the rod, where the production of an electron leads to an avalanche with the critical size, and the number of free electrons produced per unit volume per unit time. Since both the size of the critical volume and the production of free electrons vary with electric field strength, the probability density $p_i(t)$ for streamer inception is evaluated in time according to [4,5]. Due to the fact that the rate of electron production in the critical volume changes with humidity [4], lower values of the electron production rate than the ones reported in [5] are used in this paper to consider a case with high humidity.

3. The ESE concept in the laboratory under switching voltage impulses

In order to reproduce the conditions under which the early streamer concept was discovered, an electrode configuration similar to the one used in [19–21] is utilized in the simulations. The considered electrode arrangement consists of a grounded lightning rod 3.5 m tall under a plane electrode located 13 m above the ground plane. Since the details of the geometry of the tested rod are not reported in [19–21], a hemispherically capped rod with a tip radius of 0.015 m is used. For the simulation of the leader development in the laboratory, a switching voltage impulse with a peak value of 3.2 MV and a risetime of 350 μs is chosen to roughly reproduce the conditions reported in [19–21]. In addition, this voltage impulse is superimposed on a dc voltage equal to 130 kV to reproduce the thundercloud electric field of 10 kV m^{-1} according to [19–21].

Figure 1 shows the simulated streak image of a positive leader propagating in the gap under the switching voltage impulse. In order to consider the statistical time lag for streamer inception and its effect on the leader initiation time, two extreme cases for the streamer inception times are considered. The lower extreme (figure 1(*a*)) corresponds to the minimum possible streamer inception time $t_i^{(\min)}$ given by the streamer inception criterion [4]. The upper limit (figure 1(*b*)) is the probabilistic maximum streamer inception time $t_i^{(\max)}$ where the probability to produce a free electron to initiate the streamer is close to one $\int_0^{t^{(\max)}} p_i(t)\,dt \approx 1$. Thus, the streamer inception times of the considered lightning rod range between those limits according to the probability distribution function $p_i(t)$ shown in figure 1(*a*). The unstable leader inception time t_i' shown in figure 1 corresponds to the moment when the stem of the second streamer burst is thermalized and the first leader segment is created. The stable leader inception time t_1 is given by the moment when the propagation of the newly created leader is self-maintained by the existing electric field. It is estimated from the extrapolation of the leader tip position back along its continuous growth from the streak image [6]. The time to breakdown t_B is defined as the moment when the streamers in front of the leader tip reach the upper plane.

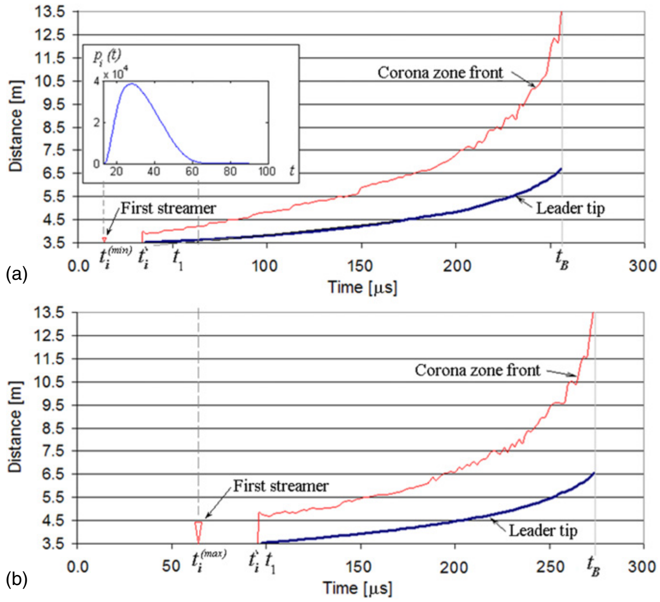

Figure 1. Simulated streak image of the propagation of a positive leader in a 9.5 m long air gap under a switching voltage impulse for different streamer inception times: (*a*) the minimum possible streamer inception time, (*b*) the probabilistic maximum streamer inception time.

As seen in figure 1, the simulated unstable and stable leader inception times t_i' and t_1 as well as the time to breakdown t_B decrease when the streamer inception t_i takes place earlier. Thus, if a streamer is 'triggered' earlier either by lowering the minimum streamer inception time or by narrowing the streamer inception probability distribution function, a reduction of the leader inception and breakdown times is obtained. This predicted improvement of the leader inception time in the laboratory by reducing the streamer initiation time agrees with the experimental results presented by Berger [19–21]. According to him, the leaders initiated from a terminal with a streamer triggering unit 'starts very early, well under the inception times of the Franklin rod leader' [19]. Based on streak images obtained during the experiment, the tested ESE device showed a time advantage of about 75 μs in the leader inception time compared with the control Franklin rod [19]. In addition, the mean value of the time-to-breakdown probability distribution of the tested ESE terminal was also lower compared with the one of the control Franklin rod [21]. Note that the simulation shown in figure 1 also predicts that the time to breakdown t_B in the air gap is reduced when the streamer initiation occurs earlier.

Unfortunately it is not possible to make a direct quantitative comparison between our predictions (figure 1) and the experimental results reported in [19–21]. This is the case since the simulations do not exactly correspond to the conditions in the experiment, since details of neither the tested rods nor the applied voltage waveform were reported by Berger. Moreover, it is noteworthy that the authors do not intend to exactly simulate the leader development from the ESE device tested in [19–21], given the lack of information about the internal circuit of the ESE triggering unit. Nonetheless, similar leader characteristics as the ones predicted in figure 1 can be expected from such a device. Even though the triggering unit of the tested ESE generates voltage pulses up to 7 kV peak value [33], such low voltages applied to the terminal tip do not influence the propagation of the leader according to our simulations. Such pulses only increase the size of the critical volume available for the production of a free electron, reducing the statistical variations of the streamer inception time.

It is important to mention that in this paper the variations in the time to breakdown caused by the geometric fluctuations of the leader path [32] are not taken into account. Thus, only the variations in the time to breakdown caused by statistical fluctuations in the streamer and leader initiation times are simulated. In addition, the sudden changes in charge and light emission that have been observed during the propagation of leaders under long time to crest in the laboratory [5] are not simulated here. This is because of the fact that laboratory leaders propagating under those conditions grow continously irrespective of the sudden changes in charge and light emission [5].

4. Effect of the voltage waveform applied in the laboratory on the propagation of positive leaders

As presented in the previous section, a reduction of the leader initiation time can be obtained under switching voltages by triggering an early streamer from a rod. However, this result has been extrapolated to the natural conditions of lightning [19–21, 26–28] using the argument that the leaders in the laboratory resemble the upward connecting lightning leaders. Based on this assumption, the manufacturers of ESE devices claim that their terminals launch upward connecting leaders earlier than a Franklin rod under natural conditions. The basis for this assumption is that the switching electric fields applied in the laboratory 'fairly approximate' the rising electric field produced by the downward lightning stepped leader [19, 21].

In order to evaluate how well the switching voltage waveform approximates the lightning electric fields, the simulations are repeated considering the electric field produced by the descent of the downward moving leader. For the analysis, the potential of the upper plane is defined such that the electric field at the ground plane is equal to the one produced by a downward leader. A straight negative leader channel descending with a continuous average velocity of 2×10^5 m s^{-1} directly overhead the rod is considered. The charge density of the downward leader channel is computed as a function of the prospective return stroke peak current according to [34].

Figure 2 shows the comparison between the switching electric field applied in the laboratory and the electric fields produced by downward leaders with charge density corresponding to different prospective return stroke peak currents. As suggested in [19], the waveforms are aligned in time such that the natural and the switching electric fields coincide at the moment when the ionization processes starts at the tip of the rod. The simulated streak images of the leaders propagating in the studied laboratory air gap, under electric fields corresponding to the approach of a downward leader with prospective return stroke currents of 3, 5 and 10 kA, are shown in figure 3.

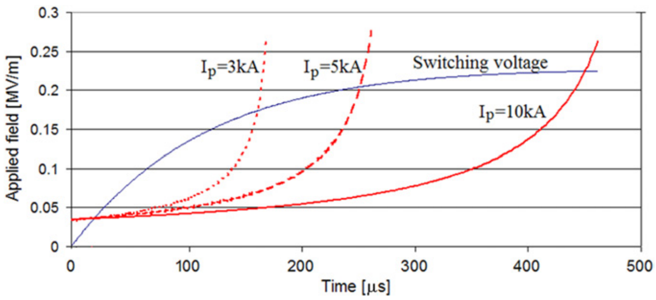

Figure 2. Comparison between the laboratory switching electric field and the electric field produced by the descent of a downward leader with different prospective return stroke peak currents.

As seen in figure 3, some features of the propagation of positive leaders under lightning-like electric fields are different compared with the case under the 'equivalent' switching waveform (figure 1). First, the lengths of the leaders under lightning-like electric fields are shorter than the leader length under the 'equivalent' switching waveform. For instance, the leader simulated under the electric field produced by a downward leader with a prospective return stroke current of 5 kA (figure 3(*b*)) is about three times shorter than the leader corresponding to the 'equivalent' switching waveform (figure 1). Second, the unstable leader inception t_i' takes place a long time after the inception of the first streamer t_i for the case of lightning-like electric fields ($t_i' - t_i$ is about 120 μs, 200 μs and 350 μs for prospective return stroke currents of 3 kA, 5 kA and 10 kA, respectively). For the switching waveform, this time difference $t_i' - t_i$ is only about 25 μs. In addition, notice that more than one aborted leader could be produced before the initiation of the stable leader in the case of lightning-like electric fields (figures 3(*b*) and (*c*)). Third, the time difference between breakdown t_B and stable leader inception t_1 is significantly shorter when lightning-like electric fields are applied. For the lightning-like waveform, the time span $t_B - t_1$ is shorter than 40 μs for the three prospective return stroke currents considered in this paper, while this time span is longer than 150 μs for the switching case.

These basic differences are mainly caused by the manner in which the switching and the lightning-like electric fields change in time (figure 2). In contrast to the switching case, the streamer inception t_i for the case of lightning-like electric fields takes place when the background electric field increases slowly. This leads to a longer dark period (time where no streamers are produced) in comparison with the switching case. This dark period ends when the applied electric field is high enough to restore the electric field at the tip of the rod, which is shielded by the space charge injected by the first streamer. After the dark period, a new streamer is produced. Nevertheless, an aborted leader can be produced if the lightning-like electric field is still changing slowly (figures 3(*b*) and (*c*)) so as to compensate the voltage drop at the tip of the newly created leader segment. Otherwise, the stable leader is incepted and starts propagating continuously as the lightning electric field rate of change quickly increases. At the same time, the front of the streamer corona at the tip of the leader channel extends with a faster velocity than the leader tip and reaches the upper

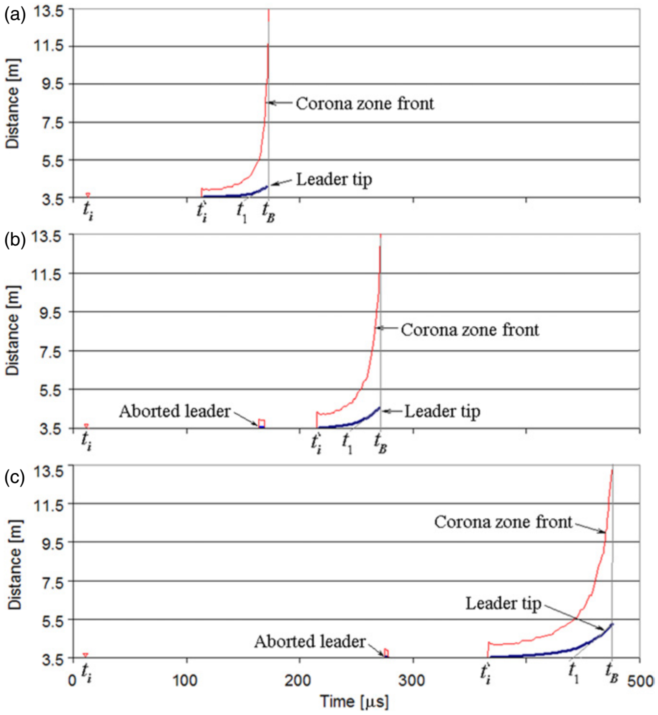

Figure 3. Simulated streak images of leaders under the electric field produced by the descent of a downward leader with different prospective return stroke currents: (*a*) 3 kA, (*b*) 5 kA, (*c*) 10 kA.

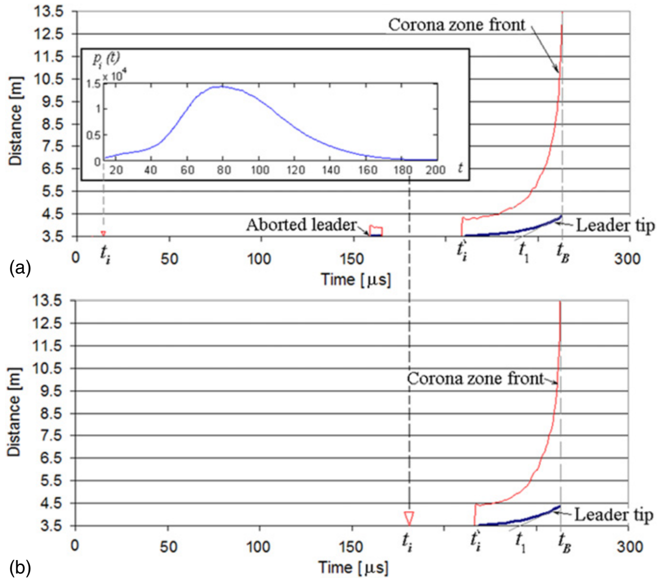

Figure 4. Simulated streak image of the leader propagation in the laboratory under the electric field produced by a downward leader with a prospective return stroke current of 5 kA for different streamer inception times: (*a*) the minimum possible streamer inception time, (*b*) the probabilistic maximum streamer inception time.

electrode soon after the stable leader inception time t_1. Hence, the time available for the propagation of the leader is short and the gap is mostly bridged by the streamers even if the leader channel is not long.

Now, let us evaluate the validity of the early streamer concept for the case of lightning-like waveforms in the laboratory. Figure 4 shows the simulated streak image of a positive leader propagating in a laboratory air gap under lightning-like electric fields for the two extreme conditions of streamer inception. A downward leader with a prospective return stroke current of 5 kA is used in this case. Observe that despite the fact that the probability distribution for streamer initiation extends for more than 180 μs, the time to stable leader inception t_1 and to breakdown t_B is not affected by the streamer inception time t_i. If a streamer is triggered earlier from a rod under lightning-like electric fields in the laboratory (figure 4(*a*)), further bursts of streamers and aborted leaders would be produced, without any significant change in the stable leader inception time t_1 compared with the case of a late streamer (figure 4(*b*)).

The above presented results clearly show that the switching voltage impulses used in the laboratory do not 'fairly approximate' the electric fields produced by the descent of a downward stepped leader as claimed in [19–21, 26–28]. Since the rate of increase of the lightning electric fields changes from slow to fast, while the switching electric field rate of change varies from fast to slow (figure 2), the development of leaders from rods under both conditions is different. Moreover, it is demonstrated that a 'time advantage' in the initiation of leaders from lightning rods under switching impulses does not imply an improvement in the leader inception under lightning electric fields at all. Hence, it is not appropiate to use laboratory experiments under switching impulses to evaluate the efficiency of rods to attract lightning, as suggested by some national standards [26, 27]. Such experiments downplay the physics of the leader discharges under lightning electric fields, as pointed out in this section. In the same manner, the presented results conclusively show that the evaluation of the conditions for initiation and propagation of leaders in real lightning cannot be based on the direct use of experimental results of leaders under switching voltage impulses. For this reason, the models derived from air gaps under laboratory switching conditions cannot be used for lightning studies given the differences in the electric field variation, as presented above. This is the case of the critical radius concept [35], the generalized leader inception model of Rizk [36] or other models based on semiempirical equations [37, 38] which are generally used to evaluate the initiation of upward positive connecting leaders under natural lightning conditions [39–41].

5. The ESE principle under lightning conditions

Similar to the analysis presented in the previous section, it can be shown that the ESE concept does not produce any improvement when the lightning rod is directly exposed to the influence of a downward moving leader. However, it is necessary to keep in mind that a glow corona may appear at the tip of grounded rods during thunderstorms, before a streamer is produced by the approach of the downward leader [42]. The glow corona produces negative ions and metaestable excited neutral species [30], which could increase the number of free electrons produced per unit volume per unit time compared with the case in the laboratory. This means that the statistical variation of the time to streamer initiation from lightning rods

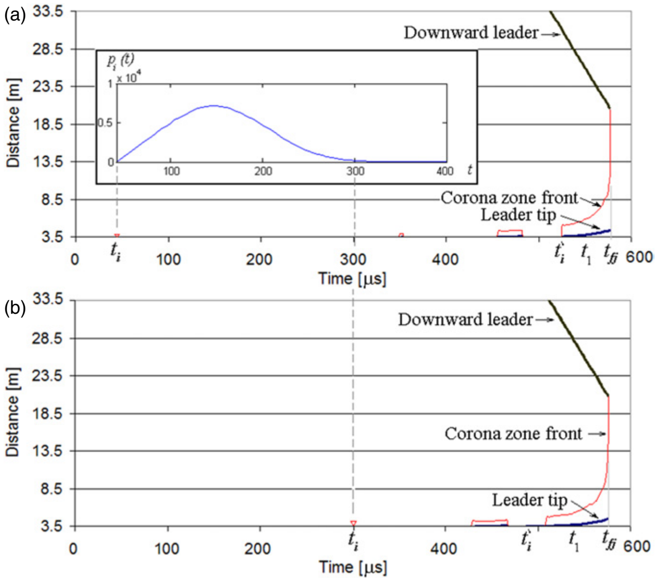

Figure 5. Simulated streak image of the leader propagation under the electric field produced by a downward leader with a prospective return stroke current of 10 kA for different streamer inception times: (*a*) the minimum possible streamer inception time, (*b*) the probabilistic maximum streamer inception time.

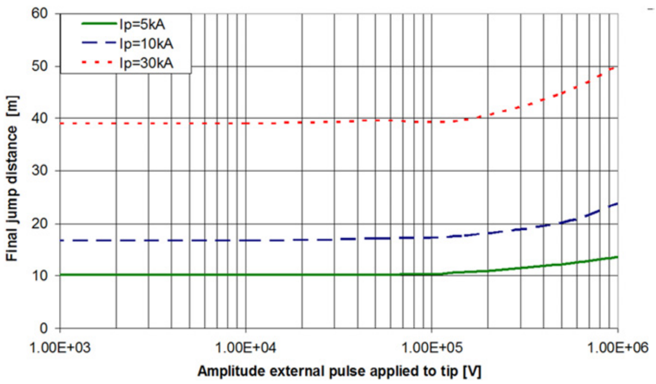

Figure 6. Simulated final jump (interception) distance as a function of the amplitude of the external square voltage pulse applied to the tip of a lightning rod. Prospective return stroke peak currents of 5, 10 and 30 kA are considered.

under natural conditions may be smaller than in the laboratory. Nevertheless, the produced glow corona could also delay the generation of streamers from grounded rods since the injected corona space charge shields the electric field close to the tip of the rod [42]. This effect would depend significantly upon the local wind velocity [30].

Due to the lack of information on the density of free electrons at the tip of grounded objects under thunderstorms, the values used in the previous sections are used here for the calculations of statistical streamer inception times under lightning conditions. Figure 5 shows the predictions pertinent to the development of an upward positive leader connecting a downward moving negative leader with the prospective return stroke peak current of 10 kA. Similar features of the leader initiation and propagation as the ones discussed for lightning-like electric fields in the laboratory are obtained. Therefore, there is no change in the initiation time or length of the upward leader by triggering an early streamer. Moreover, the connection of the downward leader with the upward leader also takes place at the same instant regardless the time of streamer inception. Even if the time difference in the streamer inception times evaluated in figure 5 is about 300 μs, there is not any 'gain' in the upward leader length by triggering an early streamer. This result clearly shows that even if ESE terminals increase the probability of streamer inception [26–28], they would not affect the initiation or the length of self-propagating upward connecting leaders.

Since most commercial ESE devices operate by the application of a voltage pulse to the tip of the rod [33], it is relevant to investigating the effect of such a voltage on the above presented results. Figure 6 shows the predictions of the distance between the downward leader tip and the rod at the moment of connection with the upward leader (final jump) for different voltage levels applied to the rod. In the simulation, square voltage pulses are assumed to be applied to the upper section of the rod at the moment of inception of the second streamer. In this way, the influence of the external voltage on the upward leader propagation is directly determined. Prospective return stroke peak currents of 5, 10 and 30 kA are considered. As seen in figure 6, there is no change in the final jump (interception) distance when applying an external voltage to the terminal tip, unless a square voltage pulse with a peak value larger than 500 kV is applied to the rod. Since the voltage pulse applied to the tip of most ESE terminals is generated from the energy supplied by the ambient electric field, the peak value of such pulses is not larger than few tens of kilovolts [19, 30, 33]. This value is far below the required voltage to make any improvement in the upward leader length at the moment of connection. Hence, the external voltage applied to the tip of ESE terminals does not influence the propagation of the upward connecting leader, contrary to the claims of some ESE manufacturers.

Another controversial issue in the ESE claims deals with the velocity of the upward connecting leader after its stable initiation. In order to compute the 'gain' in the length of a connecting leader initiated from an ESE terminal compared with a conventional Franklin rod, the ESE proponents assume that the velocity of the upward leader is close to 10^6 m s^{-1} [26, 27]. In order to illustrate the physical conditions after inception, figure 7 shows the simulated streak image, velocity and current of an upward connecting leader. A downward leader with a prospective return stroke peak current of 5 kA is assumed to descend with an average velocity of 2×10^5 m s^{-1}. Observe that after the unstable inception time t_i', the connecting leader propagates with low velocity and current (lower than 10^4 m s^{-1} and 0.5 A). As the downward leader approaches the ground, the upward connecting leader starts accelerating continuously reaching the stable propagation condition t_1. After this, the velocity of the connecting leader is close to the values observed in laboratory leaders [4–6]. Finally, the upward leader velocity reaches in this case up to about 6×10^4 m s^{-1} at the moment of interception. In addition, note that the velocity of the upward connecting leader at the moment of initiation for the simulated 3.5 m tall rod is not even comparable to the velocity of the downward leader

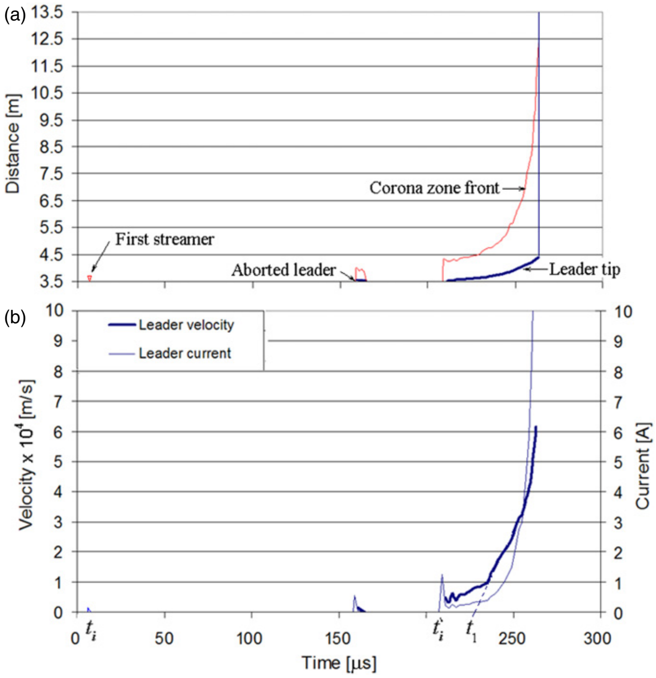

Figure 7. Predictions of the propagation of an upward connecting under the electric field produced by a downward leader with velocity of 2×10^5 m s^{-1} and the prospective return stroke current of 5 kA. (*a*) streak image and (*b*) leader current and velocity.

(assumed as 2×10^5 m s^{-1}). Similar results were obtained for prospective return stroke currents up to 30 kA. A detailed analysis of the velocity of upward connecting leaders can be found in [43]. Therefore, it is completely unrealistic to consider that the velocity of upward connecting leaders after their initiation is close to 10^6 m s^{-1} as claimed by ESE supporters [19–21, 26, 27].

The results presented in this section clearly show that the early streamer concept does not produce any effect on the initiation or propagation of upward connecting leaders under lightning conditions. Even though the early streamer concept applies for leaders propagating in the laboratory under switching waveforms, it does not influence connecting leaders propagating under the electric fields produced by a downward moving leader. Thus, the early emission of streamers from lightning rods does not lead to longer upward leaders at the moment of attachment of the downward leader and consequently to longer lightning protection zones. This is because the 'gain' in the length of the upward connecting leader attributed to ESE terminals is based on flawed concepts. At best, the ESE terminals perform similar to a conventional Franklin rod.

6. Conclusions

In this paper, the validity of the ESE concept is theoretically evaluated with an up-to-date self-consistent leader inception and propagation model based on the physics of leader discharges. It is found that an early streamer triggered from a lightning rod tested under switching impulse waveforms leads to the quicker initiation of positive leaders, in agreement with laboratory experiments. However, this ESE effect does not apply for lightning rods under the electric fields produced by downward lightning leaders. Due to the fact that the rate of increase in the lightning electric fields changes from slow to fast, while the switching electric field rate of change varies from fast to slow, the development of positive leaders from lightning rods under natural conditions and in the laboratory is different. Thus, the length of the upward connecting leader at the moment of attachment of the downward stepped leader is not affected by the time of initiation of the first streamer. This fact clearly shows that the ESE concept does not work for lightning rods exposed to the influence of downward moving leaders and that the claimed enlarged lightning protection area of ESE devices is physically not plausible.

References

[1] Schonland B F J, Malan D J and Collens H 1935 Progressive lightning: II *Proc. R. Soc. London* A **152** 595–625 (Containing papers of a mathematical and physical character 1905–1934)

[2] Schonland B F J 1952 The work of Benjamin Franklin on thunderstorms and the development of the lightning rod *J. Franklin Inst.* **253** 375

[3] Golde R H 1967 The lightning conductor *J. Franklin Inst.* **283** 451–77

[4] Les Renardiéres Group 1972 Research on long air gap discharges at Les Renardiéres *Electra* **23** 53–157

[5] Les Renardiéres Group 1974 Research on long air gap discharges—1973 results *Electra* **35** 47–155

[6] Les Renardiéres Group 1977 Positive discharges in long air gaps—1975 results and conclusions *Electra* **53** 31–132

[7] Les Renardiéres Group 1981 Negative discharges in long air gaps *Electra* **74** 67–216

[8] Gallimberti I 1972 The mechanism of long spark formation *J. Phys. Coll. (Suppl. 7)* **40** C7 193–250

[9] Bondiou A and Gallimberti I 1944 Theoretical modeling of the development of the positive spark in long gaps *J. Phys. D: Appl. Phys.* **27** 1252–66

[10] Goelian N, Lalande P, Bondiou-Clergerie A, Bacchiega G L, Gazzani A and Gallimberti I 1997 A simplified model for the simulation of positive-spark development in long air gaps *J. Phys. D: Appl. Phys.* **30** 2441–52

[11] Bondiou-Clergerie A, Lalande P, Laroche P, Willet J C, Davis D and Gallimberti I 1999 The inception phase of positive leaders in triggered lightning: comparison of modeling with experimental data *ICAE 1999: 11th Int. Conf. on Atmospheric Electricity (Alabama, USA, June 1999)*

[12] Lalande P 1996 Study of the lightning stroke conditions on a grounded structure *Doctoral Thesis* Office National d'Etudes et de Recherches A'erospatiales (ONERA)

[13] Becerra M and Cooray V 2006 A simplified physical model to determine the lightning upward connecting leader inception *IEEE Trans. Power Delivery* **21** 897–908

[14] Becerra M and Cooray V 2006 Time dependent evaluation of the lightning upward connecting leader inception *J. Phys. D: Appl. Phys.* **39** 4695–702

[15] Becerra M and Cooray V 2006 A self-consistent upward leader propagation model *J. Phys. D: Appl. Phys.* **39** 3708–15

[16] Golde R H 1973 *Lightning Protection* (London: Edward Arnold)

[17] Willet J C, Davis D A and Laroche P 1999 An experimental study of positive leaders initiating rocket-triggered lightning *Atmos. Res.* **51** 189–219

[18] Lowke J 2004 On the physics of lightning *IEEE Trans. Plasma Sci.* **32** 4–17

[19] Berger G 1992 The early streamer emission lightning rod conductor *Proc. 15th Int. Conf. Aerospace and Ground: ICOLSE (Atlantic City, NJ)* paper 38

[20] Berger G 1996 Leader inception field from a vertical rod conductor—efficiency of electrical triggering techniques *Conf. Record 1996 IEEE Int. Symp. on Electrical Insulation (Montreal, Canada, 1996)* 308–11

[21] Berger G 1993 Determination of the inception electric fields of the lightning upward leader *Proc. Int. Symp. High Voltage Engineering ISH (Yokoyama, Japan, 1993)* pp 225–9

[22] Alessandro F D, Kossmann C J, Gaivoronsky A and Ovsyannikov A G 2004 Experimental study of lightning rods using long sparks in air *IEEE Trans. Dielectr. Electr. Insul.* **11** 638–49

[23] Lee J B, Myung S H, Cho Y G, Chang S H, Kim J S and Kil G S 2002 Experimental study on lightning protection performance of air terminals *Power System Technology 2002, Proc. PowerCon 2002 (Kunming, China)* **4** pp 2222–6

[24] Heary K P, Chaberski A Z, Richens F and Moran J H 1993 Early Streamer Emission enhanced air terminal performance and zone of protection *Conf. Record Industrial and Commercial Power Systems Technical Conf. (Florida, USA)* pp 26–31

[25] Allen N L, Evans J C, Faircloth D C, Siew W H and Chalmers I D 1999 Simulation of an early streamer emission air terminal for application to lightning protection *Proc. High Voltage Engineering Symp. ISH (London)* (London: IEE) 2.208.S11-2.211.S11

[26] French Standard 1995 Protection of structures and open areas against lightning using ESE air terminals *French Standard* NF C 17 102

[27] Spanish Standard 1996 Protection of structure and of open areas against lightning using early streamer emission air terminals *Report* UNE 21186

[28] NFPA 1997 *Proposal for Lightning Protection Systems using Early Streamer Emission Air Terminals* Draft NFPA 781

[29] Gruet P 2001 A study of ESE lightning rods (Etudes des Paratonnerres á Dispositif d'Amorcage) Report DCE 2000 INERIS (National Institute of Environment, Industry and Hazards) France

[30] Van Brunt R J, Nelson T L and Stricklett K L 2000 Early streamer emission lightning protection systems: an overview *IEEE Electr. Insul. Mag.* **16** 5–24

[31] Chalmers L D, Evans J C and Siew W H 1999 Considerations for the assessment of early streamer emission lightning protection *IEEE Proc. Sci. Meas. Technol.* **146** 57–63

[32] Baldo G, Gallimberti I, Garcia H N, Hutzler B, Jouaire J and Simon M F 1975 Breakdown phenomena of long gaps under switching impulse conditions: influence of distance and voltage level *IEEE Trans. Power. Appar. Syst.* **PAS-94** 1131–9

[33] Allen N L, Cornick K J, Faircloth D C and Kouzis C M 1998 Test of the 'early streamer emission' principle for protection against lightning *IEEE Proc. Sci. Meas. Technol.* **145** 200–6

[34] Cooray V, Rakov V and Theethayi N 2007 The striking distance revisited *J. Electrostat.* **65** 296–306

[35] Carrara G and Thione L 1979 Switching surge strength of large air gaps: a physical approach *IEEE Trans. Power Appar. Syst.* **PAS-95** 512–24

[36] Rizk F 19889 A model for switching impulse leader inception and breakdown of long air-gaps *IEEE Trans. Power Deliv.* **4** 596–603

[37] Bazelyan E M and Raizer Y P 2000 *Lightning Physics and Lightning Protection* (Bristol: Institute of Physics Publishing)

[38] Petrov N I and D'Alessandro F 2002 Theoretical analysis of the processes involved in lightning attachment to earthed structures *J. Phys. D: Appl. Phys.* **35** 1788–95

[39] Dellera L and Garbagnati E 1990 Lightning strike simulation by means of the Leader Progression Model; I: Description of the model and evaluation of free-standing structures *IEEE Trans. Power Deliv.* **PWRD-5** 2009–23

[40] Rizk F 1994 Modeling of lightning incidence to tall structures: I. Theory *IEEE Trans. Power Deliv.* **PWRD-9** 162–70

[41] D'Alessandro F 2003 Striking distance factors and practical lightning rod installations: a quantitative study *J. Electrostat.* **59** 25–41

[42] Alekandrov N L, Bazelyan E M, Carpenter R B, Drabkin M M and Raizer Yu P 2001 The effect of coronae on leader inception and development under thunderstorm conditions and in long air gaps *J. Phys. D: Appl. Phys.* **34** 3256–66

[43] Becerra M and Cooray V 2008 On the velocity of positive connecting leaders associated with negative downward lightning leaders *Geophys. Res. Lett.* **35** L02801 doi:10.1029/2007GL032506