NON CONVENTIONAL LIGHTNING PROTECTION SYSTEMS

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ABSTRACT

Both theory and experimental evidence show that Early Streamer Emission (ESE) principle does not work under natural field conditions and that there is no justification at present to assume that the ESE rods perform better than Franklin rods. The hallmark of ESE technology is the application of voltage pulses to the tip of lightning rods assuming that their effects will enhance the attractive radii of lightning conductors. Analysis presented here show that any lightning rod when exposed to the electric field produced by a stepped leader will act exactly like an ESE rod because the pulsating electric field of the stepped leader simulates the action of voltage pulses that are being used in ESE rods. It is estimated that the effect of the step like electric field changes caused by the stepping process of the stepped leader on a lightning rod is equivalent to a voltage source injecting voltage pulses of tens of kV or more at intervals of 10 to 50 μs to the lightning rod. It demonstrates that the physics of the lightning attachment process of a Franklin rod is identical to that of an ESE rod and hence the attachment efficiency of a Franklin rod is identical to that of an ESE rod of identical geometry. The results presented in the paper also demonstrate that dissipation arrays cannot dissipate an imminent lightning flash either to the protected structure or to the terminal itself.

1 NON CONVENTIONAL LIGHTNING PROTECTION SYSTEMS

The external lightning protection systems used by engineers in different countries can be divided into two categories, namely, conventional and non-conventional lightning protection systems. The conventional systems use Franklin rods the performance of which has been validated in a large number of studies conducted around the globe over a span of many decades. The Early Streamer Emission rods and Dissipation Arrays (sometimes called Charge Transfer Systems) belong to the category of non conventional lightning protection systems. The latter systems have been introduced into several lightning protection standards without testing them over a long period of time in the field to assess and validate their performances. In this paper we will discuss scientific basis of these systems and their performance as reported in the scientific literature. Except for the section 2.3 which describes the results of a recent study conducted by the author, the rest of the paper is taken from a publication prepared by the author on behalf of the CIGRE working group 405 of study committee C4 [1].

2 THE EARLY STREAMER EMISION (ESE) CONCEPT

The ESE terminals used in practice are equipped with a discharge triggering device to initiate streamers from the terminal in an attempt to increase the probability of inception of a connecting leader from the terminal during the approach of a downward lightning leader [2]. According to the proponents of ESE the time advantage realized by the early inception of the connecting leader from an ESE terminal in comparison to a normal Franklin rod would provide a possibility for the connecting leader generated by an ESE terminal to travel a longer distance in comparison to that from a Franklin rod. Consequently, it is claimed that under similar circumstances an ESE terminal will have a larger protection area than a Franklin rod of similar dimensions. However, recent experimental and theoretical investigations find results that are in conflict with the claimed performance of ESE devices [3].

2.1 Experimental evidence that are in conflict with the concept of ESE

Case studies conducted by Hartono et al. [4] in Malaysia, provide undisputable evidence that lightning do bypass the ESE terminals and strike the protected structures well within the claimed protective region of the ESE devices. The same study showed that no damages were observed on structures equipped with Franklin rods installed according to the international lightning protection standard to cover the vulnerable points such as edges or corners of the structure. However, in structures where Franklin rods were installed without consideration of these high risk interception points, lightning strikes have been observed at these points.

In another study conducted in New Mexico [5], ESE lightning rods were allowed to compete with symmetrically spaced Franklin rods to validate the enhanced attractive zone of ESE devices claimed by its proponents. If, as claimed, ESE rods can initiate an upward leader before the Franklin rods and if they have a larger attractive zone, then one would expect ESE rods to be the preferential point of attachment of the lightning strikes. However, according to the observations all the lightning strikes got attached to Franklin rods and not a single one terminated on the ESE devices. This experiment conclusively proves that the ESE terminals do not have an advantage over the Franklin rods and the claimed enhanced protective range does not exist.

Proponents of ESE sometimes refer to an experiment conducted in France using triggered lightning [6] to support the action of ESE terminals. In this experiment an ESE terminal was put in competition with a Franklin rod to get attached to a down coming leader created in an altitude triggered lightning experiment. The downward moving leader got attached to the ESE terminal and the proponents of ESE claim that this proves the superior action of ESE terminals in comparison to Franklin rods. However, it is important to note that in the experiment the ESE terminal was located closer to the rocket launcher than the conventional one. The reason for the attachment of the lightning flash to the ESE rod could be simply due to the spatial advantage it had with respect to the conventional rod. Unfortunately, the positions of the rods were not interchanged to validate the claimed enhanced attractive range of the ESE terminal. Thus, one has to conclude that this experiment does not provide any evidence for the claimed superiority of the ESE terminals against the conventional ones.

2.2 Theoretical evidence that are in conflict with the concept of ESE

The whole concept of ESE is based on the observed fact that by artificial triggering of streamers from the tip of a lightning terminal (i.e. ESE rod) stressed by a switching impulse, one can cause the terminal to initiate a leader earlier than from a lightning terminal placed under identical circumstances but without the action of artificial streamers (i.e. Franklin rod) [7]. In the laboratory, it was found that the time advantage (i.e. the time interval between the initiation of leaders from ESE and Franklin rods), Δt of an ESE terminal is about 75 μs. Proponents of ESE terminals have taken this laboratory observation and extended it to natural conditions claiming that a 75 μs advantage will give rise to a length advantage equal to the product $v\Delta t$ where v is the speed of the upward moving leader. Assuming a leader speed of 10^6 m/s they claim that an ESE terminal would have a length advantage of about 75 m over a conventional rod. Thus, the whole concept of ESE device is based on two assumptions:

(a) The early initiation of leaders from ESE terminals observed in the laboratory takes place also under natural conditions. In other words, an ESE terminal can launch a connecting leader long before a conventional rod under natural conditions.

(b) The time advantage observed will translate to a length advantage of $v\Delta t$ over a conventional terminal.

Let us first assume that a time advantage exists in ESE devices when exposed to lightning-generated electric fields. In ESE technology, this time advantage was converted to a length advantage of about 50 – 75 m over a conventional rod by assuming a leader speed of about 10^6 m/s.

The majority of speeds of upward connecting leaders reported in the literature is from those in either rocket triggered lightning or from those in upward initiated lightning flashes. In these cases the upward connecting leader moves in a more or less static background electric field created by thunderclouds. These leader speeds are not relevant to the study under consideration. Yokoyama et al. [8] managed to measure the speeds of upward connecting leaders initiated from an 80 m tall tower as a result of the electric field generated by downward moving leaders. In four examples analyzed in the study they found that the connecting leader speeds just before the connection is made between them and the downward moving leaders were 1.3 x 10^6 m/s, 1.4 x 10^6 m/s, 2.9 x 10^6 m/s and 0.5 x 10^6 m/s. These speeds are similar to the one used by ESE manufactures in calculating the striking distance. However, it is not correct to use these speeds in the analysis of ESE terminals because what is required to calculate the length of the connecting leader given the time advantage is the average speed of the connecting leader. The average speed of connecting leaders measured by Yokoyama et al. [8] varied from 0.8 x 10^5 m/s to 2.7x10^5 m/s. This average speed is an order of magnitude less than the one used by ESE manufactures. Moreover, the connecting leaders photographed in the study originated from an 80 m tall structure. In general, the connecting leaders issued from tall structures are relatively longer than the ones issued by short structures during lightning interception. Long leaders have ample time to thermalize their channel and this makes them move faster than short connecting leaders. The studies conducted by Becerra and Cooray [9] show that the speed of upward leaders immediately after initiation is close to 10^4 m/s and it may increase as the leader length increases to values close to 10^5 m/s. This again shows that the average speed of connecting leaders is one or two orders of magnitude smaller than the 10^6 m/s assumed by ESE proponents. If the experimentally observed values of the average leader speeds are used in the conversion of time advantage to distant, the resulting length advantage would be of no use in many practical situations. Second, this procedure of converting the time advantage to a length advantage is not correct because the eventual length advantage depends on the ratio of the speeds of both downward and upward leaders. If this is taken into account the assumed length advantage will be less than the value calculated by multiplying Δt by the average speed of the connecting leader. Third, according to the proponents of ESE the earlier initiation of a connecting leader from an ESE device occurs in a smaller electric field than is required for the initiation of a leader by a conventional rod. However, for a successful propagation of a connecting leader a certain background electric field is needed. If the background electric field is not large enough the initiated leader could be aborted. The proponents of the ESE do not consider the requirements for the propagation of a leader and they do not consider the possibility that the initiated leaders could be aborted if the background electric field requirements are not satisfied.

Now, we come back to the first assumption. Recently, Becerra and Cooray [10] constructed a model incorporating the physics of the attachment process to simulate lightning attachment to structures. Using this model they have simulated the initiation and development of positive leaders under the influence of time varying electric fields used in laboratory as well as the time varying electric fields generated at ground level by the descent of the stepped leaders. Their results show that indeed one can obtain a time advantage in the laboratory but such a time advantage will not be present when the rods are exposed to the background electric fields of leaders. As shown in Figure 1, in order to change the striking distance significantly ESE rods have to be supplied with Mega-volt strong generators.

2.3 ESE and Franklin rods under natural field conditions

According to the ESE technology, the only difference between a Franklin rod and an ESE rod is that in the later a circuitry builds into the conductor renders the application of voltage pulses to the tip of the rod. Based on laboratory experiments it is claimed that this artificial pulsation of the ESE rod leads to an increase in the attractive distance of the ESE rod in comparison to a Franklin rod [7]. As mentioned earlier the work of Becerra and Cooray [10] shows that that this procedure will not promote the growth of connecting leaders under natural conditions. For a moment let us disregard the results of Becerra and Cooray [10]. In several ESE devices the voltage pulses that are being applied to the tip of the rod are created by utilizing the background electric field of the stepped leader to generate sparks in a gap or in a series of gaps connected between the upper part of the ESE rod and ground. Others may utilize a different mechanism to generate voltage pulses. The end result of the application of these voltage pulses to the tip of the ESE rod is to make the electric field at the tip of the ESE rod to pulsate. In other words, the basis of ESE technology is the creation of a pulsating electric field at the tip of the lightning rod.

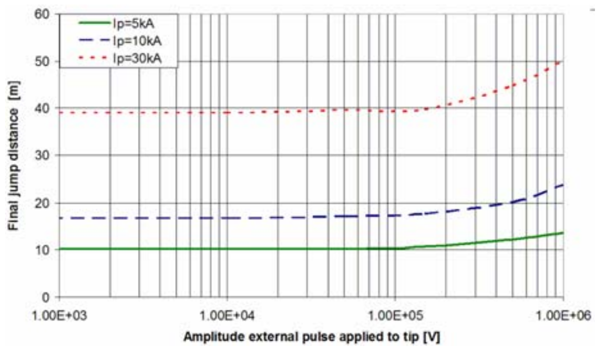

Figure 1: Distance between the downward leader tip and the ESE rod at the moment of connection between the connecting leader and the down-coming stepped leader (final jump) as a function of the voltage impulse applied to the ESE rod. Calculations are given for three prospective return stroke currents.

Let us consider the mechanism of the stepped leader. It is an established fact that the down coming stepped leader transport negative charge towards ground in a stepped manner. The research work conducted by Krider et al. [11] and Cooray and Lundquist [12] show that bulk of the charge that is being deposited on the leader channel is transported in a stepped manner. In a recent study Cooray et al. [13] estimated how the spatial distribution of the charge deposited on the stepped leader channel varies as the stepped leader extends towards the ground. In the present study, this charge distribution is utilized to calculate the electric field at ground level as the leader approaches the ground. The electric field calculated at ground level assuming that the charge on the stepped leader is transported towards ground in steps of 20 m of length is shown in Figure 2. For comparison purposes the electric field at ground level calculated for a smooth downward propagating leader is shown by a dashed line in the same figure. As one can see, the magnitude of the total field is so large that it is difficult to observe the rapid changes in the electric field produced by the individual steps.

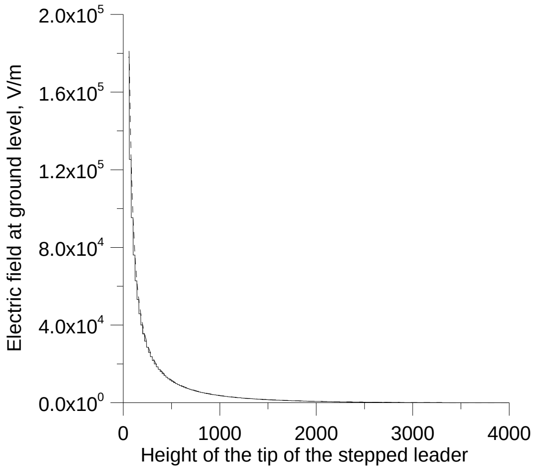

Figure 2: Electric field at ground level produced by a down coming stepped leader as it moves towards the ground. The solid line depicts the electric field corresponding to a leader moves down in 20 m long steps and the dashed line corresponding to a uniformly moving leader. The prospective return stroke current associated with the stepped leader is 30 kA.

Since the lightning rods are exposed to this background electric field of the stepped leader, the geometry enhanced electric field at the tip of the lightning rods will also follow the temporal variation of the stepped leader field. Therefore, the electric field at the tip of a lightning conductor exposed to the electric field of a down coming stepped leader will also increase in miniature steps in synchronization with the background electric field. In other words, the behavior of the electric field at the tip of a lightning rod exposed to the stepped leader field is identical to that of a lightning conductor whose tip potential is changed intermittently by application of voltage pulses. The time interval between these pulses is given by the time interval between the leader steps which lies in the range of 10 to about 50 μs. This is exactly what the ESE manufactures attempt to create artificially. Let us convert the pulsing nature of the electric field at the tip of the lightning rod exposed to the back ground electric field of a stepped leader into an equivalent voltage impulse. This can be done by isolating the lightning rod from ground by placing it a few millimeters above ground and calculating the amplitude of the voltage pulses necessary to create electric field steps identical to those produced at the tip of the lightning rod by the stepped leader. The results obtained for 10 m tall lightning rod with a 5 mm gap to ground are depicted in Figure 3 for a stepped leader associated with a 30 kA prospective return stroke current. The vertical axis gives the amplitude of the equivalent voltage pulse and the horizontal axis depicts the height of the stepped leader tip above ground. Results are shown for step lengths of 50 m (curve a) and 20 m (curve b).

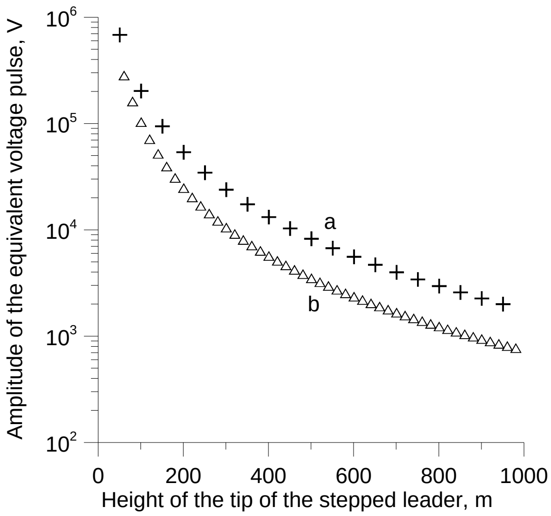

Figure 3: Amplitude of the voltage pulses that are needed to be applied to the tip of a lightning rod to simulate the electric field changes caused by the stepping process of the stepped leader. (a) 50 m step length. (b) 20 m step length. The prospective return stroke current associated with the stepped leader is 30 kA.

Note that the amplitude of the equivalent voltage pulses increases as the stepped leader nears the ground. Observe also that the equivalent voltage pulses have amplitudes in the range of kilovolts when the stepped leader is about 1 km above ground and it increases to more than 10 kV when the stepped leader is about 200 m above ground. As mentioned earlier, in many ESE rods the voltage pulses are generated passively by isolating the tip of the rod from ground. When the rod is exposed to the background electric field created by the stepped leader the gap (or gaps) fire intermittently generating the voltage pulses. The voltage pulses generated by such a process may have amplitudes in the kV range.

The above analysis indicates that the electric field at the tip of a lightning rod exposed to a stepped leader field pulse naturally. Any lightning rod in the field will behave as if it has an in built mechanism to generate voltage pulses that regulate the electric field at its tip. Thanks to the pulsating nature of the stepped leader fields, both the Franklin rods and ESE rods will function in an identical manner when exposed to the electric fields of down coming stepped leaders. Indeed, there is no need to artificially inject voltage pulses into the tip of a lightning rod because the nature itself generates such pulses without human intervention.

The main claim of ESE technology is that the application of voltage pulses to the tip of the lightning rod will increase its attractive radius. In section 2.2 we have given scientific evidence that shows that the application of voltage pulses to the tip of the lightning rod will not increase its attractive radius under natural conditions. The above analysis shows that, *even if one doubts that evidence*, one still has to treat both ESE rods and Franklin rods as having the same lightning interception efficiency.

3 THE CONCEPT OF DISSIPATION ARRAY SYSTEMS AND MOUNTING SCIENTIFIC EVIDENCE AGAINST THEIR PRINCIPLE OF OPERATION

The original idea of lightning eliminators or dissipation arrays is to utilize the space charge generated by one or several grounded arrays of sharp points to dissipate the charge in thunderclouds and thus prevent lightning strikes to a structure to be protected. The proponents of this system claimed that the space charge generated by the array will silently discharge the thundercloud. Scientists demonstrated conclusively that this will not be the case using following arguments. First, a thundercloud generates charge at a rate of about a Coulomb of charge per second and the charge production rate from a dissipation arrays is not large enough to compete with this charging process. The maximum currents from arrays as claimed by its proponents are in the range of 500 μA. However, no details of the measurements or whether this refers to the maximum current or the average is not clear. Even if this is true, it is still not strong enough to neutralize the charge in the thundercloud. Second, the mobility of small ions at ground level is about (1 – 3) x 10^{-4} m^2 v^{-1} s^{-1} and in the background electric fields of 10 – 50 kV/m the drift velocity may reach 1 to 15 m/s. Even if the array can generate charge of sufficient quantities, in the time of regeneration of charge in the thundercloud of about 10 s the space charge can move only a distance of about 10 to 150 m. Thus, the space charge would not be able to reach the cloud in time to prevent the occurrence of lightning. Facing this challenging and convincing opposition from lightning researchers the proponents of lightning eliminators accepted that the arrays are not capable of neutralizing the cloud charge. In turn they suggested that the function of the dissipation array is to neutralize the charge on down coming stepped leaders.

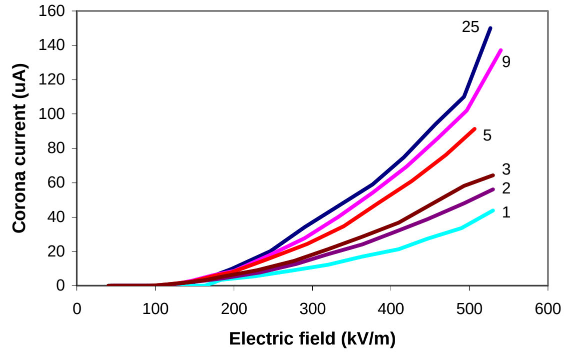

Figure 4: The corona current as a function of the background electric field from clusters of needles. The number of needles in the cluster is shown in the diagram.

A stepped leader may consist of about 5 C of charge and the dissipation array has to generate this charge in about 10 s. The proponents of dissipation arrays made the following argument to show the effectiveness of the array in neutralizing the stepped leader. A 10 point dissipation array can produce about 1 mA of current. Thus the number of points you need to generate a current that is capable of neutralizing the leader charge is 5000. In making this claim they have assumed that the current generated by a multi point array is equal to the current generated by a single point multiplied by the number of points. Cooray and Zitnik [14] conducted experiments to investigate how the corona currents produced by an array of sharp points or needles vary as a function of number of needles in the array. The lower limit of the corona current that could be measured in the experiment was about 1 μA. The results obtained are shown in Figure 4. Observe first that the corona current increases with increasing electric field and for a given electric field the corona current increases with increasing number of needles. Note, however, that for a given electric field the corona current does not increase linearly with the number of needles. This experiment clearly demonstrates that the corona current does not increase linearly with increasing number of needles.

More recently, proponents of the dissipation arrays claimed that the dissipation arrays work by suppressing the initiation of upward leaders by screening the top of the structure by space charge. A patent based on this concept has been also produced [15]. This claim was based on the study conducted by Aleksandrov et al. [16]. In that study Aleksandrov et al. showed that the electric field redistribution due to space charge released by corona discharges at the top of a high object hinders the initiation and development of an upward leader from an object in a thunderstorm electric field. It is important to recognize, however, that the corona charge issued from the terminal would not screen the sides of the terminal or the tower. Thus, as the stepped leader approaches the dissipation array a connecting leader could be issued from the sides of the terminal which is not screened by the space charge. But, the main question is whether the space charge from the needles can counter balance the increase in the electric field caused by the down coming leader. Calculations done in [14] shows that a tower without the space charge produced by the needles will launch a connecting leader before a tower with similar geometry but with space charge at the tower top. However, the space charge controlled field does not lag far behind the field that would be present in the absence of the space charge. For example, the difference in the stepped leader tip height from the tower top when the electric field at the tower top is large enough to launch a connecting leader in the presence and in the absence of space charge is no more than two meters. Thus, the reduction in the striking distance caused by the space charge is no more than a few meters.

In addition to the above points, there are several well documented cases in which lightning has been observed to strike dissipation arrays. The best procedure to conduct such a study is to compare two similar structures, one with a CTS and the other without. Several such studies have been conducted [17]. All the studies show that CTS systems were struck by lightning as well as the control structure. No reduction in the frequency of lightning strikes to structures has been observed.

The proponents of dissipation arrays claim that according to the anecdotal evidence of the users there is a reduction in the cases of lightning damage after the installation of arrays. However, this does not necessarily mean that the array has prevented any lightning strikes. First, since the array is well grounded it provides a preferential path for the lightning current to go to ground. This itself will reduce the damage due to lightning strikes even if it does not prevent a lightning strike. Second, if the array is connected to a tall mast, due to the geometry itself the presence of the array can reduce the number of upward initiated flashes. This is the case since the background electric field necessary to initiate upward leaders from a given tower increases with increasing radius of the tip. Connection of a dissipation array at the top of the mast will increase the effective radius of the mast and, therefore, will require a higher background electric field to launch a upward moving leader. This may lead to a reduction in the number of upward initiated flashes from the tower. But, as noted by Mousa [18], upward flashes are of interest in the case of towers of heights larger than about 100 m or more and any benefit can be obtained only for these cases.

4 CONCLUSIONS

Both theory and Experimental evidence presented in the paper show that ESE principle does not work under natural field conditions and there is no justification at present to assume that the ESE rods perform better than Franklin rods. The hallmark of ESE technology is the application of voltage pulses to the tip of the lightning rod assuming that their effects will enhance the attractive radius of the lightning conductor. Analysis presented here shows that any lightning rod when exposed to the electric field produced by a stepped leader will act exactly like an ESE rod because the pulsating electric field of the stepped leader simulates the action of voltage pulses that are being used in ESE rods. It is estimated that the effect of the step like electric field changes caused by the stepping process of the stepped leader on a lightning rod is equivalent to a voltage source injecting voltage pulses of tens of kV or more at intervals of 10 to 50 μs to the lightning rod. It demonstrates that the physics of the lightning attachment process of a Franklin rod is identical to that of an ESE rod and hence the attachment efficiency of a Franklin rod is identical to that of an ESE rod of similar length and geometry. The results presented in the paper also demonstrate that dissipation arrays cannot dissipate an imminent lightning flash either to the protected structure or to the terminal itself.

5 ACKNOWLEDGEMENTS

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