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COMPARATIVE ANALYSIS OF ORIGINAL AND MODIFIED LIGHTNING PROTECTION SYSTEMS

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ABSTRACT

This paper compares the performance and relative effectiveness, of the original Improved Electro-geometric Model (IEGM), the Collection Volume Model and the Self-consistent Leader Inception Model (SLIM) with their modified models proposed in this study. Data based on the isokeraunic level and field measurements presented by the Nigeria Meteorological Service (NMS) are used in assessing and evaluating the models. The mean area and the number of thunderstorm days per year of the North-East Region are computed with the Microsoft Excel spreadsheet. The results of the models are illustrated graphically. It was observed that the improved models proposed by Emechebe et al, are relatively more effective and have better performance in terms of the LPS to be applied than the original models. The modified SLIM model presented here shows that between 100-180m above the surface of the earth, the area of the radio equipment exposed to lightning strike increases slowly from 0.103-0.222 m^2 and steeply from 0.272-0.981m^2 between 200-320m. The number of lightning hits on the radio equipment decreases with the increase of the correction factor (η). The modified SLIM model recorded a mean number of hits, which decreases from $2.88*10^{-5}$- $6.47*10^{-6}$ and $4.82*10^{-5}$-$9.73*10^{-7}$respectively, with the correction factor ($\boldsymbol{\eta}$) increasing from 5-50 when the mean thunderstorm days are 65.33 and 89.42 days per year.

KEYWORDS: Analysis, LPS, Models, Nigeria

INTRODUCTION

The tropical region, especially Nigeria, is prone to a fairly high frequency of lightning strikes [1]. Records of the NMS in Nigeria reveal that lightning strikes disrupt many social services and destroy several physical infrastructures, such as buildings, electrical devices and telecommunication systems, as well as terminate both human and animals' lives [2]. It is therefore, necessary for the engineers to predict the probability of a lightning strike and propose a suitable protection model. Several methodologies have been used to locate the air terminal; the part of the LPS that interrupts the passage of the lightning current directed to a structure [2, 3]. These include the Rolling Ball Method (RBM), an Electro-Geometric Model (EGM) [3].

However, in spite of proven field observations to validate this model by Eriksson and D' Alessandra, there are still doubts about the practical application of the EGM [4, 5,]. For instance, the model does not account for the geometry and the physical specification of the terminal as well as the effect of the height of the object in determining the striking distance [6]. The physics of lightning is also not considered by the EGM; it only considers the radius of a lightning strike.

Thus, this work seeks for innovative solutions to some of the shortcomings of the EGM through the following initiatives:

- To modify the existing LPS, in order to make it more suitable for application in the North-East Region of Nigeria,
- To compare the performance and effectiveness of both the modified and the existing LPSs,
- To predict the probability of a lightning strike and propose a suitable protection model.

The proposed model will serve as a useful tool for predicting and combating lightning strikes by LPS practitioners (meteorologists, communication, broadcasting, and structural engineers, and other industrial practitioners).

Review of Popular LPS Models

The existing LPS models include the Faraday Cage (FC), Cone Protection (CP), Rolling Ball (RB), Electro-geometric (EG), Linear Progressive (LP), Collection Volume (CV), and Self-consistent Leader Inception (SLI) models. The CPM is ineffective whereas the FCM is very expensive to implement. There is no guarantee that the metallic strips in FCM will be struck by lightning in preference to some other nearby exposed points. Thus, a review is carried out on the EGM, RBM, LPM, CVM, and SLIM because they are the popularly implemented models.

The EGM is used to establish the minimum distance in which the lightning flash will not strike a structure but the ground nearby [5]. It is based on an empirical law, deduced from the exploitation of statistical data relating the striking distance (R) of lightning to the return stroke current (I). This method assumes that when the stepped leader reaches a critical distance from a ground structure where the average potential in the gap between the leader tip and the ground structure is equal to the streamer potential gradient, electrical breakdown takes place in the gap immediately and the lightning flash will be attracted to the ground structure. Because the return stroke current is the result of the neutralization of the leader charge, the peak return stroke current that results when the stepped leader makes contact with ground depends on the charge distribution of the leader channel.

A large charge on the downward leader results in a large prospective return stroke current. Consequently, a leader channel with a smaller prospective return stroke current is closer to the structure than a leader channel associated with a larger prospective return stroke current before the leader becomes attached to the structure. The connection between the leader potential, leader charge and the prospective return stroke current influenced the expression of the striking distance as either a function of leader charge or as a function of the peak of the prospective return stroke current [1]. The placement of the air terminals on a structure is designed with the Rolling Ball (Sphere) Method (RBM). The RBM method is based on the assumption that lightning can only strike points within the sphere when the lightning distance is greater than the radius of the sphere. The assumption simplifies the application of the EGM to simple structures. This method is based on the EGM and it does not take into consideration the upward leader propagation parameters of the structure to be protected [7]. It also avoids the use of the electrical, geometrical and physical properties of the structure. Worse still, tall structures are struck by lightning below the top. This further weakens the use of the application of the RBM when the radius of the sphere is smaller than the height of the structure. These limitations, renders it imperfect for a tall structure [3].

The most popular EGM is the RBM technique. The RBM is the basic planning procedure for air-terminations of common structures. Planning with the RBM leads to the possible point of strikes where air-terminations have to be placed, but without a rating of the probability of lightning strikes at each point [8, 9]. It is absolutely based on the physics of lightning. The RBM noted that the edges and corners of a rectangular flat top are possible points of strikes. However, it does not directly provide a value of the interception efficiency at the different point of strikes. To apply this technique, an imaginary sphere, typically 45 m (150 ft) in radius, is rolled over the structure. The points touched by the sphere require protection, whereas points within the volume of the sphere are protected by the RBM. Its limitations include the use of a constant radius of a given peak current. In other words, RBM assigns equal leader initiation ability to all contact points on the structure. Furthermore, it has been shown that the standard 45 m rolling ball is inappropriate for flat surfaces [10]. The effectiveness of RBM is found to be unreliable since many buildings and structures with the RBM technique were found to have been struck directly by lightning [11]. RBM does not account for the followings:

- Main lightning-related parameters, such as leader charge and its distribution, leader propagation, cumulative frequency distribution of lightning stroke currents;
- Effects of latitude on the air breakdown parameters and the subsequent results;
- Wide range of structural shapes and dimensions found in practice;
- Height of the air terminals used for protection;
- Electric field intensification created by the structure and its features as a basis for upward leader inception; and
- Variation in the lightning attachment probability of the different competing features of the structures.

However, the Collection Volume Method does.

The LPM propounded by researchers attempt to simulate both the propagation of the downward leader and the upward connecting leader until the meeting point at which a return stroke is initiated. The goal of the LPM schemes is to characterize and quantify the process of attachment and to understand how different physical parameters affect the process of attachment. Due to the fact that the exact mechanism of the LPM is yet to be known, a large number of simplifying assumptions were made in applying the LPM. The different models made different assumptions concerning the distribution of the charge on the stepped leader, the leader inception criterion, the velocity ratio and the properties of the upward connecting leader. The LPM of Dellera and Garbagnati or Rizk does not utilize the knowledge of physics of leader discharges lightning [12]. The speed of propagation of all the connecting lightning flashes is assumed to be identical (constant) in some work. However, in reality the speed varies continuously as it propagates

CVM is also regarded as the Improved EGM by a paper [11]. It originated from early research papers [13, 14, 15]. Since that time, the CVM has undergone successful development and improvement for application to common 3-dimensional (3D) structures where air terminals are installed [10, 16]. It takes a more physical approach than the EGM by using the well-known fact that the striking distance is dependent on the peak current as well as the field intensification [10]. The CVM approach takes into account the lightning downward leader to a structure, the ratio of the intensified electric field at the structure top to the value E_0 of the ambient field (K_i), the ratio of the velocity of the downward leader to the upward leader (K_v), the radius of the attractive distance and the point at which an upward leader is launched.

A particular structure intercepts those downward leaders that enter the appropriate collection volume. The collection volume is defined by the striking distance surface and the velocity-derived boundary. The sectional radius of the collected volume for a given downward leader or striking distance surface is called the attractive radius

(R_a). R_a increases with increasing leader charge and decreasing with the velocity ratio respectively. R_a is considered the most significant output parameter in the collected volume analysis because it is used to compute the area of protection of any given structure [16]. Figure 1 is the architecture of the CVM for a downward leader propagation and interception on a structure. A downward leader will only terminate on the structure or the air terminal when the striking distance is attained and the leader's path is contained within the boundaries of the collection volume [4, 17, 18]. Figure 2 illustrates the behavior of the R_a and the striking distance with respect to the varying velocity ratio and downward leader charges on a structure of 30 m [16].

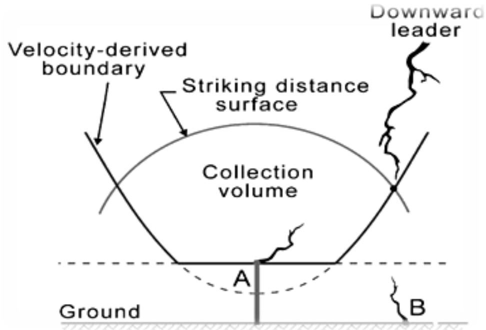


Figure 1: Leader Propagation and Interception on a Structure of a CVM Technique [16]

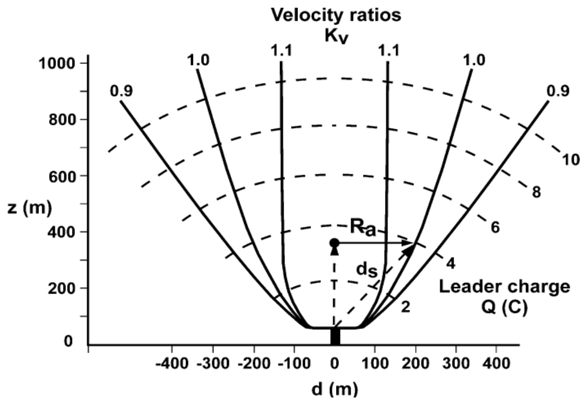


Figure 2: Collection Volume of a 30m Structure for Different Downward Leader Charges and Velocity Ratios [16]

There are doubts about the validity of a generalized behavior of the upward connection leaders. Worse still, the parameters obtained in the laboratory do not accurately describe upward connecting leaders. For these reasons, a better leader progression model capable of estimating the physical properties of the upward leaders is important.

These physical properties include the charge per unit length, the injected current, the leader channel gradient and the velocity of the upward leader under the influence of a downward moving leader [19]. The SLIM was introduced. The model evaluates the initiation of the upward positive leader considering the dynamic conditions imposed by the descent of the downward leader. The dynamic conditions include the time variation of the electric field produced by the step leaders and the space charge associated with the streamers and aborted leaders produced before the stable leader inception takes place. The leader inception model simulates the first propagation meters of an upward leader initiated from structures with and without axial symmetry. The model assumes that a stable self-propagating upward leader is initiated at the moment when the conditions are enough to guarantee its advancement at least during the first meters. The electric field produced by the downward leader does not change considerably during the time required for the inception of the upward leader. The initiation of streamers occurs before the leader inception takes place.

Model Description and Methodology

The modified analytical expressions for the attractive radius, the area of exposure and the average number of lightning strikes per year have been presented in [20]. Equations (16-23) in [20] were formulated on the basis of the following assumptions as stated in [12, 21, 22, 23]:

- The leader approaches from a given direction
- The grounded tower is freestanding and approximately axial symmetry
- The downward moving stepped leader is represented by a vertical descending linear charged channel to the tip of the LPS and the attractive radius is represented by equations (12-15)
- An upward return stroke is developed from the top of the rod towards the charged cloud center of the leader current and is modeled by equations (1-11)
- In all the models, the two leaders continually propagate towards each other until channel paths are created through which the lightning current is grounded
- The direction of propagation of the leaders, (the downward and the upward leaders) sums up to zero; an adiabatic condition.

The mean of the exposed area of the tower, the average number of lightning strikes and the mean of the thunderstorm days of Bauchi, Yola, Potiskum, Maiduguri, Nguru, Wukari, Gombe, Jos, Mubi, Jalingo, Biu and Damaturu – North-East Region were computed with the Microsoft Excel (MS Excel) spreadsheet. The analytical expressions of the original and the modified CVM, IEGM and SLIM Models were simulated and the results of the data collected at the end of the simulations were compared and illustrated graphically.

The parameters for modeling the LPSs with the variation in correction factor are given as:

$$k = 2, c = 1, \frac{t}{\tau_2} = 0.002, 1 + \left(\frac{t}{\tau_2}\right)^c = 1.002, \frac{t}{\tau_1} = 0.09, I_0 = 15\,KA, cd = 1, h = 100\,m,$$
$$Td = 65.33\, days\ per\ year, Td = 89.42\, days\ per\ year$$

RESULTS AND DISCUSSIONS

Figure 1 illustrates the behavioral patterns of the exposed area of the tower LPS against the height of the tower. Generally, it was observed that the area of exposure of a digital radio equipment mounted on a tower of height between 100-320m increases non-linearly with the increase in the height of the tower in all the models.

The modified SLIM model presented by Emechebe et al in figure 3a shows that between 100-180m above the surface of the earth, the area of the radio equipment exposed to lightning strike increases slowly from 0.103-0.222 m^2 and steeply from 0.272-0.981m^2 between 200-320m. The original SLIM model given by Becerra and Cooray shows that the area of exposure of the radio equipment to lightning strike increases slowly from 0.108-0.232$m^2$with increase in the height from 100-180m.It also increases from 0.285-1.02m^2 when the height of the mast lies between 200-320m. In the case of Figure 3b-d when the height of the Mast is between 100-320m, the area of exposure of the equipment increases steadily from: 0.257-0.569m^2 and 0.270-0.60m^2 with the modified and original Eriksson IEGM model; 2.00-8.08m^2 and

2.09-8.46m^2 with the modified and original Eriksson CVM model; 3.46-14.40m^2 and 3.64-14.99m^2 with the modified and original Petrov and Waters CVM model.

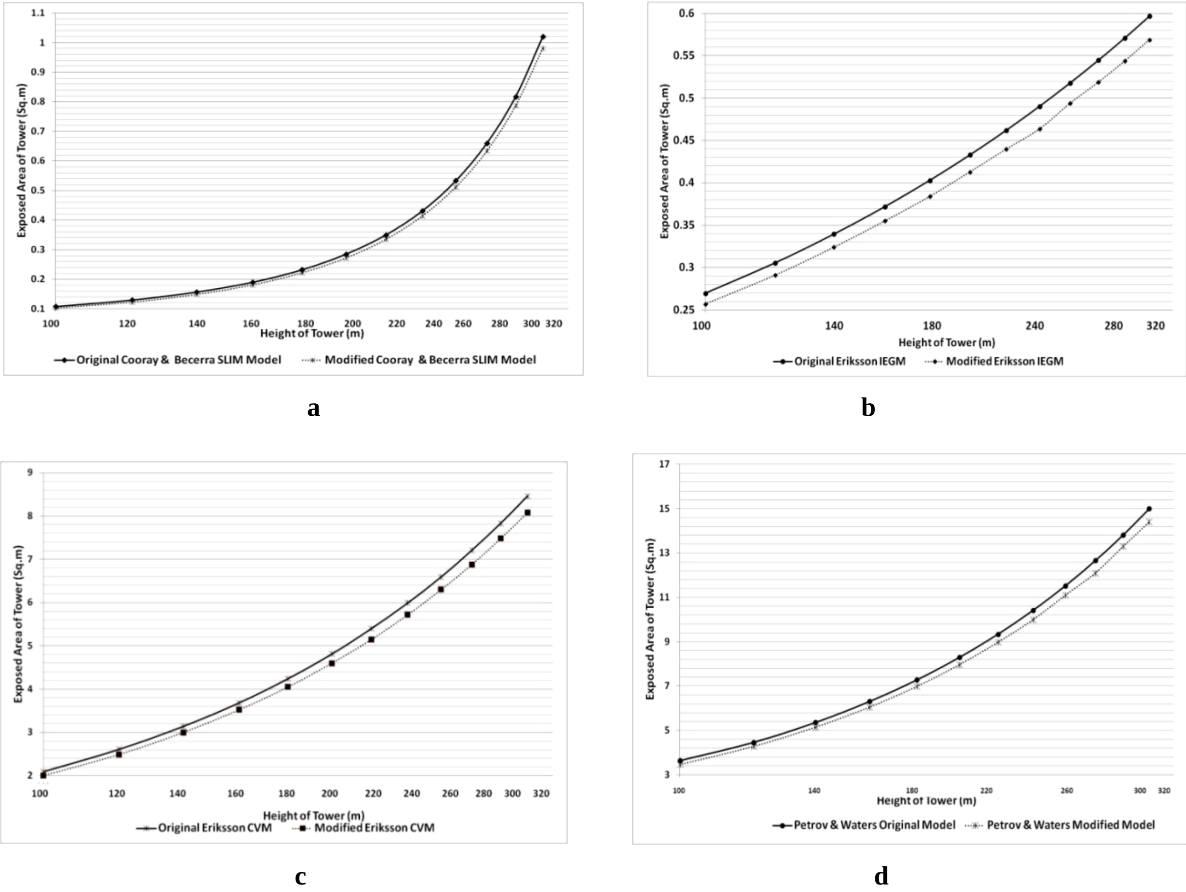
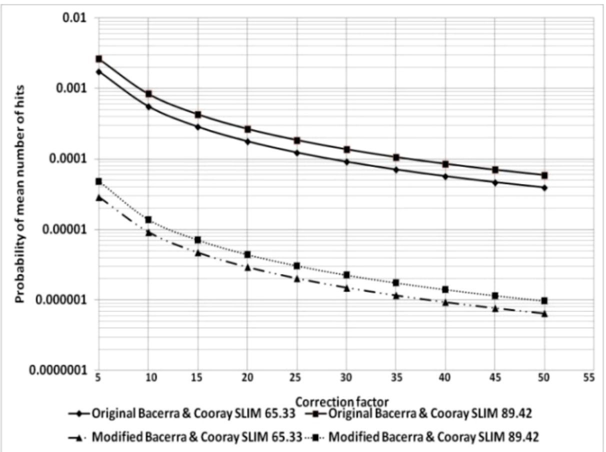


Figure 3(a): Exposed Area of Tower of SLIM Models vs. Height of Tower; (b) Exposed Area of Tower of Eriksson IEGM Models vs. Height of Tower; (c) Exposed Area of Tower of Eriksson CVM Models vs. Height of Tower; (d) Exposed Area of Tower of Petrov & Waters CVM Models vs. Height of Tower

Figure 4 describes the probability of the mean number of lightning currents which strike the radio equipment against the correction factor for a period of ten years. The number of lightning hits decreases with an increase in correction factor. Figure 4a-d shows that modified models presented by Emechebe et al experience a lower number of hits compared to the original model. The Modified SLIM model recorded a mean number of hits which decreases from 2.88*10^{-5}- 6.47*10^{-6} with the correction factor increasing from 5-50 when the mean thunderstorm day is 65.33 days per year. For the same range of correction factor and mean thunderstorm day of 89.42 day per year, the modified SLIM model recorded a mean number of hits decreasing from 4.82*10^{-5}-9.73*10^{-7}. The original SLIM model recorded 1.75*10^{-3}-3.93*10^{-5} and 2.63*10^{-3}-5.91*10^{-5} hits respectively when the thunderstorm days per year is 65.33 and 89.42 for the same range of correction factor.

The mean number of hits experienced by the equipment for the modified Eriksson IEGM and CVM, Petrov and Waters CVM for 65.33 days per year and correction factor of 5-50 are: 5.47*10^{-5}-1.06*10^{-6}, 373*10^{-4}-1.23*10^{-5} and 4.53*10^{-4}-2.10*10^{-5} respectively. Also, the mean number of hits recorded when the mean the mean number of thunderstorm day per year is 89.42 by the modified Eriksson IEGM and CVM, and Petrov and Waters CVM for the range of correction factor 5-50 are: 8.23*10^{-5}-2.40*10^{-6}, 5.61*10^{-4}-1.86*10^{-5}, and 6.81*10^{-4}-3.19*10^{-5} respectively.

The original SLIM, IEGM, Eriksson CVM and Petrov and Waters models at the mean number of thunderstorm days per year =65.33 and correction factor =5-50 experience the following mean number of hits: $1.75*10^{-3}$-$3.93*10^{-5}$, $2.51*10^{-3}$-$7.32*10^{-5}$, $1.45*10^{-3}$-$49.93*10^{-4}$, $1.26*10^{-2}$-$5.83*10^{-4}$ respectively. Similarly, the SLIM, IEGM, Eriksson CVM, and Petrov and Waters models at the mean number of thunderstorm days per year =89.42 and correction factor =5-50 are: $2.63*10^{-3}$-$5.91*10^{-5}$, $3.78*10^{-3}$-$1.10*10^{-4}$, $2.24*10^{-2}$-$7.42*10^{-4}$, $1.89*10^{-2}$-$8.76*10^{-4}$ respectively.



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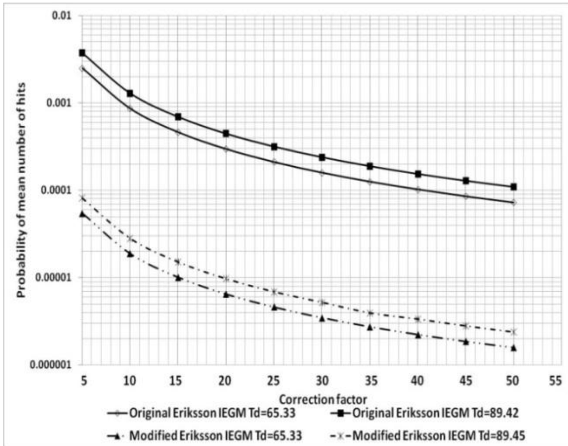

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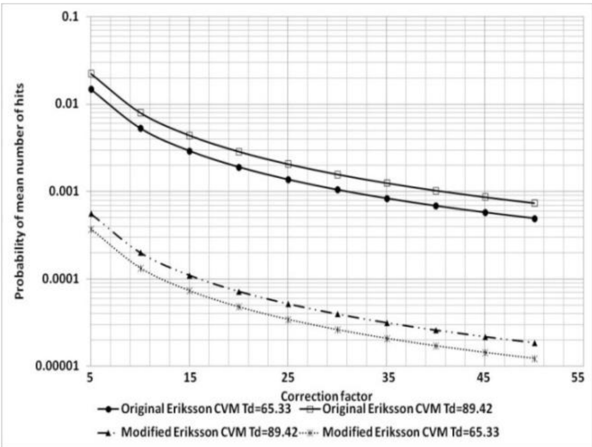

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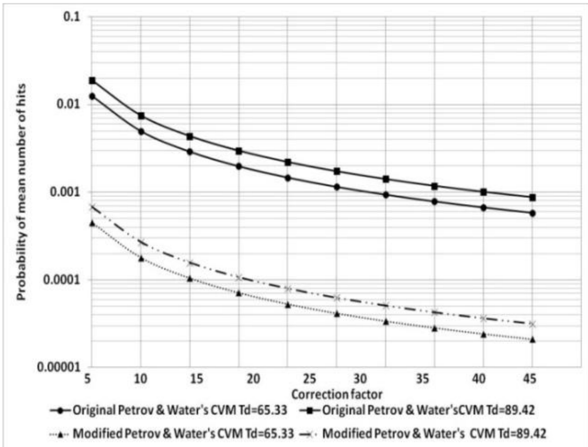

d

Figure 4(a): Probability of Mean Number of Hits of SLIM Model vs. Correction Factor; (b) Probability of Mean Number of Hits of Eriksson IEGM Model vs. Correction Factor;(c) Probability of Mean Number of Hits of Eriksson CVM Model vs. Correction Factor;(d) Probability of Mean Number of Hits of Petrov & Waters CVM Model vs. Correction Factor

CONCLUSIONS

The modified SLIM model proposed by Emechebe et al in [20] is the most suitable LPS for the North-East Region of Nigeria. The model shows that between 100-180m above the surface of the earth, the area of the radio equipment exposed to lightning strike increases slowly from 0.103-0.222 m^2 and steeply from 0.272-0.981m^2 between 200-320m. The number of lightning hits on the radio equipment decreases with the increase of the correction factor (η). The model also recorded a mean number of hits, which decreases from $2.88*10^{-5}$- $6.47*10^{-6}$ and $4.82*10^{-5}$-$9.73*10^{-7}$ respectively, with the correction factor ($\boldsymbol{\eta}$) increasing from 5-50 when the mean thunderstorm days are 65.33 and 89.42 days per year.

Further works will be focused on the influence of attractive radius on the electrical properties and characteristics of the LPS. These include electric potential difference and the capacitance of two parallel horizontal rods.

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