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Identification of the lightning vulnerable points on complex grounded structures

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Abstract

The identification of the most vulnerable points on a given structure to be struck by lightning is an important issue on the design of a reliable lightning protection system. Traditionally, the location of these lightning strike points is conducted using the rolling sphere method, through an empirical correlation with the prospective peak return stroke current. However, field observations in Kuala Lumpur and Singapore have shown that the points where lightning flashes strike grounded structures depend also on their height and shape. Since a lightning strike point is believed to be the place on a grounded structure where a propagating upward leader is first initiated, a physical leader inception model is used here to estimate the background electric fields required to initiate a stable upward leader from the corners of some complex buildings. The computed locations of the points from where leaders are incepted are compared with the damaged points on buildings struck by lightning. It is found that the corners of the buildings which are characterized by lower leader inception fields correspond to the observed lightning strike points. Furthermore, it is observed that the geometry of the buildings as well as their surrounding structures significantly influence the conditions necessary to initiate upward leaders and, therefore, the location of the most probable strike points.

Keywords: Lightning; Lightning protection; Lightning strike points; Air terminals.

1. Introduction

Air terminals are an important part of external lightning protection systems since they are designed to be the points where lightning flashes strike the protected grounded structure. For this to be the case, a stable upward leader has to be initiated from the air terminals before any other place on the structure and continuously propagate to intercept the downward coming lightning leader. Thus, the lightning leader will strike the air terminal where the conditions necessary to incept an upward leader are first fulfilled [1]. One of the prime factors that define the effectiveness of an air terminal to launch an upward connecting leader is given by its position on the structure. Thus, the basic philosophy for the location of air terminals is to determine all probable lightning attachment points on the structure [2]. For that purpose, the rolling sphere method has generally been used [3]. This geometrical method assumes that the most probable strike points correspond to the places that touch a fictitious sphere that is being rolled over the structure to be protected. The radius of this sphere has been empirically defined as a function of the prospective peak return stroke current based on lightning studies in power transmission lines. Nevertheless, there are doubts on the validity of using the same radius of the sphere for both power transmission lines,

buildings and other complex structures. Moreover, the adopted radii are only a result of compromises in standardization committees and do not consider any of the physical processes related to lightning attachment [4]. Even though some geometric modifications of the rolling sphere method have been proposed in [5, 6], a proper evaluation of the rolling sphere radius has unfortunately not been addressed yet.

Recently, the improved electrogeometric model developed by Eriksson for power transmission lines [7] has been extended and used for buildings [8]. This method assumes that any point in a structure can attach a downward lightning leader if it enters into its “*collection volume*”. This volume is determined by both the striking distance and the interception locus given by the velocity ratio of the downward and upward leaders [7]. The collection volume concept for buildings was linked with the field intensification method [9] for the striking distance calculation [8]. However, this collection volume/field intensification method is still not accepted since there are both theoretical and field facts that discredit it [10-11].

To the best of the knowledge of the authors, self consistent physics-based models have not been considered to assess the location of the preferred lightning strike points on complex grounded structures. It is because the existing physics-based methods are complicated and cannot be easily adopted in engineering applications [5]. However, a physical leader inception model that can be applied to any kind of structure has been presented recently in [12]. Unlike to the leader inception models based on local electric field, this model uses the potential distribution in front of the studied point as input. Then, a simple iterative geometrical analysis of the potential distribution is performed to simulate the first few meters of propagation of the upward leader. Using the method, the effect of the geometry of grounded structures and their surroundings on the leader inception evaluation can be considered.

As a result, different actual complex structures that have been damaged by lightning in Kuala Lumpur [13, 14] are studied with the physical leader inception model presented in [12]. The geometry of the structures and the surroundings is modeled in a Finite Element Program [15] and the leader inception electric fields for all the vertices on the structures are computed. In order to simplify the analysis, as a first approximation it is assumed that the background electric field produced by the downward stepped leader is quasi-uniform. A good correlation between the corners with the lower leader inception fields and the observed lightning strike points is found.

2. Evaluation of the leader inception condition for complex structures

2.1 Leader inception model

In order to identify the most probable lightning strike points in a grounded structure from a physical perspective, it is necessary to evaluate the leader inception condition at all the corners, edges, and flat surfaces on a structure. Nevertheless, most of the leader inception models available in the literature, namely the critical radius concept [16], the generalized leader inception criterion [17], the critical range of field intensification criterion [18], the Lalande’s equation [19] and the semiempirical leader model of Bazelyan and Raizer [19] cannot be directly applied to the analysis of complex structures. This is mainly because all of them have been derived for isolated rods or conductors and are therefore of limited use for the analysis of the inception condition of other different type of structure [12]. In addition, most of the existing leader inception models use the electric field at a given point (usually at the tip of the analysed corner or edge), which varies depending upon how the numerical singularities that occur when the Poisson’s equation is solved at sharp points. To avoid this problem, corners and edges are usually rounded off to a radius of curvature according to experience [21]. Consequently the calculated electric fields and therefore the computed leader inception values are strongly dependant on the chosen radius and the

meshing quality.

To overcome these limitations, a leader inception model was introduced by Becerra and Cooray in [12]. It is based on a physical simulation of the first few meters of propagation of an upward leader from structures with and without axial symmetry. Hence, the simulation of the leader propagation is performed through an iterative geometrical analysis of the potential distribution in front of the studied point on the structure. Because of this fact, the computed results are not affected by the way the sharp points are treated in the numerical calculations by the designer.

Thus, the leader inception model presented in [12] is used in this paper. It is assumed that a stable upward positive connecting leader is incepted only if the background electric field conditions are sufficient for the propagation of a leader at least along the first few meters. Assuming that the streamer corona is always incepted before the leader initiation takes place, the leader inception condition is then evaluated as follows:

a) The computed background potential distribution U_l is approximated to a straight line (Figure 1) with slope E_l and intercept U'_0 such that:

$$U_l^{(0)}(z) \approx E_l \cdot z + U'_0 \quad (1)$$

b) The charge $\Delta Q^{(0)}$ and position $l_s^{(0)}$ of the second corona are computed as:

$$\Delta Q^{(0)} \approx K_Q \cdot \frac{U'^2_0}{2 \cdot (E_{str} - E_l)} \quad (2.a)$$

$$l_s^{(0)} = \frac{U'_0}{E_{str} - E_l} \quad (2.b)$$

where K_Q is a geometrical factor and E_{str} is the positive streamer gradient. If $\Delta Q^{(0)} = 1 \mu C$, the leader inception condition is not fulfilled and the analysis stops. Otherwise, the simulation of the leader propagation starts $i=1$ with an initial length $l_L^{(1)}$.

c) Then, the potential at the leader's tip $U_{tip}^{(i)}$ during the current simulation step i is computed as:

$$U_{tip}^{(i)} = l_L^{(i)} \cdot E_\infty + x_0 \cdot E_\infty \cdot \ln \left[\frac{E_{str}}{E_\infty} - \frac{E_{str} - E_\infty}{E_\infty} \cdot e^{-l_L^{(i)} / x_0} \right] \quad (3)$$

where $l_L^{(i)}$ is the leader length at the current simulation step, E_∞ is the final quasi-stationary leader gradient and x_0 is a constant given by the product $v \cdot \theta$, where v is the ascending positive leader speed and θ is the leader time constant.

d) The position and charge of the corona zone in front of the leader tip are calculated as:

$$l_s^{(i)} = l_s^{(0)} + \frac{E_{str} \cdot l_L^{(i)} - U_{tip}^{(i)}}{E_{str} - E_l} \quad (4.a)$$

$$\Delta Q^{(i)} \approx K_Q \cdot \left\{ \left(E_{str} \cdot (l_L^{(i)} - l_L^{(i-1)}) + U_{tip}^{(i-1)} - U_{tip}^{(i)} \right) \cdot (l_s^{(i-1)} - l_L^{(i)}) \right\} \quad (4.b)$$

Fig. 1. Example of the linear approximation of the background potential distribution of the corner of a building.

- e) The leader advancement distance $\Delta l_L^{(i)}$ and the new leader length $l_L^{(i+1)}$ is evaluated by using:

$$\Delta l_L^{(i)} = \frac{\Delta Q^{(i)}}{q_L} \quad (5.a)$$

$$l_L^{(i+1)} = l_L^{(i)} + \Delta l_L^{(i)} \quad (5.b)$$

- f) If the leader length $l_L^{(i+1)}$ reaches a maximum value l_{max} , the leader inception condition is fulfilled. If the leader advancement $\Delta l_L^{(i)}$ starts decreasing after some steps, this suggests that the leader will stop and therefore the stable leader inception condition is not reached. Otherwise, go back to c). A typical value of l_{max} equal to 2 meters was observed to be long enough to define the stable propagation of an upward leader when space charge pockets are not considered [12]. Larger values require more analysis steps i and produce about the same result in that case.

The values of the parameters used in equations (2) to (5) are presented in Table 1 and a detailed discussion of them can be found in [12].

Table 1. Parameters used for the evaluation of the leader inception condition

<i>Sym</i>	<i>Description</i>	<i>Value*</i>	<i>Units</i>
$l_L^{(1)}$	Initial leader length	$5 \cdot 10^{-2}$	m
E_{str}	Positive streamer gradient. (2),(3),(4).	$4.5 \cdot 10^5$	V/m
E_{∞}	Final quasi-stationary leader gradient. (3).	$3 \cdot 10^4$	V/m
x_0	Constant given by the ascending positive leader speed and the leader time constant. (3)	0.75	m
q_L	Charge per unit length necessary to thermal transition. (5)	$65 \cdot 10^{-6}$	C/m
K_Q	Geometrical constant that correlates the potential distribution and the charge in the corona zone. (2), (4).	$4 \cdot 10^{-11}$	C/V.m

*Details about the chosen values can be found in [12].

2.2 Potential distribution calculation

This is the most demanding step of the leader inception evaluation in terms of the required computational time and memory. In spite of the fact that the Becerra and Cooray leader inception model makes use of the potential distribution instead of the electric field at a local point, requiring much lower computational resources for the same accuracy level, the three-dimensional (3D) electrostatic calculation of complex structures is still challenging. Nevertheless, powerful desktop computers and software are nowadays at the hands of designers and engineers, making possible the implementation of this kind of analysis in practical cases. Moreover, the Finite Element FEM based programs support CAD geometries [15], making it easier for this kind of electrostatic calculations.

Because of the complex nature of the lightning phenomenon, a complete electrostatic analysis would require the modeling of the thundercloud, the downward lightning leader, the studied structure and the surroundings. Furthermore, it would be necessary to solve the Poisson equation of the full system for every possible location of the downward leader tip (Figure 2.a), making the solution of the problem too difficult for practical purposes.

However, in order to simplify the analysis it is assumed that the downward stepped leader produces an equivalent quasi-uniform electric field E_{back} over the grounded structure [9, 12], as shown in Figure 2.b. Even though this assumption is not valid for the calculation of striking distances for high buildings (larger than about 50 m [12]), it can be used to make the comparative analysis of the leader inception from different points of a structure, significantly reducing the computation time.

Fig. 2. Example of a slice plot of the electric field logarithm close to a grounded building: *a)* including the downward coming leader *b)* using an equivalent background uniform electric field. Note the similarity on the electric fields at the close proximities of the point A in both cases.

Thus, the structure is assumed to be immersed in a background uniform electric field E_{back} inside an analysis volume, whose dimensions should be large enough to properly consider the lateral open boundaries. Therefore the width and breadth of the analysis volume are set to be several times larger than the dimensions of the structure and volume height is set equal to 600 m since the analysed structures do not exceed 110 m. Figure 3 shows an example of a FEM model of a structure, the Ångström Laboratory in Uppsala, Sweden. Note that only the main features of structure are considered in order to avoid meshing problems and to keep an appropriate number of mesh elements. The meshing problems basically occur because of the geometrical complexity and the large variation in the dimensions of some parts of complex structures. Once the model is successfully meshed and the boundary conditions are set, the system is solved.

Finally, the potential distribution along a vertical line from each analysed point to up to about 20 m is obtained for a reference background field $E_{back-ref}$ (Figure 1). Since the slope E_l and the intercept U'_0 used to approximate the potential distribution (Section 2.1) are proportional to the background field E_{back} , those values are normalized to the reference field.

Then, they are used to determine the minimum field E_{back} required to inception a stable leader by using the bisection method [21]. This minimum background field is called the stabilization Field [19].

Fig. 3. Example of the geometry model of an actual structure for the electrostatic calculation. a) Photograph of the Ångström Laboratory, Uppsala, Sweden. b) FEM model of the Ångström Laboratory. c) Full FEM model including analysis volume.

3. Study cases

In this section, the leader inception (stabilization) fields computed with the above-presented procedure are obtained for some actual complex structures in Kuala Lumpur which have been struck by lightning [5, 13, 14]. Since more than 90% of the observed lightning strike points are sharp and protruding corners [5], the analysis is only performed for these kind of points on the analysed structures. The obtained stabilization field E_{stab} at each point is normalized to the minimum stabilization field observed in the structure E_{stab}^{min} , by the ratio E_{stab}^{min}/E_{stab} . This ratio is defined as the *leader inception likelihood*. According to this definition, the leader inception likelihood factors close to one (or 100%) correspond to the points on the structure where the inception of a stable upward leader is physically more likely to occur. The obtained likelihood factors are compared in Table 2 with the observed number of strikes and with the qualitative lightning strike probability levels defined in [13].

The first study case considered is the Villa Putri apartment (110 m height) shown in Figure 4. This building has been struck by lightning seven times during the following four years after its construction in 1995, even though two non-conventional air terminals were installed on it. In order to analyze this case, the main features of the building and the surrounding structures are modeled (Figure 5). The observed damages produced by lightning on the structure as well as the normalized stabilization fields are also shown. Note that the air terminal Y (modeled as a standard rod) has the highest chance to initiate an upward leader. However, it can be seen that the protection zone of this terminal was not large enough to avoid the strikes to the corners A, B, P, Q and S, which also correspond to the places with higher inception likelihood. On the other side, observe that the second existing terminal X is not effective to protect the building since the leader inception conditions are more favorable for the surrounding corners P, Q, B and A (leader inception likelihood of 95%, 88%, 84% and

82% respectively) than for the terminal (68%). This fact agrees with the field observations which show that these points *A*, *P*, *Q* and *B* were struck by lightning six times during the period of study [13], despite of the presence of the terminal *X*.

Here it is important to mention that the leader inception conditions of corners and air terminals on tall buildings (as in this case) are different than the conditions for free standing rods. For instance, the leader inception field of the air terminal *T* on the building (56 kV/m in Table 2) is about two times larger than the stabilization field of an isolated standing terminal with the same total height (26 kV/m [12]). This fact clearly shows that the design of air terminals on buildings cannot be conducted by approximating the lightning conductors as free standing rods as is usually done, since the computed leader inception conditions for these two cases are different. In addition, it is worth to point out that the surrounding structures also influence the leader inception fields of complex buildings. Note that the corners (*P* and *S*) close to the lower surrounding building (at the left hand side of the Villa Putri building in Figure 4.a) have higher leader inception likelihood than the corners (*Q* and *R*) close to the taller surrounding building (at the right hand side in Figure 4.a). This tendency can also be seen from the observed strike points in the following study cases.

Fig. 4. Photographs of the Villa Putri building: *a*) with the surrounding structures to the sides, *b*) a close up of the upper section of the building.

Fig. 5. FEM model of the upper section of the Villa Putri building with the observed strike points (dots) and the leader inception likelihood values (percentages). The surrounding buildings are also included in the analysis but not shown in this figure.

The second study case corresponds the Faber Tower Building which has been struck by lightning four times, as it is shown in Figure 6. This building is composed by two towers ($H=90$ m, $W=30$ m, $L=70$ m) adjacent to each other and surrounded by another structure of similar height 100 m away from the point *D*. In this case, the outer corners (*A*, *Q* and *R*)

that have been struck by lightning [13] also correspond to the points where the likelihood of launching a stable leader is higher.

Fig. 6. Diagram of the most likely strike points on the Faber Towers Building. The dots correspond to the observed lightning damaged points [13] and the percentages to the leader inception likelihood values.

The third study case corresponds to two bank buildings: Industry and Pembangunan, which have been struck by lightning two and five times respectively. The buildings have different heights (70 m and 110 m) and are separated by about 30 m. During the period of analysis of the lightning strikes [13], there was an air terminal at the center of the Pembangunan building (Figure 7). Similarly to the Villa Putri building, in this case an air terminal *T* on the top of the building is the more likely point to inception an upward leader (likelihood factor of 100%). Nevertheless, this terminal did not protect the outer corners of the building (*Q*, *P* and *Q*) which were damaged by lightning and are also likely to initiate upward leaders (leader inception likelihood of 91%, 82% and 78% respectively). On the other side, note that the corners of the Bank Pembangunan have higher leader inception likelihood factors in comparison with the Bank Industry. Hence, the corners *B* and *C* on the Bank Industry are much less likely to initiate upward leaders in comparison with the points *P* and *S* on the Bank industry, consistent with the observed strikes. Whereas the point *A* has the higher leader inception likelihood on the Bank Industry, where all the lightning strikes to that structure occurred.

Fig. 7. Diagram of the vulnerable strike points of two bank buildings with different height. The dots correspond to the observed lightning damaged points [13] and the percentages to the leader inception likelihood values.

The last analysed structure is a cluster of buildings in Kuala Lumpur, whose FEM model is shown in Figure 8. Each building (40 m height) has a triangular facade in addition to the parapet walls and is closely spaced (separated about 20 m) to the other buildings. Basically, the observed lightning strikes have occurred at the outer corners of the building cluster. However, also the triangular facades of the inner buildings (*K* and *L*) are likely to start a connecting upward leader and could therefore be vulnerable places to be struck.

Table 2. Computed leader inception fields E_{stab} for four real structures and observed lightning strikes

Case 1: Villa Putra Apartment				
Corner	E_{stab} [kV/m]	Likelihood L [%]	Observed strikes	Probability level [13]
Y	56.0	100	No Data	
P	58.4	95	2	High
Q	59.0	88	1	High
B	64.7	84	2	High
A	68.1	82	1	High
S	76.4	72	1	High
Z	78.4	71		Low
X	82.5	68	No Data	Low
R	91.2	61		
Case 2: Faber Towers Building				
Corner	E_{stab} [kV/m]	Likelihood L [%]	Observed strikes	Probability level [13]
Q	82.9	100	2	High
A	89.5	92	1	High
D	98.5	84		High
R	99.3	83	1	High
B	103.3	80		Low
S	103.7	79		Low
P	109.4	75		Low
C	128.1	64		Low
Case 3: Industry and Pembangunan Bank Buildings				
Corner	E_{stab} [kV/m]	Likelihood L [%]	Observed strikes	Probability level [13]
T	57.4	100	No Data	
Q	62.9	91	1	High
R	67.3	85		High
P	69.7	82	1	High
S	73.5	78	3	High
A	129.2	44	2	High
D	151.7	37		High
B	181.4	31		Low
C	206.4	27		Low
Case 4: Cluster of buildings				
Corner	E_{stab} [kV/m]	Likelihood L [%]	Observed strikes	Probability level [13]
D	91.8	100	1	High
E	100.9	91	1	High
A	119.7	76		High
K	119.5	76		Medium
F	139.3	66	2	High
L	146.5	62		Medium
B	147.2	62		High
C	152.6	60		High
G	156.2	58		High
H	164.5	55		Medium
I	217.6	42		Medium
J	231.1	39		Medium

Fig. 8. Diagram of the vulnerable strike points of a building cluster. The dots correspond to the observed lightning damaged points and the percentages to the leader inception likelihood values. Because of the symmetry of the structure, not all the corners were labeled.

4. Conclusions

It has been shown in this paper that there is a clear correlation between the observed strike points on actual complex buildings in Kuala Lumpur and the background fields required to inception upward leaders from them. The points on a structure which are more likely to initiate a stable upward leader correspond to the most vulnerable places to be struck by lightning. This result confirms the hypothesis proposed by Golde [1] that a lightning flash strikes the grounded point where an upward leader is first initiated. In addition, it is found that the conditions required to inception stable upward leaders from grounded structures depend not only on the background electric field produced by the downward leader (related to the prospective return stroke current) but also on the geometry of the analysed buildings and the surrounding structures. This suggests that a reliable evaluation of the lightning strike points on a grounded structure should also take into account the geometry of the structure and the surrounding buildings. This fact cast doubt on the validity of the rolling sphere method, which uses a constant sphere radius that is only a function of the prospective return stroke current when it is applied to complex grounded structures.

It is important to point out that this analysis is conducted to determine the points on grounded structures which are more likely to initiate an upward leaders and, consequently, to assess about the location of the most vulnerable lightning strike points. This is just the first step in the design of the lightning interception system on a structure since it allows to efficiently locate the air terminals. However, it does not provide further information such as the number of air terminals that are required to protect the structure. The illustration of this fact can be seen for instance in the Villa Putri Building (Figure 5). In this case the terminal X is found to be inefficiently located in a place where it is not likely to initiate upward leaders before the surrounding points (corners P, Q, B and A). Whereas the air terminal Y on the top floor of the building is the most likely strike point although there are other places (P, Q and S in Figure 5) where the upward leader inception is also highly likely to occur. Hence, these points have to ‘compete’ in the presence of a downward leader and therefore the number and location of the air terminals to properly protect the structure must be defined by considering both the striking distance and the attractive radii [7] of each one. In such a case, the position, height and prospective return stroke current of the downward leader have to be considered as well as the relative speeds of the upward and downward leaders. Then, the protected and

unprotected zones in the structure can be identified and an optimum design can be performed. An extensive analysis of this issue will be subject of a future publication.

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Figure captions

Fig. 1. Example of the linear approximation of the background potential distribution of the corner of a building.

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