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Lightning Interception on Elevated Building

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Abstract--Lightning protection air terminals are placed on structures and other grounded objects with the purpose of capturing the lightning stroke. A well estimation of the lateral protection distance is crucial in predicting the protection area of the lightning rod. This paper focus on a 3-D numerical modelling of lightning attachment based on physical phenomena leading to the formation and the development of the positive upward discharges. The application of our physical model was made for rods on earthed structures.

Our model takes into account the real nature of the protected area. The influence of the edges and the corners of the structure on the LPS is investigated.

The purpose of our 3D model is to present numerical predictions in order to ensure an efficient lightning protection system.

Key-Words:-Lightning, electric fields, protection, finite element method, modeling.

1 Introduction

Direct stroke causes accidents when the lightning strikes a building or a specified zone. This can cause considerable damage, usually fire.

To protect a structure against direct lightning strokes, a preferred impact point is selected to protect the surrounding structure and conduct the flow of the electric current towards the ground, with minimal impedance on the path followed by lightning. This is provided by lightning conductor systems.

Up to now, the placement of air terminals on structures is often designed with the rolling sphere method (RSM), which is based on the electrogeometrical model (EGM) [1]. As this model does not take in account both downward and upward leaders and their propagation parameters and also the electrical and geometrical properties of the protected structures, it remains imperfect. In particular for high buildings that are not considered in the standards when the rolling sphere radius is smaller than the structure height and where several striking points may occur. However, the knowledge in the domain of the physics of lightning has been improved, especially through the experiments in large air intervals [2], so it seems reasonable to refine this highly empirical model by a physical approach.

The growing need for a more and more rigorous protection has oriented scientists towards numeric models. Numerical modelling of lightning attachment involves the physical conditions of formation and propagation of upward leaders emitted from a Lightning Protection System (LPS). The optimised placement of the air terminals ensures that the most efficient lightning protection system (LPS) is installed. No physical model is available in literature and nothing is advised in the standards. Our model is based on physical phenomena leading to the formation and the development of positive upward discharges under the influence of their own field and the field produced by the negative downward leader [3].

Some results for rods on a flat ground have been presented at ICLP'2004. It was demonstrated that it is possible to use it instead the Electrogeometrical Model especially for tall rods [4], and especially when structures of high vertical extent are concerned.

In this paper, the application of our physical model was made for rods on earthed structures. The purpose of our 3D model is to present numerical predictions in order to ensure an efficient lightning protection system.

Our numerical model is firstly presented. As our model is a Leader Progression Model, the negative and positive leaders are modelled by a succession of charged segments [4]. Each leader is simulated by a linear charge distribution λ and a corona charge Q at the tip.

The electric field and the potential spatial distributions are computed numerically by solving the Laplace's equation. Using simple assumptions respectively on the conditions for upward leader inception [6] [7] and downward-upward leader junction [4], the maximum lateral distance of protection is computed as a function of the return stroke current, the lightning rod height, the structure parameters and the downward-upward leader velocities ratio ($Rv = v_d/v_u$).

The computation can be made for any incoming downward leader trajectory (oblique or vertical). It is of importance to show what is the protective zone offered by a lightning conductor placed on the top of a high elevated structure, which is not a simple extrapolation of results obtained for a rod placed on a flat conductive ground. This applies also to the lightning protection of transmission lines, especially in mountainous areas. In the second issue, the influences of the edges and the corners of the structure on the LPS are investigated. We exhibit the competition between upward leaders when these several potential lightning striking points have to be taken into account. It applies to the placement of roof or edge conductors needed to reduce the probability of side flashing. An example of failure of the EGM will be shown.

2 The Electrogeometrical model

The electrogeometrical model is based on an empirical law, deduced from the exploitation of statistical data, relating the striking distance ds (i.e. the distance between the downward leader head and the extremity of the Franklin rod when the condition for the initiation of an upward leader and the tip of the Franklin rod are reached) to the return stroke current I [1]:

$$d_s = 10 \cdot I^{0.65} \quad (1)$$

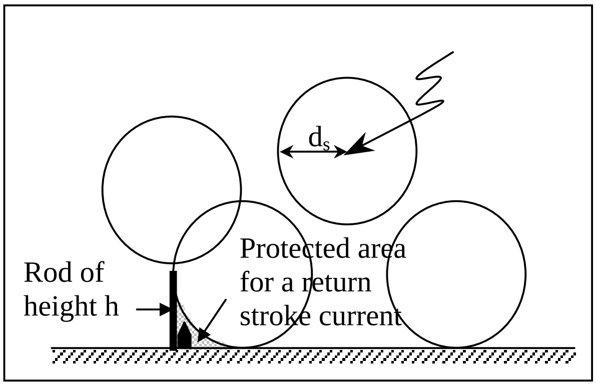


Fig. 1 Determination of the protected area by the Rolling Sphere Method

The vertical distance between the vertical axis of the rod and the vertical axis of the downward leader is called lateral distance. Obviously, if the lateral distance exceeds a certain value D, the junction is no more achieved. D is designated as the maximum

protective lateral distance. The rolling sphere method (RSM) based on the electrogeometrical model gives the following empirical relation between D and I, for a rod height h:

$$D = \sqrt{2.d_s.h - h^2} \quad (2)$$

The rolling sphere method is based on the assumption that no lightning can strike any point outside the sphere if its striking distance is greater than the constant radius of the sphere. The electrogeometrical model is relatively easy to apply to simple structures. However, many scientists agree that it has inherent limitations making it difficult to apply across a wide range of the structures and heights. The main drawbacks of the electrogeometrical model are as follows:

- It is not suited for the case of competing objects.
- It does not account for the simple geometry of the launching point, e.g., the air terminal.
- It does not account for both downward and upward leaders and their propagation parameters and also the electrical properties of the protected structures;

Added to this, it has been observed that tall protected structures are sometimes struck by lightning below their tops, on the edges [2].

This leads to uncertainties about the actual striking point on the considered structure especially for high buildings that are not considered in the standards when the rolling sphere radius is smaller than the structure height, and where several striking points due to significant local electric field intensification may occur (on corners or edges).

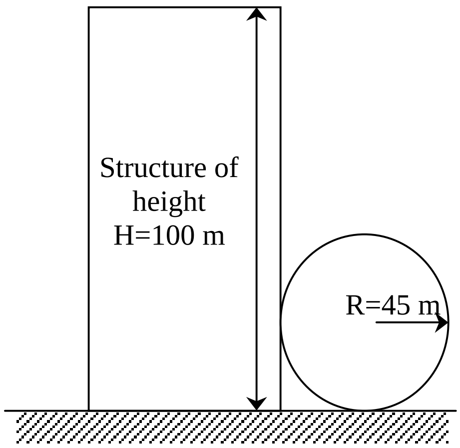


Fig. 2 An example of a problem when using the electrogeometrical model

However, it is necessary to make a dynamic simulation of the leader propagation based on computation of the combined electric field in order to define the most likely leader channel paths.

3 Presentation of our model

The proposed model will use physical considerations on the lightning interception. It is based on the knowledge of the discharges processes in long air gaps and on the analysis of experimental results obtained with natural or artificial lightning.

The ground is considered as a flat conducting surface. As our model is a leader progression model (LPM), the negative and positive leaders are modelled by a succession of charged segments [3], [4], [5].

To simulate the propagation of the downward and upward leaders towards each other, it is necessary to consider the velocity ratio Rv, i.e. the ratio of the downward leader velocity to the upward leader's. Generally, this ratio is arbitrary fixed to one. In reality, this ratio should not be treated as a constant. Indeed, the upward leader propagates in an increasing electric field, due to the approach of the downward leader. To take this into account, we choose for Rv a range of values from 0.5 to 4.

Each leader is simulated by a linear charge distribution λ and a corona charge Q at the tip [4], [5], [6]. These distributions are established on the basis of the streamer extension zone, more precisely over the minimal length of the streamer resulting from the top of a point, at the moment of the birth of the leader. The choice of a minimal length brings to a minimal charge for the ascending leader, what will give a higher reliability of the protection.

Let us study the formation of a streamer corona at the top of a rod plunged in an electric field during the approach of a downward leader (fig. 1). The average length of the streamer filaments is Ls. This extends of the top of the rod until a distance where the intensity of the electric field reaches a value of 5 kV/cm for a positive streamer (or 11 kV/cm for a negative streamer) [7]. By approximating the streamer zone to a half-sphere [6], this leads to the equation :

$$E_s = \frac{Q}{2\pi\varepsilon_0 L_s^2} \qquad (3)$$

where Q (C) is the distributed charge in the streamer zone which develops at the top of the point and Ls the half sphere radius.

When the streamer zone advances of one step, the charge Q is distributed on an Ls (m) segment length. Besides, if λ (C/m) is the linear distribution of the load along this leader segment, the equation will be:

$$E_s = \frac{\lambda L_s}{2\pi\varepsilon_0 L_s^2} = \frac{\lambda}{2\pi\varepsilon_0 L_s} \qquad (4)$$

The recent studies on air gap discharges in positive polarity evaluate this minimal charge λ_{min}=50µC/m. The value of the corona charge Q_u is deduced from the equation (2):

$$Q_u = \lambda L_s = 2\pi\varepsilon_0 L_{min}^2 E_s = \lambda_{min}^2 / (2\pi\varepsilon_0 E_s) \qquad (5)$$

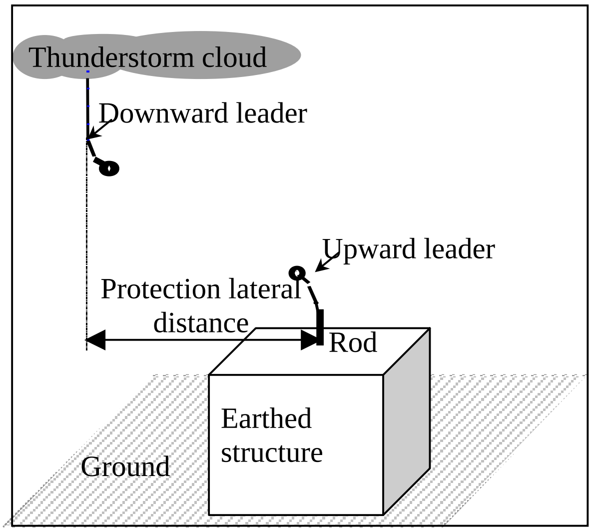


Fig. 3 An illustration of downward and upward

For the downward negative leader, λ_d (C/m) is related to the return stroke current I (A) by the equation [6]:

$$\lambda_d = 0.43\ 10^{-6}\ I^{0.65} \qquad (6)$$

From (5) and (6) the downward leader corona charge is given by the following expression:

$$Q_d = 3{,}33.10^{-9}.I^{4/3} \qquad (7)$$

Both linear charge density and corona charge are maintained constant throughout the propagation.

The electric field and the potential are calculated, by solving the Laplace's equation in the 3D volume between the cloud bottom and the ground surface. The finite element method was chosen with well fitted mesh refinement on the edges and the corners of the structure. The region where the electric field intensity is high is divided into smaller and finer tetrahedrae.

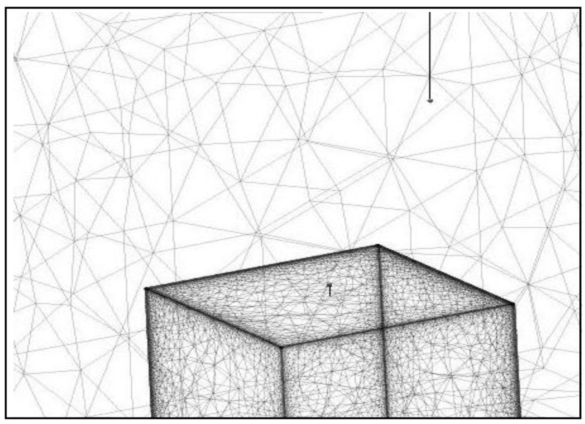


Fig. 4 A 3D visualisation of the used meshes in the volume (cloud-downward leader-structure-rod)

A successful capture by a Franklin rod needs three conditions to be fulfilled:

- Formation of an upward leader at the tip of the Franklin rod.
- Stable propagation of the upward leader (from the rod) towards the downward leader.
- Final junction between the two leaders.

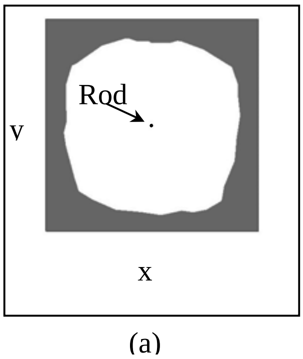
The tall structure introduces a significant change of the field repartition between the cloud and the ground. Added to this, it has been shown that tall structures are stricken on edges or on corners [2], [8]. Then, we have to take them into account in our calculations. In order to be more restrictive, some assumptions were made about the determination of the onset electric field for the formation of an upward leader. The electric field was calculated at different fixed points at 1m from the rod tip, and all the edges and the corners. When its value at one of these points is greater than or equal 5kV/cm, there will be a formation of upward leader.

At each step, the electric field and the potential are calculated at fixed distance from the leader tips over various directions. The next step is then directed along the maximum mean field line. Between each step, the electric field, along the straight line which join the upward and downward tips leaders, is calculated and compared to the minimal propagation electric field of the positive streamer (5 kV/cm at atmospheric pressure). As the upward leader goes to the capture of the downward leader, we opted to this minimalist approach. When all the computed values are greater than or equal to 5kV/cm, we consider that the conditions for the junction between the upward and downward leaders are fulfilled. If the upward leader was born from the rod, this is leading to a successful interception of lightning. In the opposite case, if it is one which arises from a corner or edge, the attachment of lightning occurs with the structure, leading to a failure of the lightning protection system.

4 Result and discussions

During a thunderstorm, the ambient electric field reaches high values. It appears an intensification of the electric field on a protected structure not only on the lightning rod but also on its corners and edges. These places on the structure will be then vulnerable points. The modelling results which follow indicate that these vulnerable points are much more likely struck.

In figure 5, we show the distribution of the electric field on the roof (a) and on a frontage (b) of a protected structure during a thunderstorm. We notice that besides the lightning rod, obviously the corners and the edges are involved in this phenomenon. So, we must take into account in our calculation all these points where there is high electric field intensification.



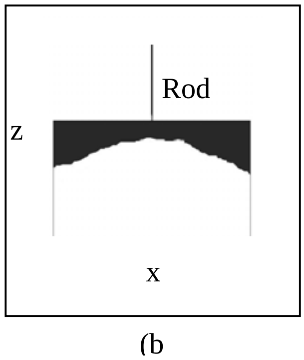


Fig. 5 Electric field distribution on a protected structure during a thunderstorm

Firstly, we wanted to know how behaves a corner of a building in the presence of downward leader. It is possible to demonstrate that there will be connection between an ascending leader and a corner by using our model.

Let us consider a structure without LPS. In figure 6, an example of the calculation of the attractive radius of a corner is given according to the geometry of the structure (the height H and the width W) and the lightning current intensity I.

We notice that the more the structure is high and slender, the more corners are vulnerable.

Hence, these results are of most practical interest in the field of lightning protection and confirm those found by other researchers [8], [9] [10].

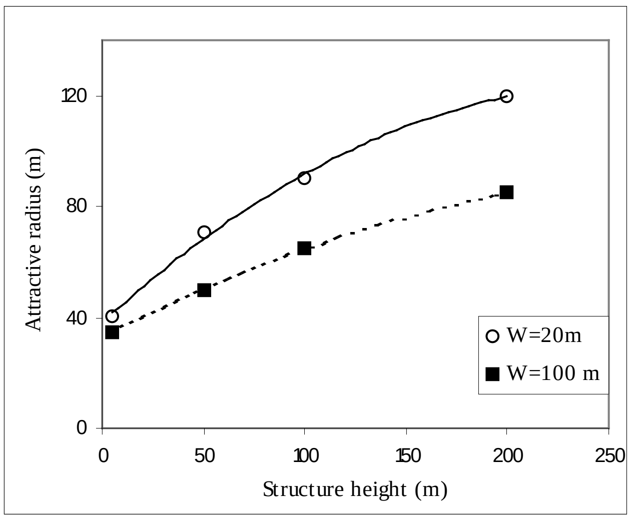


Fig. 6. The attractive radius of corners of rectangular structures as a function of height and width of the structure. I=10kA, Rv=1

In the second issue, the influence of the edges and the corners of the structure on the LPS are investigated. The electrogeometrical model is the only reference used in the international standards, but it does not consider the existence of corners and edges. So, we wanted to verify if a protection built on the basis of this model is really reliable.

For example, we considered a square structure of height H=100 m and of width W=40 m. For a lightning current of I=10 kA, (1) and (2) lead to a height of the Franklin rod h=11 m, which will be centrally placed on the roof of the building. As it is shown in figure 7, the lateral distance D offered by this rod is supposed to be sufficient to protect this structure.

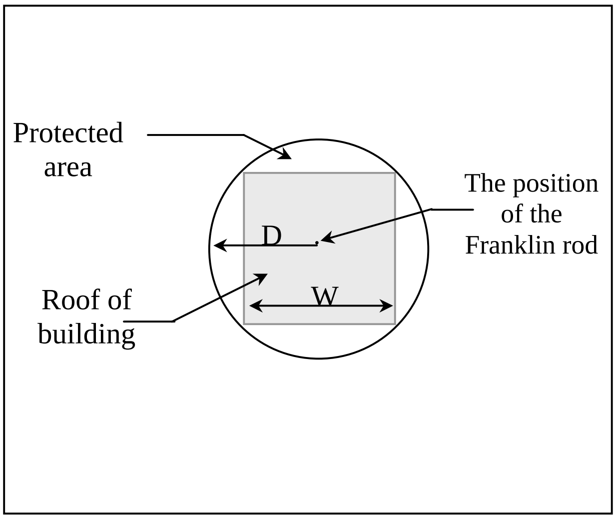


Fig. 7. An illustration of the protected area by using the electrogeometrical model

This “protected” structure is considered in our calculations. The simulation, using our model, shows that downward leader does not always strike the lightning rod. So, the structure is not well protected. Figure 8 gives an example of a corner strike. It also exhibits the competition between upward leaders. Indeed, at ICLP’2004, we showed that when several rods are installed on a flat ground, the launch of an upward leader at the tip of one of them strongly influences the conditions for leader inception at the other rod tips. The same phenomenon is observed on other vulnerable structure points.

Another interesting situation will be found according to the height h of the rod. Figure 9 illustrates an example of the successful protection when a 20 m high Franklin rod is used.

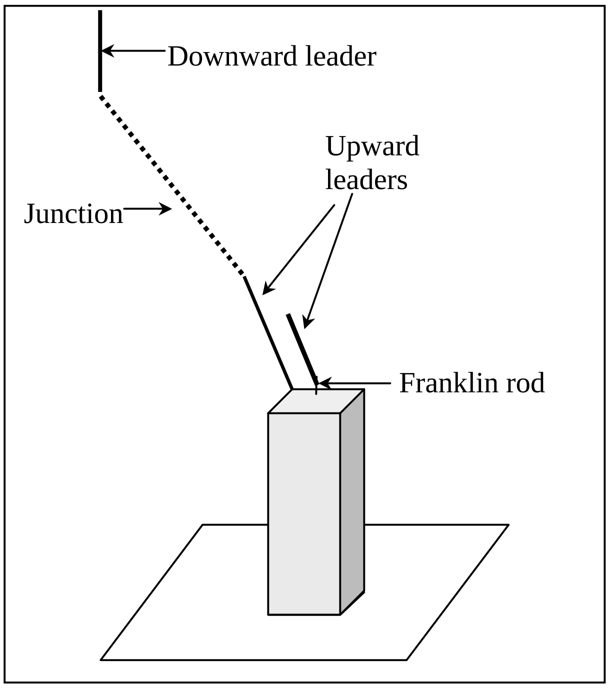


Fig. 8. A 3D illustration of the failure of the electrogeometrical model. Junction with the structure. I=10 kA, Rv=2.

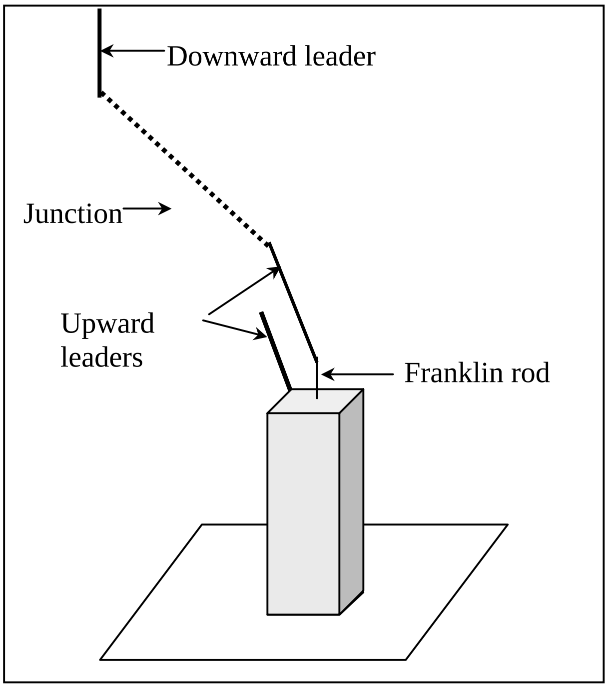


Fig. 9 A 3D illustration of a protected structure. Junction with the Franklin rod. I=10 kA, Rv=2.

There is a common observation of bad reliability of short air terminations–placement at a considerable distance from the “vulnerable” points of the structures. Field observations show that if the height difference between the air termination and the structure is small, the positioning of the air termination is much more critical. Rezinkina [11] used the so called ‘’electrostatic factor’’ method. She defined the ratio between the maximum level of electric field strength on object E_s and on lightning rod E_r upon electrical field (fig. 10), similar to one that precedes to a lightning discharge:

$$k_d = E_r/E_s \quad (8)$$

and if $k_d > 2.0$, the objects at the nominated distance d from the air termination (of a height h) are protected (fig. 11).

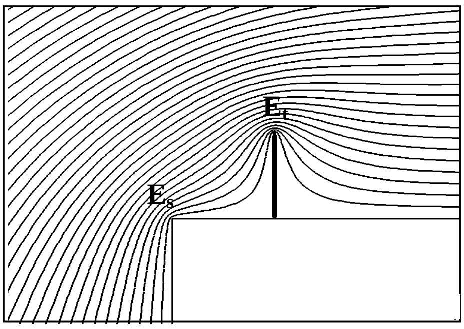


Fig. 10 Equipotential lines distribution during a thunderstorm

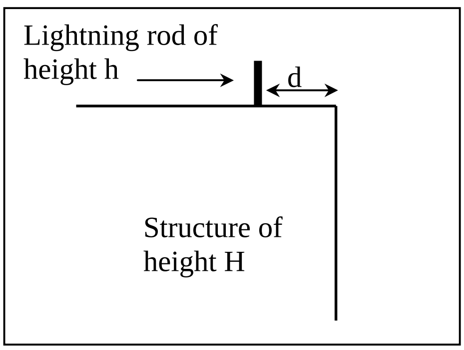


Fig. 10 An illustration of a protected edge

Our model is used to verify this criterion. On figures 12 and 13 we display two computed results. These figures show that despite kd=3.1, we have junction with the edge or the corner and a failure of the protection.

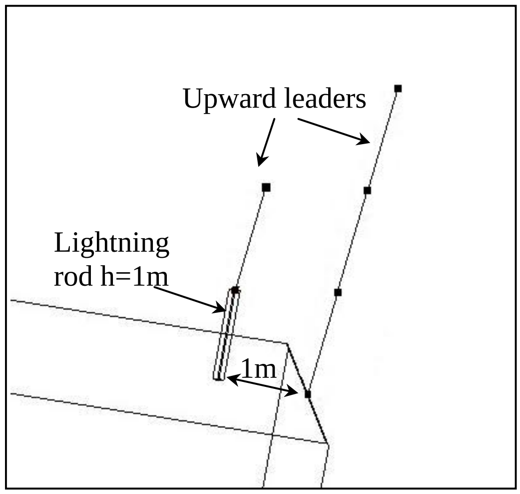


Fig. 12 An example of a competition between 2 upward leaders. Junction with the edges. I=10 kA, Rv=2, kd=3.1

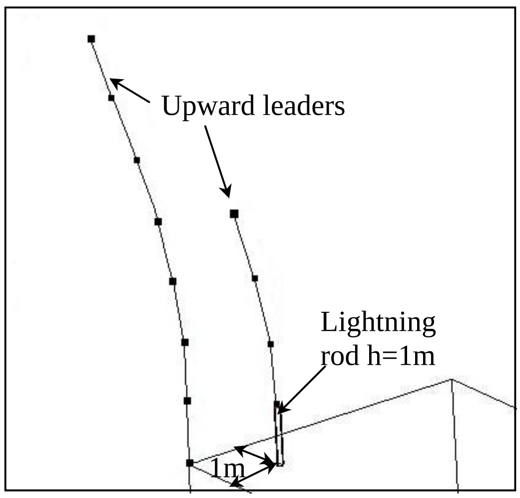


Fig. 13 An example of a competition between 2 upward leaders. Junction with the corner. I=10 kA, Rv=2, kd=3.1

5 Conclusion

In the present study, a successful analysis was conducted using numerical model which is based upon the physical phenomena leading to the formation and the development of a positive upward leader in the field produced by the negative downward leader charge and by some other competing upward leaders. It applies to the placement of roof or edge conductors needed to reduce the probability of side flashing.

The 3D numerical computations show that when we want to protect a building, we have to take into account all the parts of this structure where the electric field intensity can be high. Indeed, we demonstrated that for example a corner can attract the lightning.

Our model confirms that the model on which the international standards are based is limited and exhibits the competition between upward leaders when these several potential lightning striking points on the structure have to be taken into account. That explains the striking of some high protected structures. For all of these reasons, we think that this model could be a fine alternative to the replacement of the electrogeometrical model.

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