3D MODIFIED ELECTROGEOMETRIC MODEL FOR EVALUATING LIGHTNING IMPACT PROBABILITIES OVER STRUCTURES

C. Sigogne, P. Pignolet, T. Reess, A. De Ferron
UPPA Laboratoire de Sciences pour l'Ingénieur Appliquées à la Mécanique et au génie Electrique Equipe Génie Electrique,
2 Ave P. Angot, 64053 PAU Cedex 9, France
G. Berger, G. Lafon, G. Serrie
ABB Pole Foudre, 1, avenue des Victimes du 11 Juin 1944, 65200 Bagnères de Bigorre, France
S. Pédeboy
METEORAGE, Centre Hélioparc, 2 Ave P. Angot, 64053 PAU Cedex 9, France

Abstract: In the lightning protection domain, the vulnerability of structures to lightning is commonly estimated by using the rolling sphere method (RSM). Moreover, this method is recommended in the International Standard IEC 62305-3. This is an electrogeometric model (EGM) which consists in rolling over the structure an imaginary sphere the radius of which depends on the estimated peak current of the lightning flash return stroke. The sphere center is considered as the location of the negative downward leader tip which propagates vertically to the ground. Thus all the surface contact points are considered to require protection, whilst the unaffected volumes are assumed to be protected. However, the major drawback is that this model does not take into account some aspects like the ground influence (ground conductivity and local field reinforcement), the upward leaders development and other climatic and geographic parameters.

In order to evaluate the lightning impact probability over a structure, we propose in this paper a 3D method based on the electrogeometric model application by mainly taking into account the upward leaders development. The structure profile is enhanced at locations where the reinforcement of the electrical field at the ground is the most important. Then, applying the rolling sphere method on this new profile, the surface generated by the different trajectories of the center of the modified rolling sphere is deduced and lightning impact probabilities are evaluated.

This new approach has been applied to the case of the observatory of the Pic du Midi de Bigorre in south of France where a lightning station is installed. So the numerical results are compared to the observations on site, to any experimental measurements and to the lightning detection network data.

I. INTRODUCTION

In France, lightning density is generally low. However a global analysis of data provided by METEORAGE, the operator of the French national lightning locating system, has pointed out an interesting site at the Pic du Midi located in the Pyrenees (south of France) at high altitude (3,000 m top mountain elevation)[1].

This site is occupied by an astronomical observatory, a so-called Télé Diffusion de France (TDF) antenna which is a 100 meters height broadcast antenna and some intermediate buildings beside (Figure 1). It is also a major spot for tourism.

A 5 meters height testing lightning rod has been installed on a tower located approximately at 150 m far from the TDF antenna on the east side of the site in order to evaluate its efficiency. The lightning rod is attached to an experimental platform: the DIMM platform.

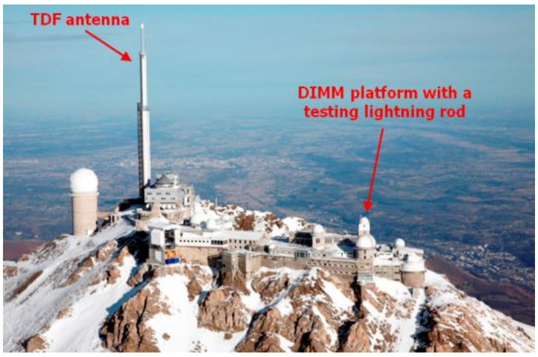

Figure 1. Photography of the top of the Pic du Midi with the tall TDF antenna and the testing lightning rod

II. EVALUATION OF LIGHTNING IMPACT PROBABILITIES

A. *Basic Description of a Negative Downward Flash*

The commonly accepted description of a negative downward flash is to consider that the negative charge at the base of the cloud induces an electric field between the cloud and the ground sufficiently important to initiate the development of a downward leader. Due to the leader propagation towards the ground, the electric field between them is amplified. Approaching the ground, the electric field becomes so high that upward leaders can be generated from protuberances on the ground. This approach considers that the junction between the downward and upward leaders is done when the field reaches the critical value of 500 kV/m. At this time, the distance between the downward leader tip and the ground is defined as the striking distance.

B. *Electrogeometric Model*

The striking distance D is usually deduced from experimental investigations and inferred from the following approximated formula [2] :

$$D = A \times I_p^{\,b} \tag{1}$$

Where D is expressed in meters, I_p is the peak value of the lightning current of the first return stroke in kiloamps and A and b are constants. For these two constants, the international standard of lightning protection IEC62305-1: 2006 recommends the values: A=10 and b=0.65 [2].

For structures protection against lightning, the electrogeometric model is implemented by the rolling sphere method. A first assumption consists in assuming the equipotential surfaces around the leader tip as spherical and no deformable. Secondly, it is considered that the striking distance is the same regardless of the nature and form of the ground structure. Consequently, the impact points are determined for each object of the structure at the striking distance D of the downward leader tip, as if it is surrounded by an imaginary sphere of radius r_s=D. In the case of a structure such as a group of buildings, this method is applied by rolling the sphere on the structure profile (Figure 2.a). All points of this structure in contact with the sphere may be struck by lightning. Conversely, objects not in contact with the sphere are considered protected against negative flashes whose the current intensity is higher than I_p. In terms of lightning protection, if the sphere comes into contact with a protective device without touching the objects, these ones are considered to be protected.

C. *Modified Rolling Sphere Method*

As it was mentioned above the rolling sphere method does not consider the ground influence, upward leaders development and other environmental parameters. In particular to take into account the emission of upward leaders from areas where there may be a significant electric field enhancement, we have modified the previous model using the main results given by G. Berger and S. Aït-Amar [3]. These results are issued from a 3D computational code of lightning protection taking into account the real geometry of the structure to be protected, the propagation of the downward and upward leaders with their average relative velocities[4]. In the case of a lightning rod, the relative position of the upward and downward leader tip, just before the final jump, are determined depending on the height of the lightning rod and the lightning peak current. A parametric investigation from this code application allowed to establish analytical relationships approximating the radius L_{up} and the height h_{up} of the cone swept by the upward leader from a lightning rod as functions of the rod height h and of the peak return stroke current I_p [3]:

For h < 6m:

$$L_{up}(I_p,h) = \frac{0.054.h.I_p - 0.178.h + 0.124.I_p + 1.057}{3.02 - 0.19.h} \tag{2.1}$$

For h ≥ 6m:

$$L_{up}(I_p,h) = (3.h^{0.2} - 4.2).I_p^{\,2/3} + 0.22.I_p \tag{2.2}$$

$$h_{up}(I_p,h) = 0.054.h.I_p - 0.13.h + 0.124.I_p + 0.37 \tag{3}$$

According to Cooray et al. [5], the striking distance (or the sphere radius r_s) must be redefined as the distance between the upward and downward leaders tip just before the junction. This new striking distance r_{ms} is almost independent of the rod height, and varies with the lightning current, such as:

$$r_{ms} = 4.2\ I_p^{\,2/3} \tag{4}$$

Where r_{ms} is the modified striking distance in meters and I_p is the peak lightning current in kiloamps.

Considering that the volume associated with the upward leader emission is an integral part of the structure, protected areas are determined by rolling the modified sphere with the radius r_{ms} over the entire modified structure (Figure 2.b).

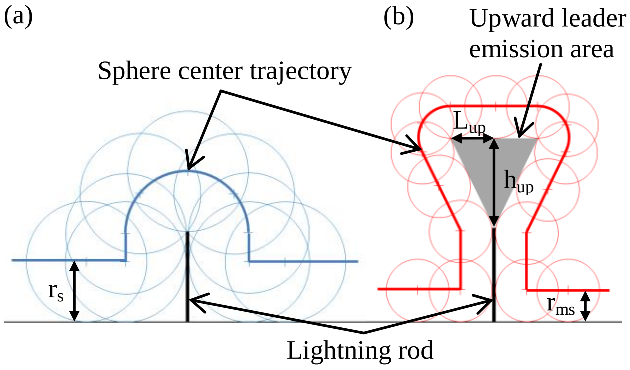

Figure 2. Comparison of sphere center trajectories
(a) The rolling sphere method (blue line)
(b) The modified rolling sphere method (red line).

D. *Evaluation of Lightning Impact Probabilities.*

From the application of the rolling sphere method on a structure, Lalande has calculated a collecting effective area and deduced from the area swept by the sphere center, the lightning impact probability on an aircraft [6].

We propose to apply the same method over the relatively complex profile of the observatory structure at the Pic du Midi de Bigorre. The aim is to highlight the areas that could be struck by lightning and to evaluate their probability to be struck compared to the other parts of the structure.

In a 3D problem, the surface swept by the sphere center is build by moving the rolling sphere over structure in the two horizontal directions. This surface denoted A_s corresponds to the different positions of the negative leader tip which may attach to the structure just before the junction.

Each point $C_s(i)$ of this surface A_s corresponds to a position ”i” of the rolling sphere center when the sphere is in contact with the structure. For each sphere position ”i”, its contact points $\gamma_s(i)$ may be associated with its center located at the point $C_s(i)$.

When the rolling sphere is moving on a flat portion of the structure (e.g. the ground or a plane roof of a building), a single position $C_s(i)$ of the center of the rolling sphere corresponds only to a single contact point $\gamma_s(i)$.

In contrast, in the case of a salient point (a lightning rod tip or a building corner), when the rolling sphere is moving, the position of its center Cs(i) turns around this salient point and draws a spherical portion $\alpha_s(i)$ around the same contact point $\gamma_s(i)$

Thus, for a given incremental step used to swip the structure area each contact point $\gamma_s(i)$ can be associated with a number $N_s(i)$ of different positions of the center of the sphere with which it is in contact.

By normalizing $N_s(i)$ (corresponding to the partial surface $\alpha_s(i)$) associated to each contact points $\gamma_s(i)$ by the total number of points N_{Ts} forming the total surface A_s, it is possible to establish an impact probability P(i) for each contact point $\gamma_s(i)$.

$$P(i) = \frac{N_S(i)}{N_{Ts}} = \frac{\alpha_S(i)}{A_S} \qquad (5)$$

In the case of Figure 3, the testing profile corresponds to a 3D representation of a pyramid shape. This profile is represented by the blue volume on which is applied the rolling sphere method (Figure 3.a). The deduced sphere center trajectory T_s, is represented by the red dotted area. The number $N_s(i)$ of rolling sphere center position associated with each profile point $\gamma_s(i)$ is shown in curve (Figure 3.b). So, it can be noted that the largest number of points associated N_{smax} corresponds to the top of the pyramid shape. Conversely, a band around the base of the pyramid shape is associated with no trajectory point. Indeed, here the geometric profile implies that the rolling sphere cannot be in contact with this band. Therefore it corresponds to the protected volume.

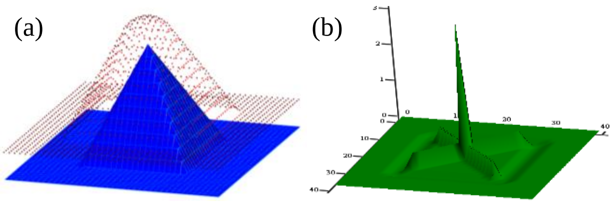

Figure 3. Determination of impact probabilities from the rolling sphere method application on a pyramid profile

E. Application to the Pic du Midi

The Figure 4 and the Figure 5 show the results obtained by applying the two methods on the 3D profile of the Pic du Midi.

The Figure 4 illustrates the rolling sphere method application to a 3D profile of the Pic du Midi (Figure 4.a). A sphere which radius is given by the Eq. (1), provides the trajectory swept by its center (Figure 4.b). From this trajectory is deduced the impact probabilities on the whole site (Figure 4.c).

The modified rolling sphere method application is illustrated by the Figure 5. In this case, the upward leader emission is taken into account by adding cones on the profile of the Pic du Midi. In particular two cones are placed at the top of the TDF antenna and of the lightning rod (Figure 5.a). The modified rolling sphere radius given by the Eq. (4) generates a new trajectory (Figure 5.b) and new probabilities (Figure 5.c).

So the method presented here provides an impact probability related to the peak current for each point of the studied structure. As expected the probability distributions (Figure 4.c and Figure 5.c), exhibit two remarkable peaks: the biggest one corresponds to the probability of lightning impact on the TDF antenna, the second one corresponds to that on the lightning rod.

For a 10kA current the new modified method that we propose and the original rolling sphere method provides respectively the following impact probabilities:

- on the TDF antenna 14.9% against 9.6%
- on the lightning rod 2.9% against 5.6%

III. DISCUSSION

These results are inconsistent with the experimental observations on the site. The observed impacts on the Pic du Midi mainly occur on the TDF antenna [1].

An explanation of this discrepancy could be the fact that the electrogeometric model, which is the base of this method, considers only negative downward flashes. Moreover, the proportion of downward flashes is generally reduced for tall structures or at high elevation which are mainly struck by upward flashes [7].

Moreover, the present method does not take currently in consideration the influence of the elevation of the structure location and is much more adapted for structures located at low elevation. The site of the Pic du Midi is at a high altitude which can greatly influenced the probability distribution of lightning impacts. However there is currently no simple and reliable model in this case, so it will be necessary to improve that method which allows the calculation of the probability for each point of a site to initiate an upward flash. By coupling the two methods, the impact probability on a whole site could be calculated whatever the flash type.

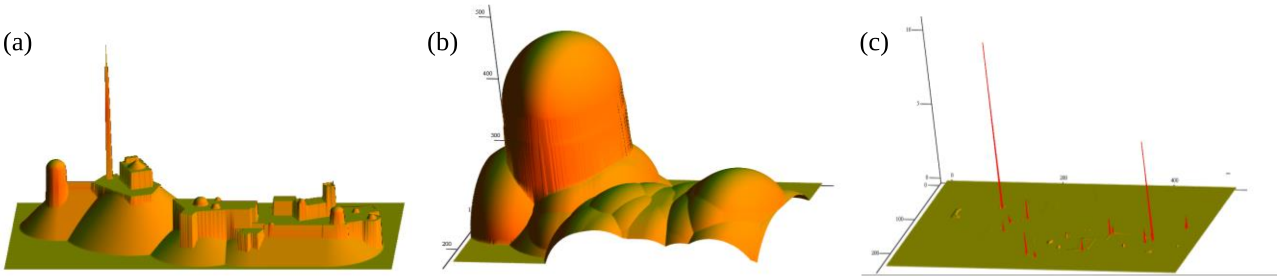

Figure 4. Rolling sphere method application for I_p=10kA: (a) 3D representation of the Pic du Midi, (b) Surface swept by the moving sphere center, (c) Deduced probability distribution.

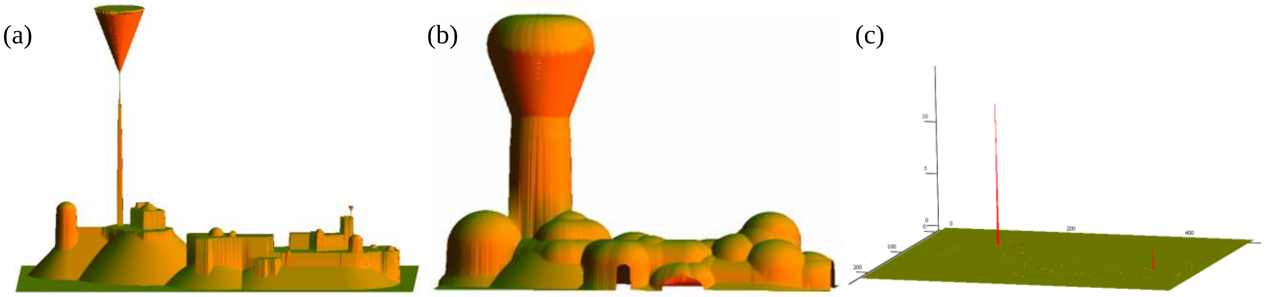

Figure 5. Modified rolling sphere method application for I_p=10kA: (a) 3D representation of the Pic du Midi with the upward leaders inclusion, (b) Surface swept by the moving sphere center, (c) Deduced probability distribution.

Finally, leaders being emitted from protuberances, the modified rolling sphere method is only adapted nearby theses protuberances. In the case of a plan, it could be better to use the rolling sphere method. So the spheres radii deduced from both methods being different, it could be interesting to employ a transition like this used by Petrov et al. [8].

IV. SUMMARY

The evaluation of the lightning flash density is of crucial importance to the risk calculations especially for the Lightning Protection Standards. The probabilities of lightning impacts on the Pic du Midi deduced from the application of the 3D modified rolling sphere method indicate that the largest probability of lightning impact corresponds to the TDF antenna as expected. However some discrepancies in regard with experimental observation have to be noted.

Indeed, there are many important factors which can affect lightning impact occurrence such as soil humidity, airstreams due to geographical situations (valleys, mountain tops, etc.). These and other factors can be responsible for the observed inhomogeneity of the spatial distribution of lightning ground flash density.

Obviously it is the first step in the development of this model and it will be necessary to improve two main aspects: the transition between field reinforcement zone and areas where the field is homogenous and the probability for each point of a site to initiate an upward flash.

So, to conclude, using lightning data provided by METEORAGE we hope to reach more accurate probabilities of lightning impacts on the Pic du Midi.

V. ACKNOWLEDGMENT

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