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MODELING OF LIGHTNING STREAMER FORMATION AND PROPAGATION IN WIND TURBINE BLADES

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ABSTRACT

The positioning of lightning air terminations along a wind turbine blade is a complex issue to consider when designing the lightning protection of wind turbine blades. According to the IEC 61400-24 on lightning protection of wind turbines, the interception efficiency depends on the effectiveness of the air termination in enhancing the electric field and attracting the lightning discharge, thus shielding the blade surface and preventing electrical breakdown of the blade material. However, the number and location of the discrete receptors may be difficult to establish, since their performance is significantly influenced by the presence of conducting materials inside the blade.

The design and validation of the lightning air termination system of a blade, as well as the evaluation of the effects of internal conductive components, involve high voltage tests, which are expensive and usually require complex setups. Furthermore, the tests may need to be repeated when a new conducting element is included in the blade with unpredictable effects for the lightning protection system. Numerical methods to determine the areas of a structure more likely to be struck by lightning have proved to be a useful tool to establish the preliminary design of the lightning protection of wind turbines. However, these methods mainly concern the lightning exposure on a macroscopic level while more detailed models containing the blade internals with multiple streamer initiations will add great value to the detailed design process.

The present paper presents a method to investigate the origin and propagation of streamers from different conductive elements of the blade when exposed to a high electric field. The calculations are performed using dynamic simulations with the finite element method, and the results have been correlated with high voltage tests in the laboratory. The algorithms developed are intended to be a new and improved tool for the design of the blade lightning protection

system, in particular to assess the effectiveness of the air termination system and the effects of internal conductive materials.

The simulation models can involve a high level of detail and therefore be used in the detailed positioning of air terminations in blades equipped with conductive elements such as carbon fiber or electrical monitoring systems (load, temperature, etc.).

ACRONYMS AND SYMBOLS

FEM: Finite Element Method

HV: High Voltage

LPS: Lightning Protection System

Positive and Negative discharge:

Discharge generated at the high voltage electrode charged at positive and negative polarity respectively with reference to ground.

1. INTRODUCTION

Numerical methods are a useful tool to verify the efficiency of the lightning protection system of a blade, provided they have been previously validated with tests or field experience, according to [1]. In particular, the FEM simulation of the electric field in structures exposed to a high electric field have been used in lightning protection to determine the areas of the structure with high risk of direct lightning strikes [2], [3], [4].

The simplest method utilized to calculate electric field conditions is the electrostatic simulation. This method consists in applying a background electric field around a structure, in order to determine the field enhancement at the structure. While this method may indicate areas of the structure with higher risk of direct lightning strikes, it provides little information about the path that the discharge will follow and the eventual strike point. Therefore, a more sophisticated method needs to be developed.

This paper studies the streamer formation and propagation on wind turbine blades by means of

dynamic simulation of the static electric field in magnitude and direction. The model used in the simulations is a simplified setup representing the incoming leader and the tip of the blade under different conditions. The aim of this study is to correlate the simulation results with high voltage test results, in order to validate the dynamic simulation method and be able to apply it to more complex configurations.

Three different cases have been simulated and tested. Case 1 investigates the accuracy of the simulation model to determine the path followed by the discharge, while cases 2 and 3 focus on the strike point.

The models and the method used in the FEM simulations are described in section 2. The results of the FEM simulations for the different study cases are presented in section 3. Section 4 shows the test setup and procedure followed in the laboratory tests, as well as the tests results. Finally, the outcome of the simulations and tests is analyzed and correlated in section 5.

2. MODEL AND METHOD

2.1 Model

The purpose of the model is to reproduce the blade surface at the tip, where the lightning receptor is located and the probability of lightning strike is highest [1]. The model consists of an insulating panel equipped with a copper receptor connected to ground. A spherical copper electrode with a diameter of 125mm is connected to the HV impulse generator and is elevated 200mm above the panel. The purpose of the HV electrode is to simulate the tip of a downward moving stepped leader.

The material chosen for the insulating panel is Teflon due to its high breakdown strength, which prevents the panel being punctured during the tests.

Three cases are studied, with different grounded elements placed on and under the panel in order to influence the direction and path of the discharge (Fig. 1).

- In Case 1, a spherical copper electrode with a diameter of 10mm is placed under the panel vertically aligned with the HV electrode (Fig. 1a). The electrode is connected to ground.

- In Case 2, a copper wire with a diameter of 1mm is running along the panel, over the external surface (Fig. 1b).
- In Case 3, a flat aluminum tape 80mm wide is stuck over the external surface of the panel (Fig. 1c).

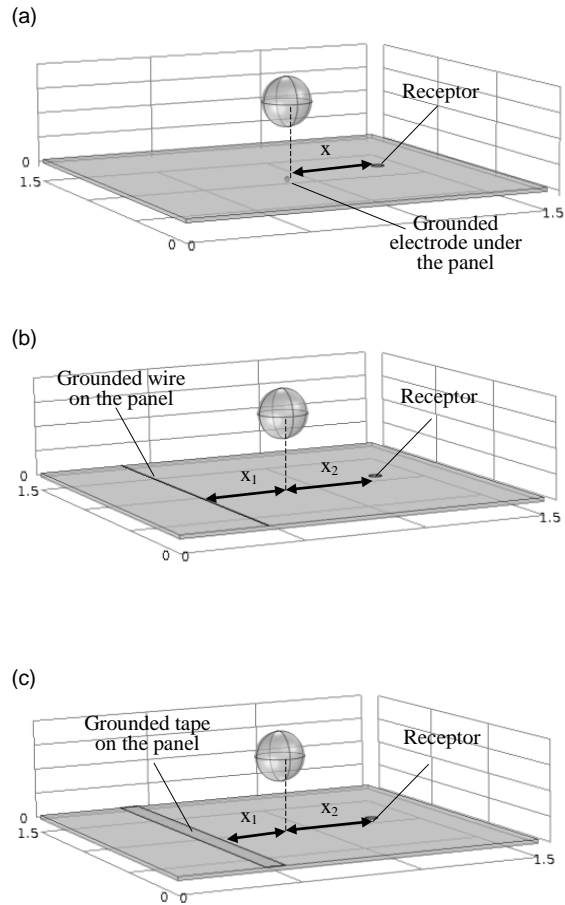


Figure 1. FEM simulation cases. (a) Case1 with a grounded electrode under the panel, (b) Case 2 with a grounded wire on the outer surface of the panel, (c) Case 3 with grounded aluminum tape on the outer surface of the panel.

Several simulations have been performed for the 3 cases, varying the position of the HV electrode in the horizontal axis, in order to modify the path and direction of the discharge. In Case 1, the grounded electrode is moved with the HV electrode, so that both are always vertically aligned. Table 1 summarizes the horizontal positions of the HV electrode.

Table 1. Position of the HV electrode in the 3 cases

Case 1	x [m]	
	0.3, 0.4, 0.5, 0.6	
Case 2	x1 [m]	x2 [m]
	0.4	0.4
Case 3	x1 [m]	x2 [m]
	0.5	0.3
	0.4	0.4
	0.5	0.3

2.1 Method

The method used to determine the origin and propagation of streamers from the conductive elements of the models described in section 2.1 is based on FEM 2D dynamic simulations. The 2D simulations correspond to the cut plane represented in Fig. 2.

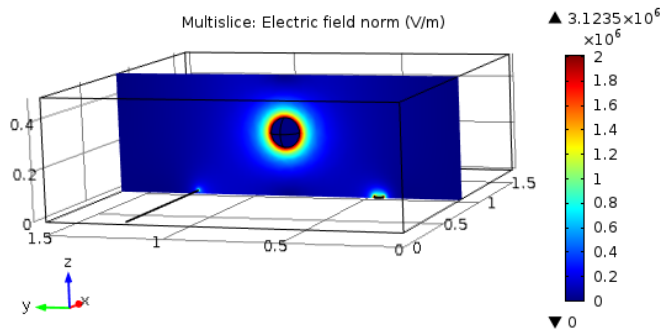


Figure 2. FEM 2D simulation of a cut plane of the model for case 2.

The simulations are performed with the software Comsol Multiphysics, and consist of an iterative process with the following steps:

- A certain potential is applied to the HV electrode, sufficiently high to generate an electric field enhancement higher than the dielectric strength of air in the vicinity of the conductive components.
- The electric field in the model is calculated using the equations for electrostatic conditions.
- In the zones where the electric field in the air is exceeding its dielectric strength, the specific volume of air becomes conductive to simulate the initiation of a streamer. The streamer takes the potential of the conductive element from which it originates, and may be at either HV or ground potential.
- The model is recalculated according to step 2 with the new distribution of potential.

During the iteration process, streamers are initiated both at the HV electrode and the grounded components. Some of these streamers will develop while others will die, depending on the electric field enhancement at the tip of the streamer. The iteration process ends when one of the streamers originated at the HV electrode meets a streamer incepted from the grounded components, closing the path of the discharge. Fig. 3 show a sequence of the iteration process for case 1, where a streamer originated in the receptor propagates towards the HV electrode.

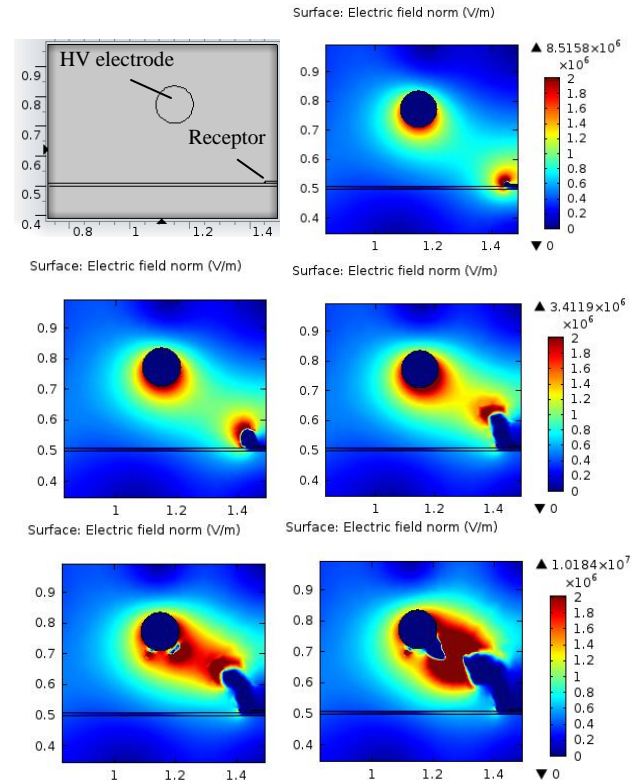


Figure 3. From left to right and down, sequence of the iteration process of the streamer origination and propagation from the receptor to the HV electrode.

3. FEM SIMULATION

The model used in the simulations is described in section 2.1. Three cases are studied, with the HV electrode at the different horizontal positions specified in Table 1. The method followed in the simulations is explained in section 2.2.

Case 1

The simulation results in Fig. 4 show the electric field in the last iteration of the simulation process, when the discharges initiated at the HV electrode and at the receptor meet.

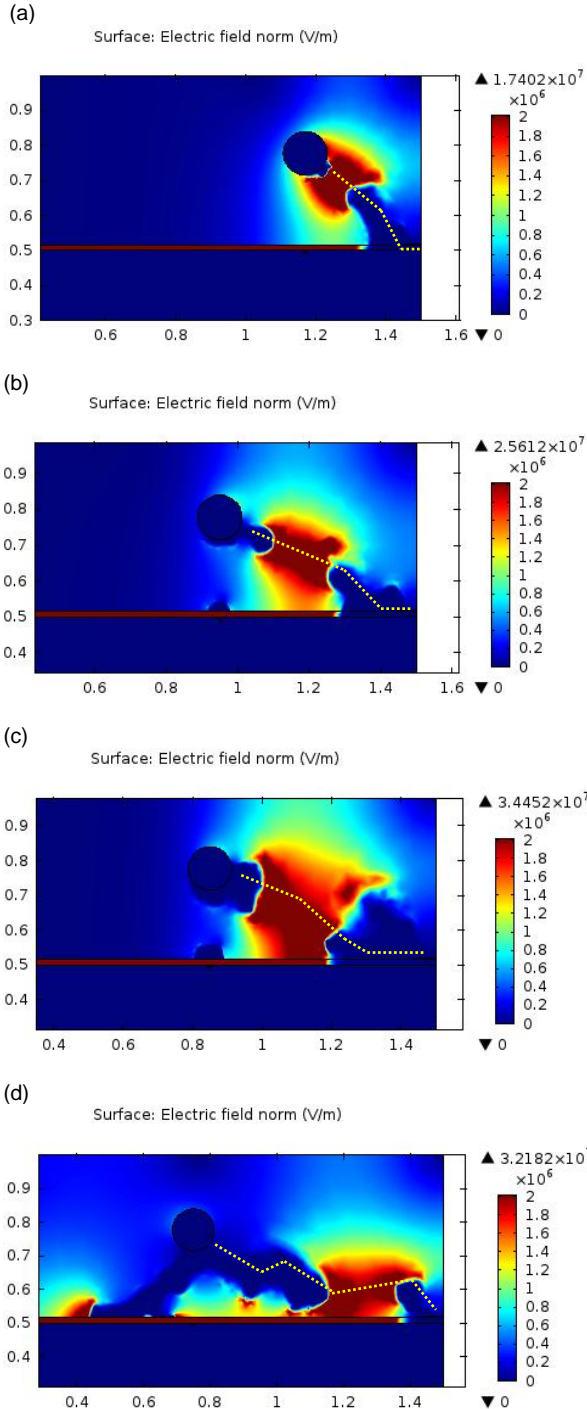


Figure 4. Case 1, electric field in the last iteration of the simulation process. The path of the discharge is marked with a yellow dotted line. (a) $x=0.3\text{m}$ $V=350\text{kV}$, (b) $x=0.4\text{m}$ $V=400\text{kV}$, (c) $x=0.5\text{m}$ $V=450\text{kV}$, (d) $x=0.6\text{m}$ $V=500\text{kV}$.

The grounded electrode under the panel is vertically aligned with the HV electrode for all the positions. The potential applied to the HV electrode is set in each simulation so that it is the

minimum voltage that allows the discharge to propagate, and varies between 350 kV and 500 kV. The path of the discharge has been marked with a yellow dotted line.

It is observed in Fig. 4 that the point where the discharge coming from the grounded receptor and the HV electrode meet is closer to the HV electrode at short distances. The potential applied to the HV electrode is higher when increasing the distance, producing longer streamers in the HV electrodes towards the grounded electrode under the panel. The discharge coming from the receptor sweeps the surface in simulations a, b and c. However, in simulation d the path is through the air, with some branches towards the panel, and the junction point is closer to the receptor.

Case 2

The simulations in Fig. 5 show the electric field when the discharges initiated at the HV electrode meet the discharge initiated at the receptor. The path of the discharge has been traced on a yellow dotted line.

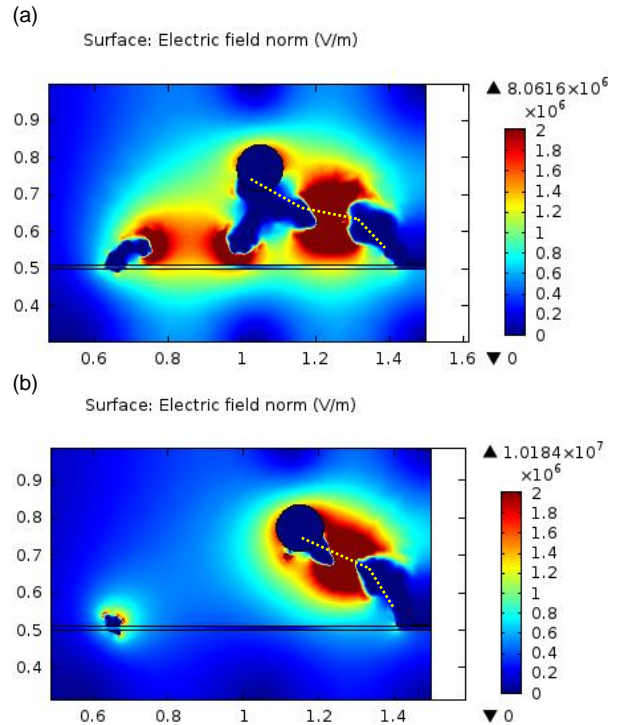


Figure 5. Case 2, electric field in the last iteration of the simulation process. The path of the discharge is marked with a yellow dotted line. (a) $x_1=0.4\text{m}$, $x_2=0.4\text{m}$ $V=400\text{kV}$, (b) $x_1=0.5\text{m}$, $x_2=0.3\text{m}$ $V=400\text{kV}$.

Fig. 5 shows that the discharge is directed towards the receptor in both cases. However, in the case there is a branch of the HV discharge directed to the grounded wire, and long streamers initiated on the grounded wire.

Case 3

The simulations in Fig. 6 show the electric field when the discharges initiated at the HV electrode meet the discharge initiated at the receptor or the grounded tape. The path of the discharge has been traced on a yellow dotted line.

In case 3, the discharge is directed towards the grounded tape when both the receptor and the band are at the same distance from the HV electrode. When the HV is located closer to the receptor, the discharge goes to the receptor, although long streamers are initiated on the tape.

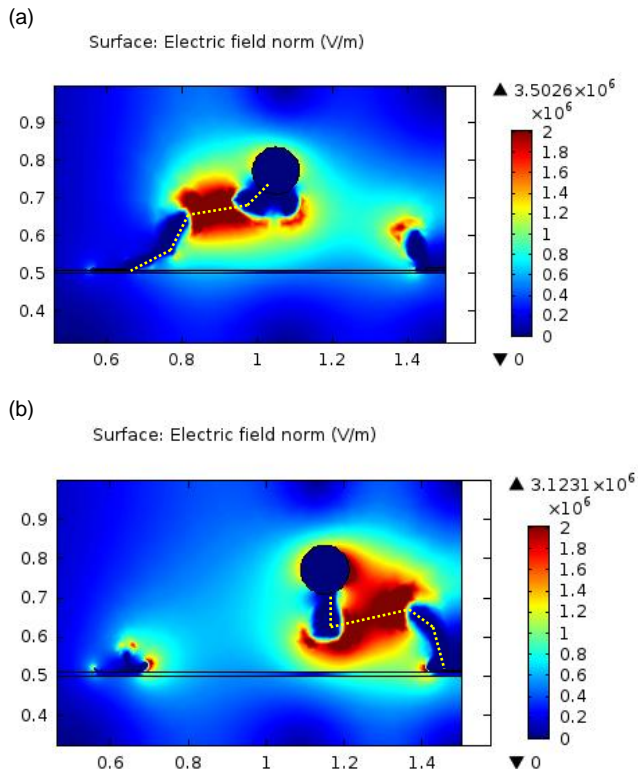


Figure 6. Case 3, electric field in the last iteration of the simulation process. The path of the discharge is marked with a yellow dotted line. (a) $x_1=0.4m, x_2=0.4m, V=400kV$, (b) $x_1=0.5m, x_2=0.3m, V=400kV$.

4. HV TESTS RESULTS

The models simulated in section 3 have been built and tested in the HV laboratory. Fig. 7 shows the laboratory setup for the 3 cases.

The lightning impulse voltage applied to the HV electrode followed the $1.2/50\mu s$ waveform

according to [5], and the voltage peak varied between 360 and 380 kV. Six impulses were applied for each polarity and position.

UV pictures of the discharge were captured in order to correlate the path followed by the discharge in the tests with the results of the simulation.

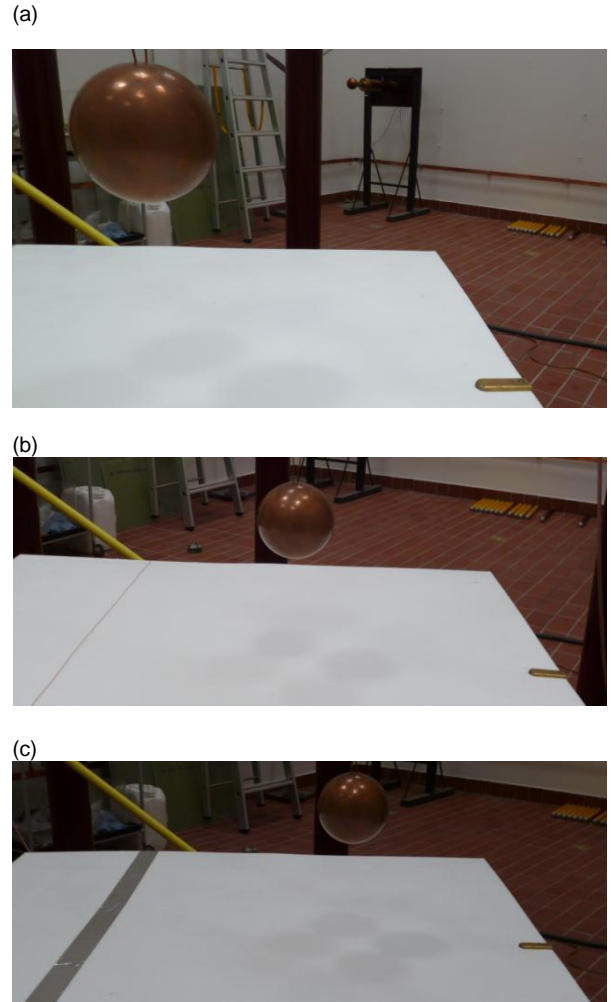


Figure 7. test setup for case 1. (a) Grounded electrode under the panel, (b) Case 2: grounded wire on the panel surface and (c) Case 3: grounded tape on the panel surface.

Case 1

Fig. 8 shows UV pictures of discharges with positive polarity for the different distances between the HV electrode and the receptor for case 1.

Table 2 summarizes the results. The parameter x' is the percentage of the distance between the HV electrode and the receptor where the discharge sweeps the surface of the panel.

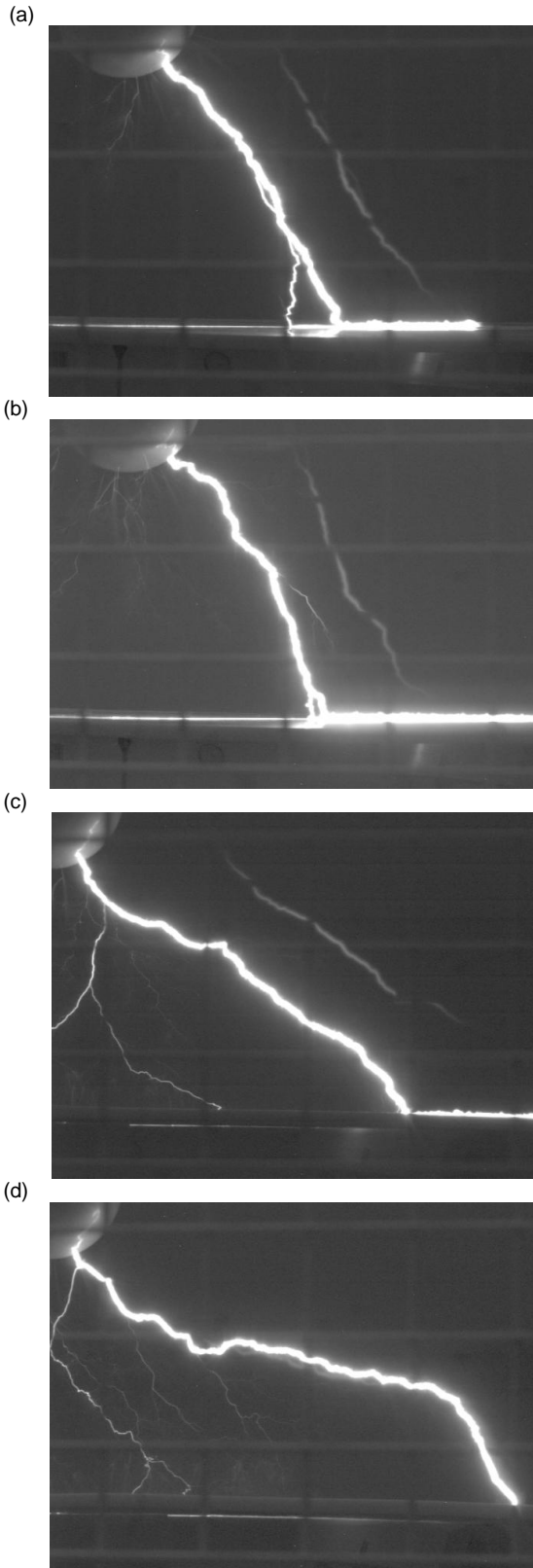


Figure 8. UV pictures of discharges under lightning impulse voltages in setup 1, for an electrode horizontal distance x of (a) 0.3m, (b) 0.4m, (c) 0.5m, (d) 0.6m

Table 2. Path of the discharge in case 1

x [m]	Polarity	Average x'
0.3	+	57%
	-	0%
0.4	+	59%
	-	0%
0.5	+	36%
	-	*
0.6	+	0%
	-	*

(*) The voltage applied to the HV electrode did not generate the discharge. The reason for not increasing the voltage was avoiding attachment to the grounded electrode with the resulting puncture on the panel.

Case 2

In Case 2, the focus was put on the direction of the discharge, which attached either to the receptor or to the wire. Table 3 shows the percentage of discharges that attached the receptor in relation to the total number of discharges applied.

Table 3. Direction of the discharge in case 2: Percentage of discharges attaching the receptor.

x_1 [m]	x_2 [m]	Polarity	Discharges to the receptor
0.4	0.4	+	55%
0.4	0.4	-	11%
0.5	0.3	+	89%
0.5	0.3	-	100%

When the HV electrode was at 0.4m from both the wire and the receptor, half of the discharges reached the wire for positive polarity, while most of them went to the receptor for negative polarity. When the HV electrode is closer to the receptor, most of the discharges attached the receptor in both polarities.

Case 3

Case 3 was focused on the direction of the discharge, similarly to Case 2. Table 4 shows the percentage of discharges that struck the receptor in relation to the total number of discharges applied.

Table 4. Direction of the discharge in case 3: Percentage of discharges attaching the receptor.

x_1 [m]	x_2 [m]	Polarity	Discharges to the receptor
0.4	0.4	+	0
0.4	0.4	-	25
0.5	0.3	+	100
0.5	0.3	-	100

When the HV electrode is at 0.4m of both the grounded tape and the receptor, most of the discharges reached the tape, while when the HV electrode was closer to the receptor, all the discharges attached the receptor.

5. DISCUSSION

In case 1, the simulations coincide with the tests on the positive discharge sweeping the surface of the panel when the HV electrode is at 0.3, 0.4 and 0.5 m. When the HV electrode is at 0.6m from the receptor, both simulation and tests show that the discharge reaches the receptor through the air without sweeping the surface. The reason for that might be the charge generated by the streamers on the grounded electrode under the panel, which repel the discharge initiated at the receptor.

In case 2 and 3, the attachment point determined in the simulations coincides with the predominant attachment point in the tests. In the case where both the receptor and the grounded wire received 50% of the discharges, the simulation shows long streamers from the component not involved in the attachment.

However, the simulation presents several drawbacks. First of all, it is not possible to differentiate positive from negative polarity, and therefore the particularities of both types of discharge are missed. Secondly, the results of the simulations are strongly influenced by the electrical parameters assigned to the model, such as permittivity or conductivity. Relatively small variations of these parameters results in significant differences in the path and direction of the discharge. Finally, the dynamic simulation tries to reproduce the real event in time domain, but the same potential is applied to the HV electrode during the entire process of the discharge while in the tests a voltage impulse is applied.

6. CONCLUSIONS

The dynamic simulation method presented in this paper shows promising results when correlating it to tests results, in particular to discharges with positive polarity. There are still drawbacks with the simulation, mainly related to the electrical parameters of the model and the difficulties in reproducing the time domain nature of the lightning event. However, further investigation and developing of the presented method are expected to result in an accurate tool to determine the lightning attachment points in complex geometries

such as wind turbine blades, thus facilitating the design of the lightning protection.

Developing the tool to work for 3D geometries with varying dimensions, requires a more definite and quantitative criteria for evaluating the attachment point. This topic as well as how to model flashover characteristics in both bulk materials as well as along interfaces (dry/wet/polluted) is targeted for future research.

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