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Research paper

Simulation of Lightning Strikes on Photovoltaic Farms

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ABSTRACT

This paper presents a novel approach to the simulation of the most common type of cloud-to-ground lightning strikes applied to a Photovoltaic farm with the view to validating its lightning protection system generally based on the electro-geometric model as prescribed in the relevant international standards.

It will be limited to the study of the electrostatic field distribution generated by a downward-stepped leader progressing towards a large Photovoltaic Farm with a focus on its effect on the power electronics converters operating under lightning stress conditions.

The Simulation was programmed using MATLAB's Partial Differential Equations Toolbox based on the Finite Elements Analysis.

1. INTRODUCTION

Despite over a century of research in lightning discharges, there is hardly any aspect of this field that is fully understood for it not to require further research.

This paper introduces a novel simulation of the Cloud to Ground Negative (CGN) lightning stroke based on the resolution of the electrostatic Poisson equation, using the Finite Elements Method (FEM), implemented on MATLAB.

In the first part of this work, we will describe our recently developed CGN lightning model which reflects our understanding of the latest developments in the scientific knowledge about lightning discharges as published in the specialist documentation by expert researchers in this still extremely active field of research [1-8].

The model's ambition is to provide us with a tool that simulates as many aspects as possible of the lightning discharge processes. In its current implementation, the model will only simulate the final stage

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of cloud charge separation, the stepped leader initiation, and its downward progression and will stop just before its interception by the upward leader.

The second part will be an application of the model to the protection of a medium-sized photovoltaic (PV) farm where the Lightning Protection System (LPS) is sized using the electro-geometric model (EGM) as described in the relevant applicable national and international standards [9-12].

We will conclude with a discussion of the simulation results and the necessary future development of our model in the light of those results and work on mitigating as much as feasible of its many current limitations.

2. NOVEL SIMULATION MODEL OF CGN LIGHTNING STRIKES

2.1 Lightning simulation models classification

In a paper cited in [1], Rakov and Uman have defined four model classes based on what is considered to be the most salient aspect of lightning, which is the return stroke. These are the gas dynamic, the electromagnetic, the distributed circuits, and the engineering models.

Each one of the above types is generally concerned with solving a certain type of equations and each existing or new lightning return stroke model will fall within one or infringe on several of those types [1].

Our model, based on resolving Maxwell's equations, can be described as an electromagnetic-type simulation model. It can also be extended to other types at different stages of its future development.

2.2 Simulation model presentation

For a CGN lightning model to be deemed comprehensive, it will have to address the main processes involved, namely:

- Cloud charge formation and separation
- Leader's initiation
- Stepped leader progression
- Stepped leader interception by upward leader(s)
- Return stroke(s) and associated dart leader(s)
- Ensuing processes: K, J, continuous current, etc.[5].

None of the above-mentioned items is satisfactorily understood due mainly to the variety and extreme complexity of the processes involved. Furthermore, it is now well established that most, if not all the upper atmosphere electric phenomena like sprites, elves, etc. are just part of one bigger picture of atmospheric discharge phenomenon as illustrated in Fig.1.

Our model will try to address the first three items listed above based on pioneering work by some eminent names [2-4] and on more recent efforts by equally prestigious names in the profession [5-8].

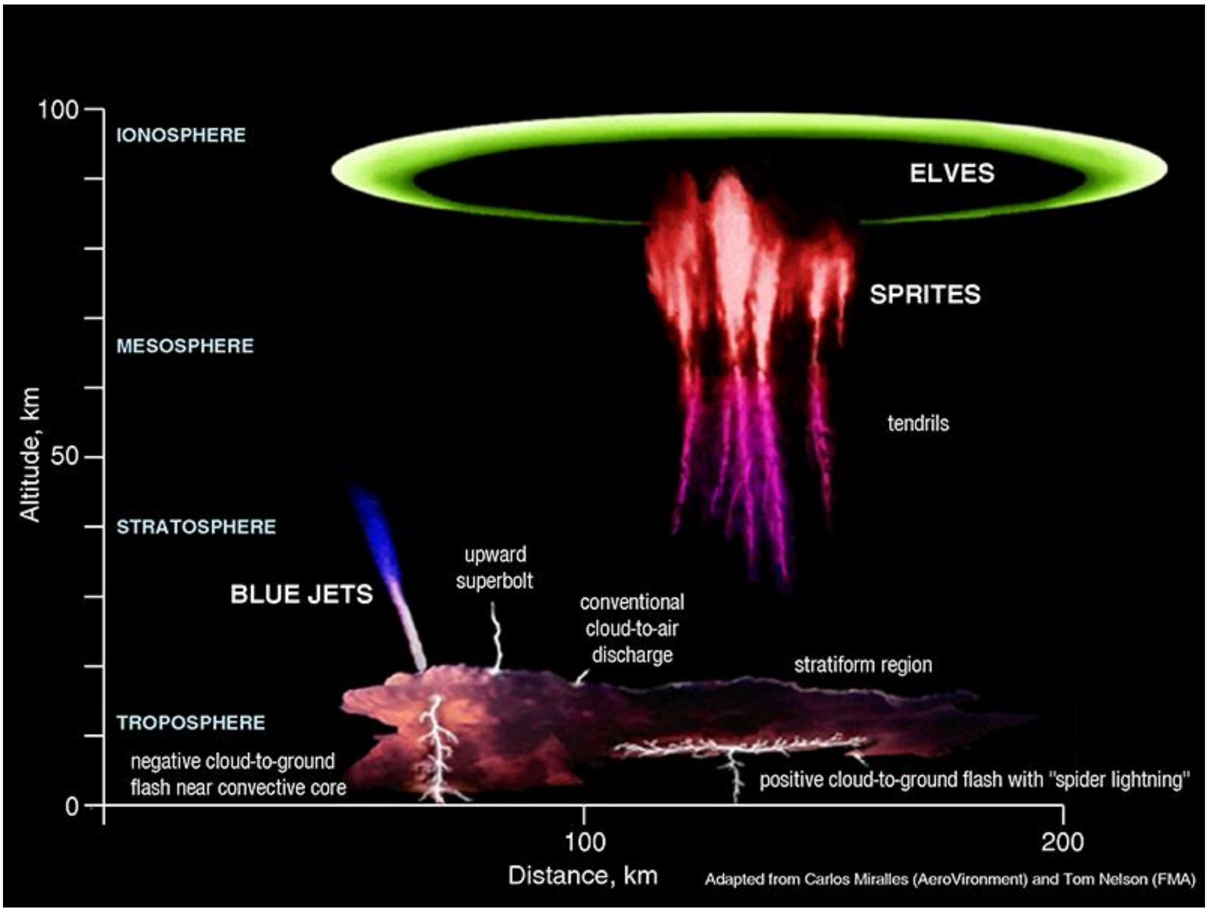

Fig 1. An illustration of atmospheric discharges with different kinds of transient luminous events: https://www.nssl.noaa.gov/education/svrwx101/lightning/types/

2.2.1 Cloud charge separation

The sheer size, complexity, and ephemeral nature of thunderclouds render their study extremely difficult. The electrical and thermodynamic processes within the cloud are closely interlinked as the charge generation and separation are related to the interactions between different cloud particle populations in different thermo-hydrodynamic states [5].

As this simulation is limited to the CGN, we have used considerations thoroughly discussed in [5-8] which in turn refer largely to [2-4], to end with the model shown in Fig. 2.

"Figure. 2", represents a mature cloud cell immediately before a CGN leader initiation where the main positive charge occupies the upper region, the main negative charge mainly concentrated at the bottom of the thundercloud, and a relatively smaller positive charge adjacent to it conferring to the thundercloud its tripolar topology.

2.2.2 Leader initiation

The presence of a pocket of positive charge in the vicinity or within the negative charge area will intensify the electric field in the space between them. This forms the conditions that will aid the initiation of the first step of the downward leader as shown in Fig. 3.

2.2.3 Stepped Leader downward progression

Once initiated and if the conditions for a stepped leader progression are met then a second, third, and nth step is formed until the leader's channel reaches a distance from the ground where it will be intercepted by an upward leader.

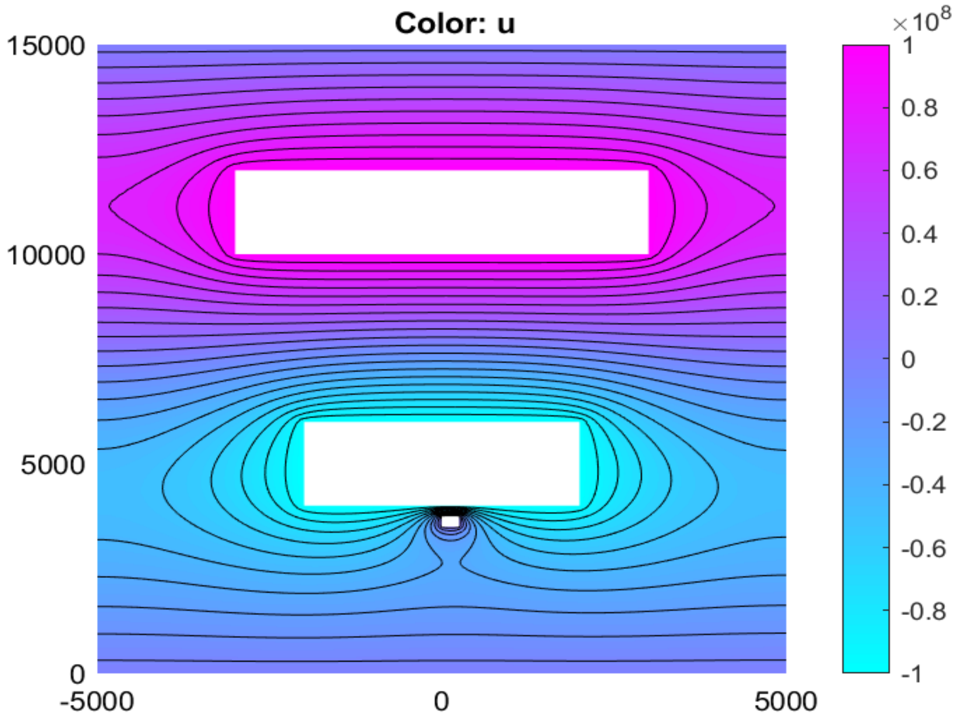

Fig 2. Cloud charge separation before leader initiation

Various models for leader-stepped progression are presented in the literature of which we selected the following for their relative similarity with our model.

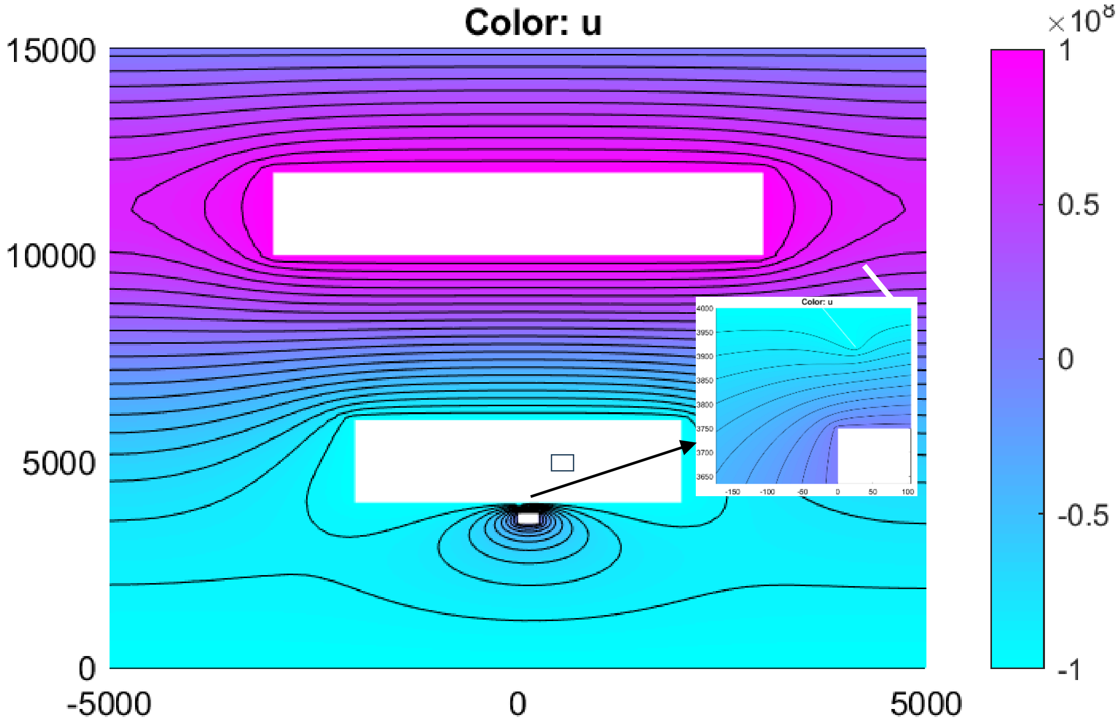

Fig 3. Initiation of the downward-stepped leader

In [13], V. Cooray and Aravelo link the stepping process to the lightning discharge's peak current, and in [14], Beroual et al simulate the leader to a circuit formed by a succession of RLC links each one constituting a step.

For Syssoev et al [15], the step-formation process is modeled, to begin with the appearance of space stems and some of them evolve into space leaders. As for M'ziou et al in [16], they propose a hybrid method, which is a combination between the Simpson method and finite difference time domain (FDTD) method for evaluating the radiated electromagnetic field.

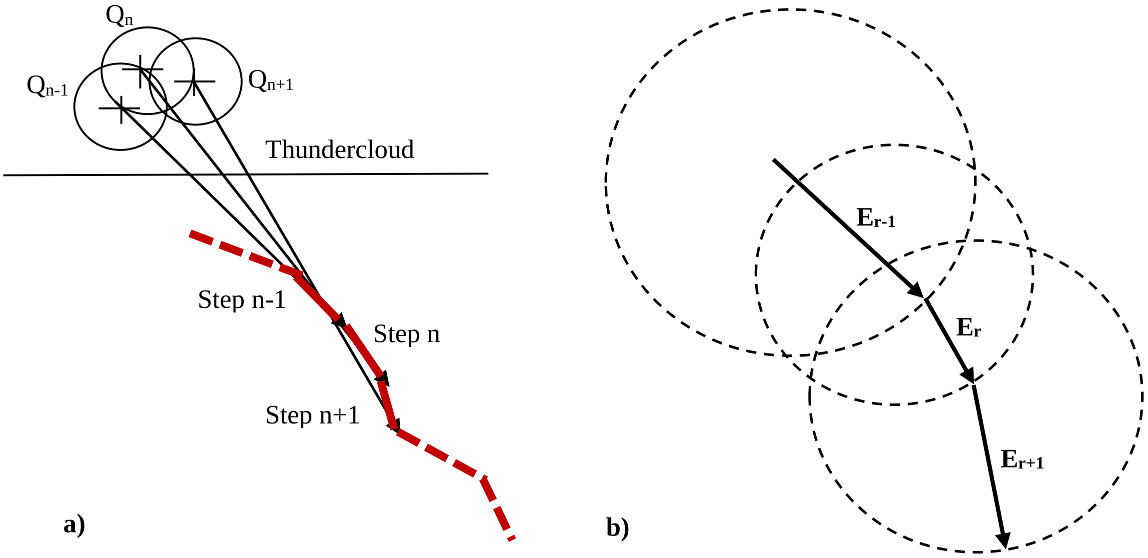

Fig 4. Leader step formation process

Our approach is similar to the one adopted in [13] but instead of linking the stepping process to the peak current, we assert that the stepping nature of the downward leader is due to fluctuations of the charge center position resulting from the turbulent charge generation and separation taking place within the thundercloud.

The main assumption made in developing our step formation process is that the leader tip is subjected to two fields (forces):

- one ambient due to the presence of the main negative charge at the bottom of the cloud and by influencing its image on the ground.
- another field due to the fluctuations of the same negative charge around the position of its 'barycentre' within the cloud.

In Fig. 4.a, we show how the leader tip jumps from its (n-1) to the nth, then to the (n+1) position in response to slight fluctuations of the negative charge, and Fig. 4.b, shows the direction of the resulting field at each step.

2.3 Program flowchart

In Fig. 5 below, we present a flowchart of the model clarifying its organization:

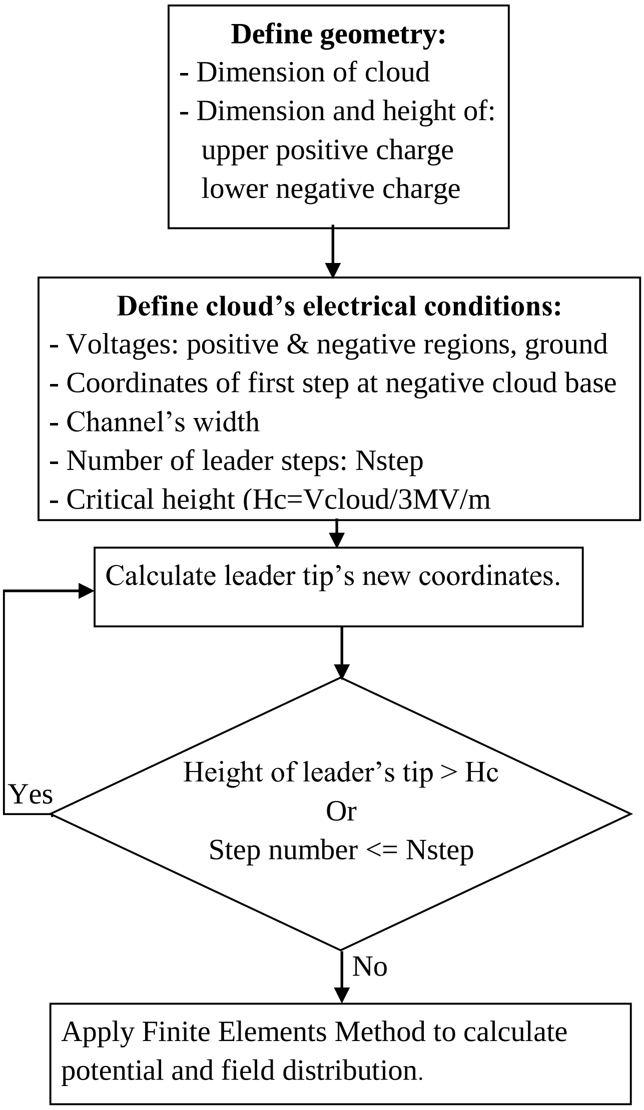

Fig 5. Flowchart of the simulation model

2.4 Electrical Potential and field computation using the Finite Element Method (FEM)

The FEM is a proven method for resolving Partial Derivative Equations (PDEs), especially for curved, complex geometries where other simpler calculation methods are difficult to apply. It is generally rarely used in open geometries because of the need to define boundary conditions very accurately but the increase of computer power and the development of extremely powerful software packages and methods have significantly extended its application domain [17-19].

We have used MATLAB's PDE application and PDE ToolBox, to program our simulation model.

Once the domain configuration is defined as per the flowchart in Fig. 5, our program defines the geometry to be able to complete the meshing or subdivision of the entire domain into subdomains or elements.

We then allocate physical properties to the various areas constituting the domain and define the boundary conditions on selected edges for a well-posed MEF problem.

An application of our simulation model is presented in Fig. 6 below:

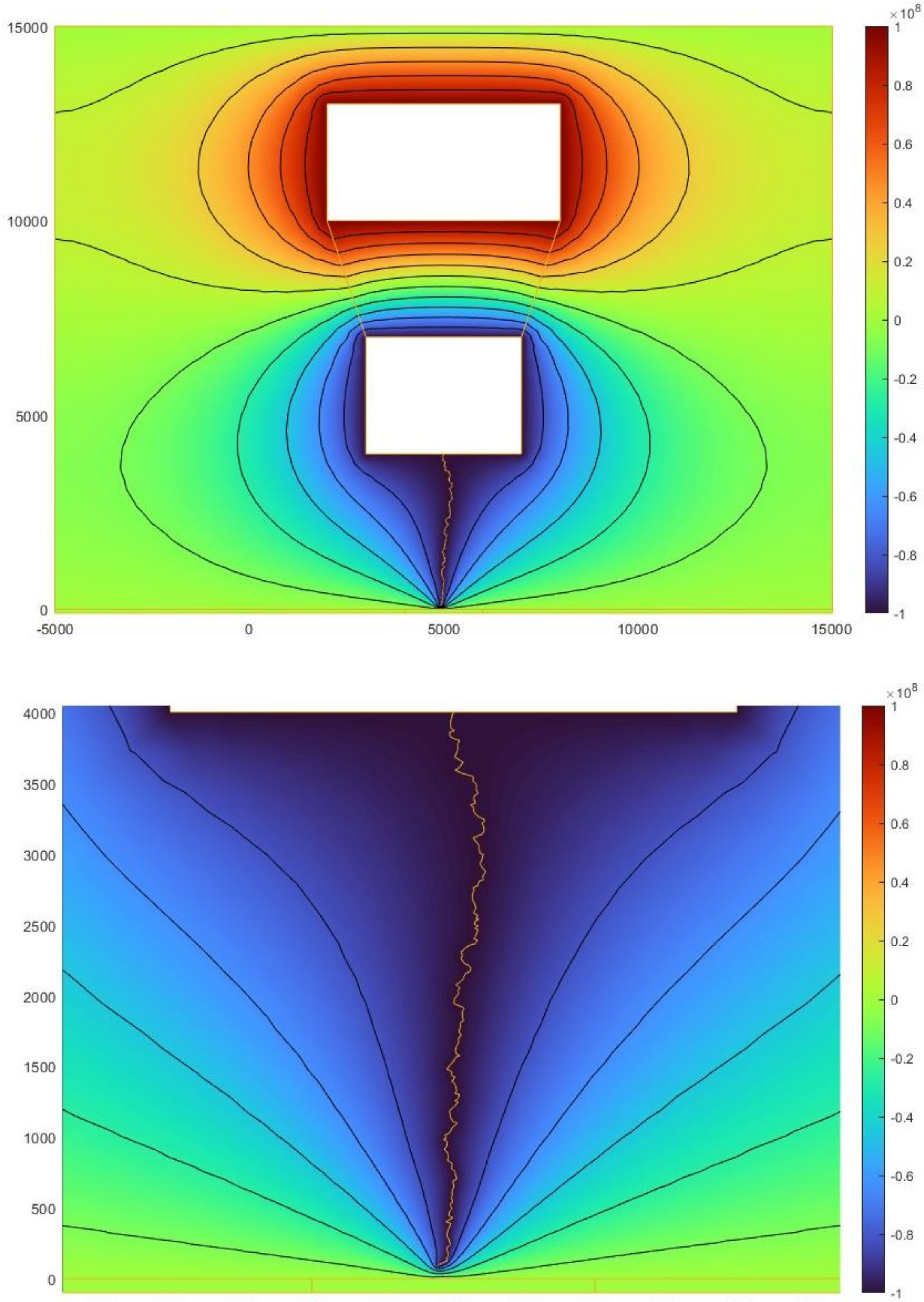

Fig 6. Calculation example using the simulation model.
Top: Electric potential distribution in the domain created by the charge separation.
Bottom: Zoom in the region between the underside of the cloud and the ground.

3. APPLICATION OF THE SIMULATION MODEL TO A PHOTOVOLTAIC FARM

3.1 PV farm Lightning Protection System (LPS)

The first step in any lightning protection exercise is a thorough risk assessment following IEC-62305-2 or IEEE/NFPA equivalent in North America, which provides a procedure for the evaluation of risk (based on different types of loss) to a structure, due to lightning flashes to earth. For example, in large-scale PV applications, economic losses may be the dominating factor that determines which type of surge protection should be employed [20].

Fig. 7 shows a typical grid-connected PV farm layout consisting of PV panel strings, an inverter room, and the connection to the grid.

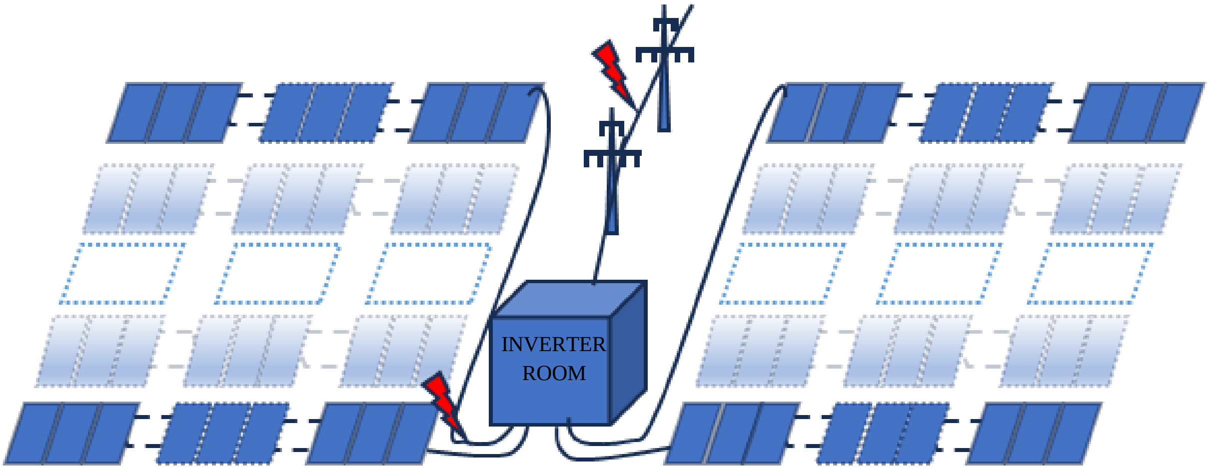

Fig 7. Typical grid-connected PV farm.

3.2 The Electro Geometric Model (EGM) applied to the protection of PV farms

Once the results of the risk assessment are known, and if those results recommend the provision of an LPS, then the protection methods prescribed in the standards will be implemented.

Amongst the protection methods applied, the EGM is the most popular, especially for electrical transmission and distribution networks for which it was originally designed.

The EGM uses the rolling sphere concept which stipulates that a circular arc of radius 45.7 m would closely define the boundary of the protection zone [20-22]. This result can be visualized by imagining a sphere of 45.7-m radius, rolling over the earth's surface, wall, and air terminals. Objects touched by the rolling sphere are susceptible to be struck while those not touched will be protected [10, 20-22].

The rolling sphere method has been included in the NFPA with the 46-m sphere radius and has also been accepted by IEC [10], which defines four protection levels of 99%, 97%, 91%, and 84% which using CIGRE log-normal lightning stroke current distribution corresponds to 2.9 kA, 5.4 kA, 10.1 kA, and 15.7 kA, respectively and the rolling sphere radii for the corresponding classes become 20 m, 30 m, 45 m, and 60 m, respectively [10].

With more recent advances in our understanding of discharge physics of long air gaps and consequently of the lightning attachment mechanism, several limitations of the rolling sphere method become apparent of which [10]:

- The sphere radius is only a function of the critical current and not the height of the rod, ground wire, or the building on which air terminals are installed.
- The rolling sphere method does not account for the effect of the building topology on the lightning exposure of an air terminal.

3.3 Simulation model application

We will be applying our simulation model to the two IEC extreme radii values of 20m and 60m by adjusting the critical height Hc accordingly.

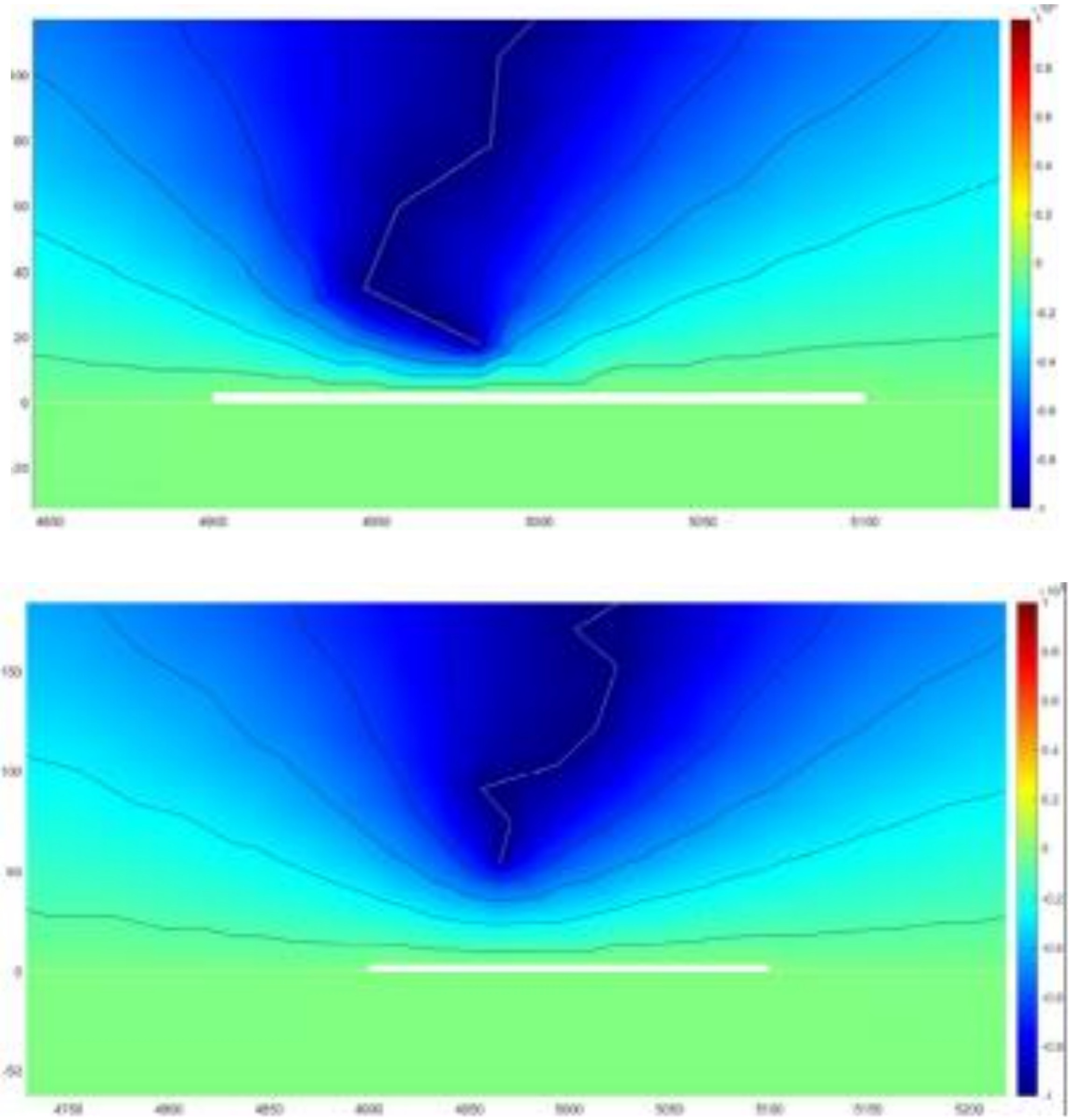

Fig 8. Simulation of a CGN on a solar farm:
Top: protection radius=20m,
Bottom: protection radius=60m.

Fig 9. shows the most onerous situations when lightning strikes at either end of an inverter:

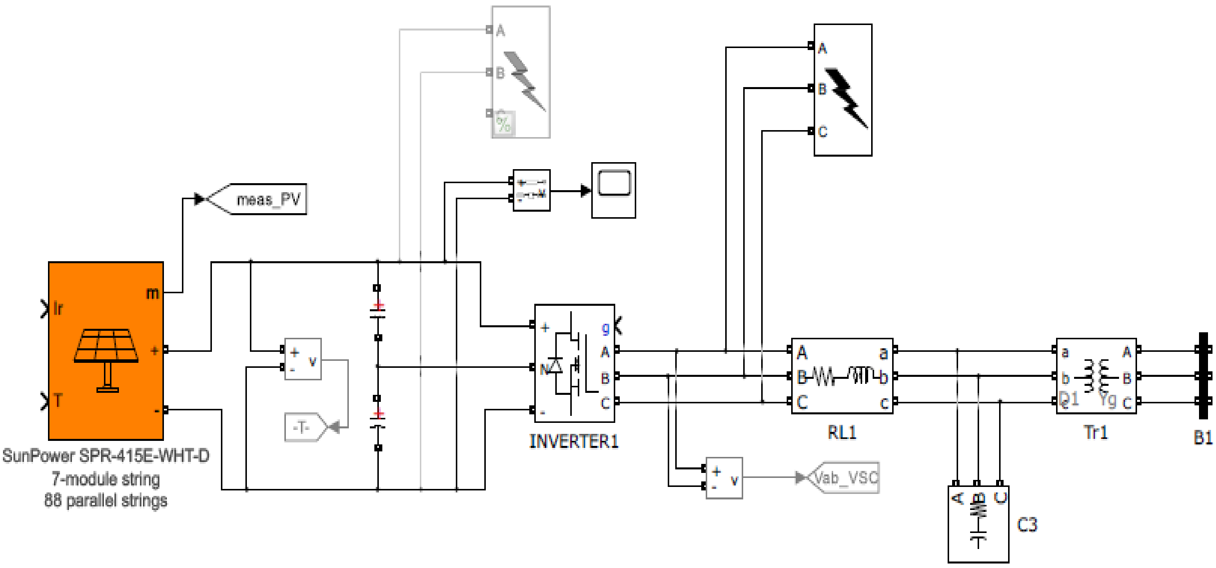

Fig 9. Simulation of a direct stroke on the DC side or the AC side of the inverter

The simulation of a direct impact on the DC side or the AC side of the inverter was carried out using MATLAB/Simulink and confirmed the generally accepted finding that a strike on the grid side of the inverter results in higher voltage levels implying larger surge protection ratings.

In Fig. 10, the Inverter's output voltage before and after a lightning strike is shown:

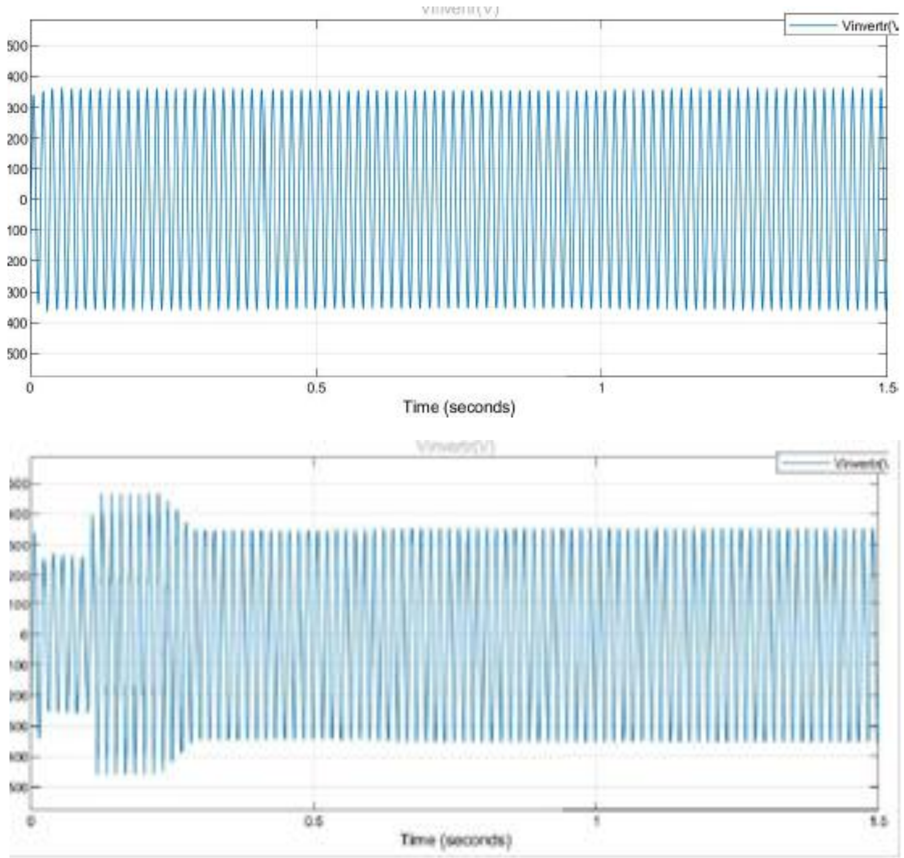

Fig 10. Inverter's output voltage, Top: Before lightning impact; Bottom: After impact at 0.02s

3.4 Comments on simulation results

Protection radii are correlated with the striking distance concept, the smaller the protection radius the smaller the striking distance as shown in Fig. 8.

Both top and bottom simulations in Fig. 8 confirm that the PV installations are adequately protected as a direct lightning stroke is likely to hit one of the air terminals if those are correctly sized, spaced, and earthed as required by the applicable standards.

Simulation of a direct lightning strike near the Inverter's terminals has confirmed that resulting overvoltages will lead to the selection of larger surge protection devices to adequately protect the Inverter and other associated equipment.

4. CONCLUSION

The novel simulation model of the negative cloud-to-ground lightning strikes presented in the first part of this paper does not have the pretension of equaling or even approaching the depth or reach of references cited in [11 to 13].

It does however have the ambition of setting the scene for studying the atmospheric discharge phenomenon as a whole, by addressing every one of its processes individually and understanding how they interrelate to form the bigger picture.

We deeply believe that the most powerful tool in our possession is to try to simplify the concepts as much as possible. For example: explaining the tortuosity of the stepped leader by the fluctuations of the charge epicenter's position within the cloud has allowed us to obtain realistic lightning channel forms compared to the literature.

Our model has also proven its usefulness when applied to lightning protection by addressing at least one of the electro-geometric model's limitations as it can take into consideration the particularities of the structure to be protected.

As any lightning simulation model must address the challenging lightning protection issues, the model was applied to the protection of major power conversion equipment within a PV farm and has shown the necessity to take into consideration the lightning impact on sizing surge protection devices.

In our next research effort, we will model what is generally considered to be the defining aspect of lightning: the return stroke, based on cloud and ground charge dynamics.

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