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On the Lightning Incidence to Wind Farms

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***Abstract*—Lightning strikes are a common cause of damage to wind turbine blades. This paper intends to discuss the lightning incidence to wind turbine parks considering both downward and upward lightning discharges. The analysis is based on numerical simulations performed with the Self-consistent Leader Inception and Propagation Model SLIM. It is found that the calculated annual frequency of strikes due to downward lightning is several orders of magnitude smaller than field observations in the Horns Reef 1 wind park. This shows that upward lightning discharges should be considered in order to obtain proper estimates of the lightning incidence to wind turbines. Thus, it is also found that the thundercloud electric field required to trigger upward lightning from wind turbines depends on whether the discharge is self-triggered or nearby-lightning triggered. A discussion about the existing limitations to estimate the upward lightning incidence in wind parks is presented.**

Keyword: lightning incidence; upward lightning; wind turbine

I. Introduction

Estimation of the average number of lightning flashes striking a wind farm is important for utilities and manufacturers to evaluate their costs of maintenance and reparation. However, the actual number of lightning strikes to wind farms observed is generally larger than the values estimated based on the average ground flash density of the site. As an example, the estimated number of lightning strikes to a 20 km^2 wind farm in the Horns Rev 1 area in Denmark was about 6 per year [1]. This value was estimated considering the total area of the farm and using the historic average ground flash density of 0.3 strikes per km^2 per year. However, the field observations have shown instead more than 50 strikes per year [1]. On the other hand, the electro-geometric method predicts that the blade tip will receive all of the lightning strikes to wind turbines, contrary to field observations showing lightning damages locating even several meters away from the tip of the blade [2]. These disagreements between estimates and observations [2] indicate that there is still a lack of understanding of the process how lightning flashes strikes wind turbines.

Even though several studies evaluating the lightning attachment to wind turbines have been published in the literature [2][3][4], they are only consider downward lightning. This is also the case of the IEC standard addressing the lightning protection of wind turbines, which only considers the incidence of downward flashes [5]. According to the observations of lighting attachment to the elevated objects such as towers and wind turbines [6] [7], the incidence of upward lightning is significantly higher than for short objects. Since wind turbines are becoming larger and larger, with maximum tip heights superior to 100 m, it is expected that they trigger upward lightning under thunderstorms [8]. Recent measurements have also shown that the lightning flashes to wind turbines are initiated by upward leader discharges without the presence of a close descending discharge [6][9]. Thus, this paper intends to revisit the subject of the lightning attachment to wind turbines considering both downward and upward lightning by using the Self-consistent Leader Initiation and Propagation Model SLIM [10][11][12].

II. The self-consistent leader inception and propagation model –SLIM–

SLIM simulates the initiation and propagation of the upward positive leader launched from grounded objects. It follows the chronological sequence of discharges taking place from a grounded object under the influence of the thundercloud and the downward stepped leader. It includes the evaluation of the first and subsequent (precursor) streamers, the upward positive leader inception and propagation, as well as the final jump when the lightning attachment completes.

Even though SLIM has been generally used to analyse lightning attachment in downward lightning [10], it has been here extended to study the dynamic initiation and propagation of upward positive leaders in upward lightning. Upward lightning can be divided into negative and positive flashes, due to the polarity of the charge dominating in the thundercloud. Since the flashes with negative polarity represent the majority of upward lightning discharges [6][7], they are studied in this paper. Negative upward lightning from tall structures is preceded by a positive upward lightning leader discharge. It has been recently shown that this positive upward leader can be self-initiated under the static thundercloud electric field E_{cloud} or triggered by nearby lightning discharges causing a fast increase in the thundercloud electric field at ground level ΔE_{cloud} [6].

Even though the presence of the space charge layer created by glow corona initiated from irregularities at ground level may strongly distort the ambient electric field E_{back} generated by the thundercloud close to ground [13], this effect is neglected in the present study. Since the generation of corona on the water is limited due to the lack of protrusions on its surface, this assumption is valid for estimations related to offshore wind parks. In the case of onshore wind parks, a careful analysis of the distortion of the space charge layer on the ambient electric field is required as in [13][14][15]. Thus, the background ambient electric field produced by the thundercloud is here calculated as:

$$E_{back} = E_{cloud} + \Delta E_{cloud} \quad (1)$$

In the case of self-initiated upward discharges ΔE_{cloud} is equal to zero. For the case of nearby-lightning-triggered lightning flash, the change of the thundercloud field is assumed to grow exponentially according to:

$$\Delta E_{cloud} = a * e^{bt} \quad (2)$$

where the constants a is taken equal to 150 while the parameter b is assumed to range between 100 and 230. These values have been obtained by fitting the time evolution of the background electric fields measured in nearby-lightning-triggered flashes reported in [6]. An example of the background field in such a case is shown in Figure 1.

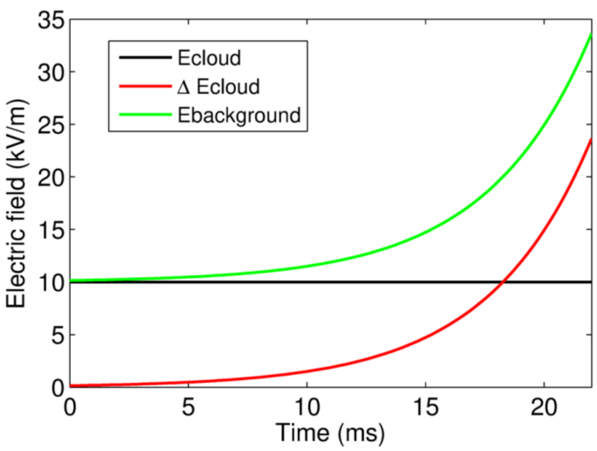

Figure 1. Example of the background electric field under a nearby-lightning triggered flash.

III. Lightning Attachment by Downward lightning

In order to perform the analysis with SLIM, let us consider a wind turbine with hub height of 80 m and blades 44 m long and protected with n=6 lightning receptors each. Observe that this turbine geometry has a maximum turbine height slightly larger than in the Horns Reef 1 wind park (of about 110 m). The receptors are assumed to be located at the blade tip, and 25, 30, 35, 39 and 42 m from the turbine axis. Figure 2. shows an example of the lightning attachment surfaces calculated with SLIM for each receptor at a blade angle of 60 degrees and a prospective return stroke current of 8 kA. They are calculated as the surfaces where the downward stepped leader is attached by any of the upward connecting leaders initiated from the lightning receptors on the blade. As it can be seen, the attachment surfaces need to be calculated with care due to the overlap at some angles between the lightning attraction areas of the receptors of two blades. Once the attachment surfaces are properly estimated, it is possible to calculate the lightning attraction area a_k for each receptor (k=1, 2, … n) as the exposed area for each attachment surface "seen" by the descending leader (i.e. from the top view). For this return stroke current and blade angle, the calculations show that inblade receptors are not fully protected by the tip receptor (which has the largest lightning attraction zone in most cases).

Even though the calculation of the attraction areas has already been attempted in the literature [2][3], those estimates are not accurate due to several reasons. First, they have been obtained with a collective volume concept that assumes that the upward leader velocity is the same of that of the downward leader (i.e. a unitary velocity ratio). In addition, the collective volumes are not defined by the actual lightning attachment point but only by the condition of initiation of the upward connecting leader. Instead, SLIM self-consistently calculates the upward leader velocity under the influence of a descending stepped leader such that the lightning attraction areas correspond to the surface defined by actual attachment points. For those reasons, the lightning attraction areas estimated for instance in [3] are significantly larger than the estimates obtained with SLIM as shown in Figure 3.

Based on properly estimated lightning attraction zones under downward lightning, the annual number of strikes to the three blades in a wind turbine due to downward lightning N_d can be correctly calculated as:

$$N_d = 3N_g \int_{5kA}^{200kA} \left(\int_{0°}^{360°} a_{(pk)}(I_p, \theta) f(I_p) g(\theta) d\theta \right) dI_p \quad (3)$$

where N_g is the ground flash density, I_p is the prospective return stroke current, and a_{pk} is the lightning attraction area of the k-th receptor p_k which is a function of the blade angle θ (defined from the vertical). The term $f(I_p)$ is the CIGRE probability density function of the first-return stroke peak currents and $g(\theta)$ is the uniform probability density function for the blade angle θ. Observe that the integral term defines the equivalent lightning attraction area a_{equiv} of a single blade considering the return stroke peak return stroke current probability distribution and the rotation of the blade.

Interestingly, the calculated equivalent lightning attraction area a_{equiv} is only about 0.034 km^2 for the considered wind turbine geometry. This means that the estimated number of strikes due to downward lightning strikes to a wind farm with 80 turbines (as in Horns Reef 1) would be about 8.16 times the ground flash density. If the same ground flash density as in [1] is used for Horns Reef (0.3 strikes per km^2 per year) then the estimated number of strikes to the complete wind park would be more than two orders of magnitude smaller than observed.

This result clearly shows that downward lightning cannot explain the observed lightning incidence to wind farms (e.g. in Horns Reef 1) and that it is upward lightning the main cause of the observed number of strikes to wind turbines.

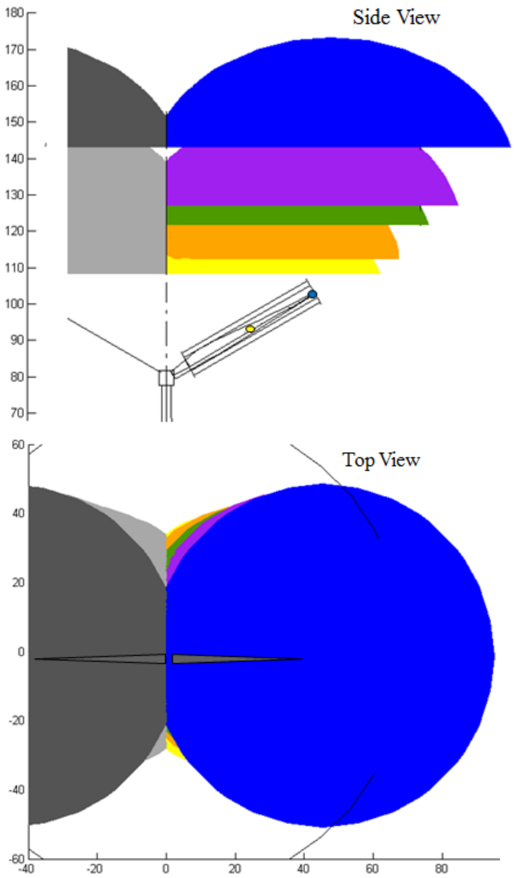

Figure 2. Calculated lightning exposure zones for the Vestas V-90 turbine at an angle of 60 degrees at 8 kA

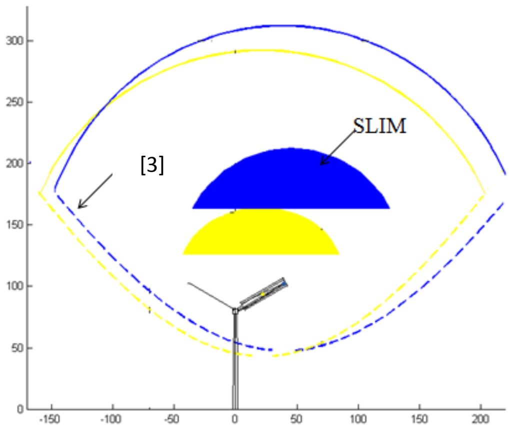

Figure 3. Comparison of the lightning attraction zones estimated by SLIM and the collective volume used in [3] for the tip and inner most receptor (separated by 25 m) at a blade angle of 60 degrees and a prospective return stroke peak current of 15 kA

IV. Lightning Attachment by Upward Lightning

In order to discuss the lightning incidence to wind parks due to upward flashes, it is necessary to first assume that a lightning strike in such a case takes place only when the a stable upward leader is initiated from a turbine. Thus, a upward lightning flash is assumed to take place when the background electric field E_{back} exceeds the critical electric field E_{stab} required to initiate a stable positive upward leader.

This critical electric field E_{stab} in self-initiated discharges is as a function of the tip height [12] and the electrostatic shielding produced by the geometry of the studied object. Figure 4 shows the calculated critical electric field E_{stab} for different receptors in the turbine blade for an angle of 60 degrees. As it can be seen, upward positive leaders initiated from the tip (receptor 1) need the lowest background electric fields in order to trigger upward lightning. This result agrees with observations of positive upward lightning were mostly of the discharges initiated from the blades tip of the wind turbines [16]. As the distance of the receptors to the blade tip increases, the electrostatic shielding of the blade itself causes a significant increase of E_{stab} .

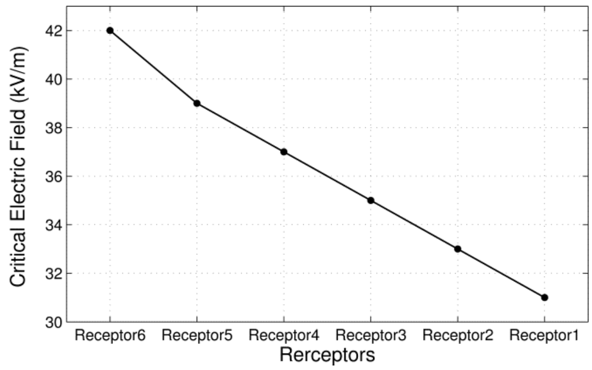

Figure 4. Critical electric field E_{stab} of self-initiated upward positive lightning for different receptors for the blade angle equal to 60 degrees

It is important to point out that the critical electric field E_{stab} of a wind turbine changes periodically with time as the blades rotate. Figure 5 shows the calculated critical electric field E_{stab} for the tip receptor on all blades. The angle θ is defined between the axis of blade A and the vertical axis, as shown in Figure 6. As it can be seen in Figure 5, E_{stab} is minimum when blade A are at their highest most position (when its blade angle θ equal to 0) and reach a maximum when the height of two blade tips are at the same level (at θ equal to 60, -60). Observe that there is a change of about 20 % between the maximum and minimum critical field for a turbine as it rotates. This change is mostly related to the change in tip height at different rotation angles.

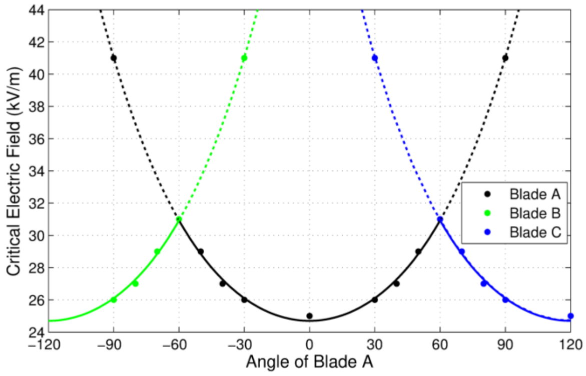

Figure 5. Critical electric field E_{stab} for the tip receptors on the blades when blade A rotates the upper surface.

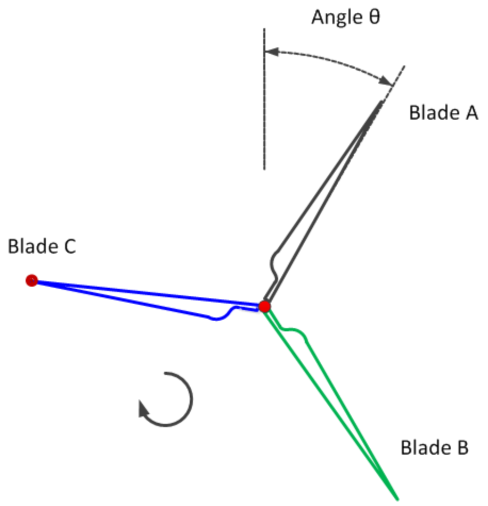

Figure 6. Illustration of the blades and angle θ

The impact of the rise-rate of the electric field produced by the nearby lightning discharge on initiating the upward lightning from the blade of wind turbines has been analyzed here. The rise-rate of the electric field is expressed by equation (2) with varying the parameter b, shown in figure 7. The critical electric field required of the inception of the upward leader is calculated with the various rates of electric field changes. This study shows that the initiation of upward positive leaders strongly depends on the rate of change of the thundercloud electric field. Figure 8 indicates how the critical electric field changes for different values of the parameter b and the corresponding transient electric field change. The critical electric field is calculated according to whether the stable upward positive leader is initiated or not when the ΔE_{cloud} reaches 10kV/m. Observe that the estimated critical electric field is significantly smaller in the case of nearby-lightning triggered upward lightning compared with the case of self-triggered discharges.

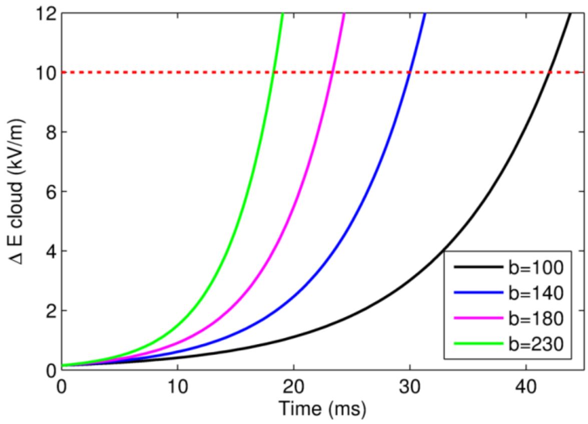

Figure 7. Different rates of change of the thundercloud electric field according to differet b value in equation 2

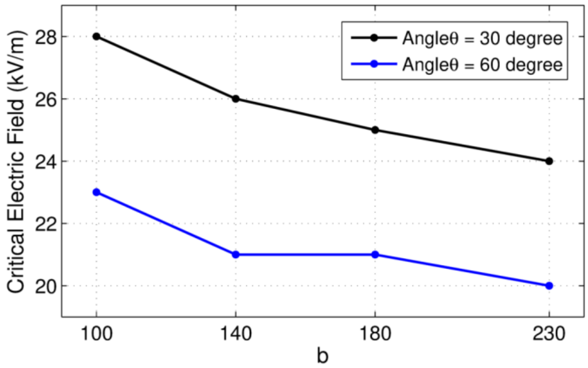

Figure 8. Calculated critical electric field changes for different values of the parameter b

Now that the critical electric field E_{stab} has been calculated for both self-initiated and nearby-lightning triggered upward positive leaders, the next step is to attempt to evaluate the incidence of upward lightning from the turbine. Unfortunately there is no established procedure to evaluate the total annual lightning incidence of upward flashes N_u. In the literature, only a rough estimate of N_u for a single turbine can be obtained by using an empirical relationship derived by Eriksson [17] as:

$$N_u = 24 \times e^{-6} {h_s}^{2.05} N_g - N_d \tag{4}$$

where h_s is the effective height of the structure which for offshore turbines corresponds to the tip height. This equation estimates an annual flash density for the Horns Reef 1 wind park (with 80 turbines) of about 8.2 flashes per year. This estimated value is still one order of magnitude smaller than the observations quoted in [1].

Observe that estimations of N_u based on the lightning flash density N_g (as in (4)) neglect the fact that wind turbines have a higher probability to be struck by lightning compared with their surroundings [8]. It is also reported that the incident of lightning strikes increases dramatically in the near surrounding of the tall object, formatting a lightning hot spot [18]. For this reason, the actual lightning flash density N_g to a wind park area is likely to increase compared with the historical values reported before the turbines were installed. Therefore, the lightning flash density N_g in the area where a wind park will be installed is not known beforehand.

Instead, the annual flash density due to upward lightning N_u to a wind park should depend on the number of times per year where the thundercloud electric field exceeds the critical electric field E_{stab} of a turbine. This could be calculated if both the number of thunderclouds formed per year and the thundercloud electric field probability distribution function would be known for the corresponding site. Unfortunately, none of those are standard parameters of lightning engineering interest and for that reason they are not well known. Although the number of thunderclouds formed per year could be related to the keraunic level (i.e. the number of days a year when thunder is heard), one could not account for the number of times in a day that a thunderstorm is formed. Furthermore, upward lightning events have also been reported to occur with little or no lightning activity [19] as to produce thunder. Therefore, the keraunic level provides only a lower limit value for the number of thunderclouds formed per year. On the other hand, the probabilistic distribution of thundercloud electric fields is difficult to measure since it is strongly dependent on the local structure of thunderclouds and the space charge layer created by glow from the ground surface. Thus, there is unfortunately no proper information as to be able to estimate the incidence of upward lightning triggered by wind turbines.

It is important to point out that the annual flash density to a wind park N_u also depends on the number of simultaneous upward leaders initiated from different turbines in the park under the same storm. As reported in [9][20], several successful upward positive leaders can develop from different wind turbines during the same lightning event. Proper estimates of the number of simultaneous upward leaders require complex simulations of all the turbines in the wind park and the evaluation of the thundercloud size compared with the wind park area.

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