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On the attachment of dart lightning leaders to wind turbines☆

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ABSTRACT

Wind turbines are prone to damages due to lightning strikes and the blades are one of the most vulnerable components. Even though the blade tip is usually protected in standard designs, lightning damages several meters away from it have also been observed in some field studies. However, these damages inboard from the tip cannot be explained by the attachment of downward stepped leaders or the initiation of upward lightning alone. In this paper, the attachment of dart leaders in an upward lightning flash is investigated as a mechanism of strikes to inboard sections of the blade and the nacelle of large wind turbines. Dart leaders in an upward lightning flash use the channel previously ionized by the preceding stroke or the continuous current. The analysis is performed with the self-consistent leader inception and propagation model (SLIM). A commercial large wind turbine with 45 m long blades and hub height of 80 m is analysed as a case study. The impact of the prospective return stroke peak current, the rotation angle of the blade and the wind on the location of lightning strikes on this mechanism is analysed. The probability of lightning attachment of dart leaders along the blade for the case study is also calculated. It is shown that this damage mechanism could create a new strike point only when the blade of a wind turbine rotates sufficiently from its initial position (at the inception of the initial upward leader) until the start of the dart leader approach. Thus, dart leader attachment is a mechanism that can explain lightning strikes to the nacelle and to the inboard region several meters away from the blade tip in large wind turbines. However, dart leader attachment cannot explain the lightning strikes observed in the close vicinity of the blade tip (in the region between 1.5 and 6 m from it).

1. Introduction

Lightning is a major cause of severe damage and unplanned downtime in wind turbines. Replacement of components damaged by lightning strikes is remarkably expensive due to high costs involved and the long repair time necessary [1]. According to the damage records [2], the blades of the turbine are the components most vulnerable to lightning damage. They have the highest frequency of damage by direct strikes and the highest repair cost due to the structural failure [2,3]. This high probability of lightning strikes is usually explained by the height of wind turbine blades which is much larger than that of the surroundings [4]. As wind turbines increase in height, the frequency of upward initiated lightning is expected to augment [4]. This fact has been supported by several independent field observations indicating that upward lightning is the main mechanism of damage for tall wind turbines (with tip height above 100 above sea or ground level) [4–8]. Moreover, it has also been recently suggested that the initiation of upward lightning is easier from wind turbines than from static objects due to the rotation of the blades [9]. This means that wind turbines can readily trigger upward lightning under certain meteorological conditions, increasing the expected lightning incidence compared with the surroundings [4,9].

Lightning protection of wind turbines follows the same general principles as standard structures. Thus, lightning receptors along the blade are generally installed and connected to internal down-conductors or conductors placed external to or under the blade surface [10]. Both field observations [6,11] and laboratory experiments [12] have shown that the receptors are not the only places where lightning attaches to the blade. The region of the blade away from the tips and towards the blade root is also likely to be struck. For instance, laboratory experiments show lightning attachment points at the middle of the blade, with arcs burning on the blade surface or penetrating into the blade boards [12].

In order to explain the observations in the field, the static conditions for inception of upward connecting leaders from turbine blades under the presence of downward stepped leaders were ana-

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lysed in [13,14]. It was found that the blade tip is the most probable lightning strike point under downward lightning. Moreover, it was concluded that the inboard areas further than 3 m from the blade tip are not exposed to direct downward lightning strikes, even for prospective return stroke currents lower than 10 kA. This result disagrees with the field surveys where inboard areas as far as 5 m from the blade tip have been reported to have a small, but still significantnt lightning attachment probability [11].

Recent field studies show that upward lightning is most likely to strike the tip of wind turbine blades [15–17]. Numerical analysis also shows that the so called "self-triggered" and "other-triggered" upward lightning is most likely initiated from the tip receptor in wind turbine blades [18]. Thus, observed lightning damages inboard the blade away of its tip cannot be explained by the initial stage of upward lightning or by the attachment mechanisms generally present in non-moving structures. The rotation of turbine blades has also been recently considered as a possible explanation of lightning inboard damages away from the blade tip [4,9,19]. It has been suggested that a phenomenon called 'swept stroke', a common lightning mechanism of damage in aircraft industry, occurs when a lightning strike first attaches to a blade receptor. It takes place when the flash channel is swept along the trailing edge of the blade due to its rotation. Although the displacement of the channel along the trailing edge in wind turbines is not known, damages due to swept strokes in aircraft industry are usually up to about 10 m in length [20]. Since the rotation velocity of turbine blades is lower than the average aircraft speed, it is expected that the lightning channel sweep along a blade can only damage the area in the proximity of the tip receptor (up to few meters from it). Therefore, the 'swept stroke' mechanism cannot explain the attachment points observed several meters away from blade tip.

An additional lightning mechanism where a subsequent leader discharge attaches to a different blade due to the rotation of the turbine has been also proposed in [4]. This mechanism has been recently suggested as a plausible physical explanation of the lightning damages observed several meters inboard of the blade [21]. Since there has not been any solid assessment in the literature of such a lightning attachment mechanism, this paper intends to quantitatively evaluate its effects on the distribution of strike points in large wind turbines. The analysis is performed with the Self-Consistent Leader Inception and Propagation Model (SLIM) where the attachment of dart leaders is simulated. In this case, upward connecting leaders initiated from receptors on the blade of a wind turbine propagate towards dart leaders occurring prior to subsequent return stroke current pulses in upward lightning flashes. The effect of the prospective return stroke peak current, the wind speed as well as the rotation of blades on the lightning termination is considered in this evaluation.

2. Interception of lightning dart leader from wind turbine blades

According to the observation of the operating wind turbines, a significant amount of lightning strikes to the blades of the wind turbines are due to upward lightning [22–24]. Upward leaders generally initiate from the tip of the blade as it reaches its highest point when the background electric field reaches a critical threshold condition [9]. After inception, an upward positive leader ascends and bridges the gap between the wind turbine and the thundercloud establishing an initial continuous current (ICC). The propagation of the upward leader and the continuous current constitute the initial stage of upward lightning which usually lasts several hundreds of milliseconds [25].

One or more lightning dart leader-return stroke sequences can take place after the period of no current at the end of the initial

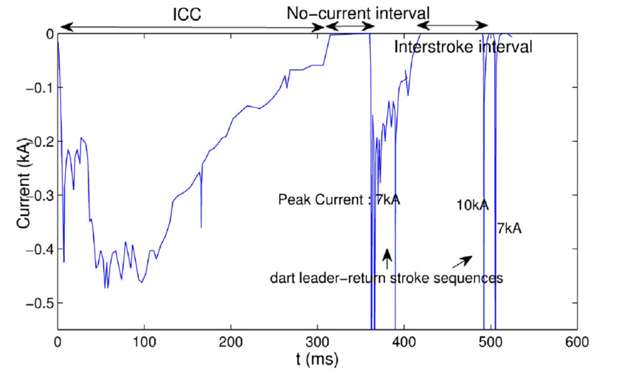

Fig. 1. Example of the current measurement of a upward lightning flash initiated from a tall tower on Monte San Salvatore, Switzerland [21].

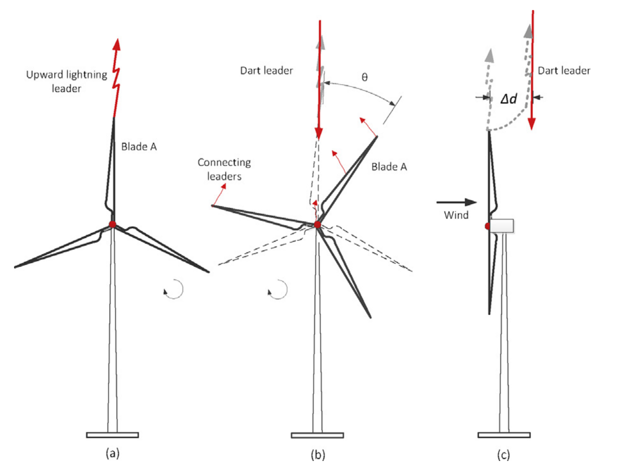

Fig. 2. Mechanism of attachment of dart leaders to wind turbine blades. (a) Initiation of the upward lightning leader, (b) Interception of the first dart leader, (c) Translation of the remnant channel due to wind.

stage. After the time interval Δt_{total} consisting of the initial continuous current stage Δt_{ICC} and the following no-current interval Δt_{NoC} (lasting up to several tens of milliseconds), a first lightning dart leader-return stroke sequence can appear (as shown in Fig. 1). It is caused by a dart leader descending along the remnant channel preheated by the initial continuous current (ICC), which is directly above the nacelle. Since the blades of the turbine rotate an angle θ within this interval Δt_{total} (as shown in Fig. 2), a gap is formed between the remnant channel and the turbine blade. Thus, upward connecting leaders can be incepted not only from the tip but also from receptors inboard the blade. This process is evaluated here as the worst case scenario of lightning attachment to the inner blade receptors by the dart leaders. Observe that the attachment of subsequent dart leaders does not cause a significant change in the lightning strike point since a limited rotation of the blade is expected within the short duration of the interstroke interval.

Wind also plays a role in this scenario since the remnant channel is displaced downstream by a distance Δd depending on the wind speed and the time duration Δt_{total}. Furthermore, intensive turbulence of air flow is produced in the vicinity of the blades, especially the tip of blade [26]. This turbulent flow and the rotation of the blade accelerate the recovery of the temperature and the density of the preheated channel close to the struck blade during the no-current interval. Consequently, it is likely that the air in the remnant channel has recovered to near-atmospheric conditions at the moment of the attachment of a dart leader. Thus, upward connecting leaders initiated by approaching dart leaders are here considered to propagate under near-atmospheric conditions.