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# On the estimation of the lightning incidence to offshore wind farms

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ABSTRACT

Field observations have shown that the frequency of dangerous lightning events to wind turbines, calculated according to the IEC standard 61400-24:2010, is grossly underestimated. This paper intends to critically revisit the evaluation of the incidence of downward lightning as well as self-initiated and other-triggered upward flashes to offshore wind power plants. Three different farms are used as case studies. The conditions for interception of stepped leaders in downward lightning and the initiation of upward lightning is evaluated with the Self-consistent Leader Inception and Propagation Model (SLIM). The analysis shows that only a small fraction of damages observed in the analysed farms can be attributed to downward lightning. It is also estimated that only a small fraction (less than 19%) of all active thunderstorms in the area of the analysed farms can generate sufficiently high thundercloud fields to self-initiate upward lightning. Furthermore, it is shown that upward flashes can be triggered even under low thundercloud fields once a sufficiently high electric field change is generated by a nearby lightning event. Despite of the uncertainties in the incidence evaluation, it is shown that upward flashes triggered by nearby positive cloud-to-ground flashes produce most of the dangerous lightning events to the case studies.


## 1. Introduction

Wind energy is an important source of the renewable energy with a rapidly increasing installed capacity [1]. More and more wind farms are installed to meet the growing demands of energy consumption. These wind farms are usually constructed on the top or the ridge of hills in offshore regions where no nearby object has a comparable height. For this reason, wind turbines are vulnerable to lightning strikes, with an increasing risk of damage as their height increase (currently reaching heights larger than 100 m).

The estimation of the incidence of lightning strikes to wind turbines is essential in the assessment of the risk of damages, providing information for the cost-benefit evaluation of the entire wind farm. Currently, the procedure to evaluate the average annual frequency of flashes attaching to a wind turbine is defined in the International Electrotechnical Commission IEC standard 61400-24:2010 Wind turbines — Part 24; Lightning protection [2]. It is calculated as the product of the local lightning flash density, the lightning collection area and an environmental factor [3]. This evaluation is based on the lightning collection area concept used for objects of moderate height, exposed mainly to downward lightning strikes [4].

However, field observations have shown that the actual number of lightning strikes to wind farms is several times higher than the estimates based on the procedure given by the standard [5–7]. Moreover, studies based on lightning location systems (LLS) have shown that the lightning incident in the close vicinity of the wind turbines and communication towers is much higher than for the surrounding region, forming a lightning hot-spot [8,9]. This lightning hot-spot phenomenon is mostly attributed to upward lightning initiated from these elevated objects, which cannot be assessed based on the lightning collection area concept. The frequent occurrence of upward lightning triggered from wind turbines has also been observed in field studies using high speed video [10–12].

In upward lightning, an upward propagating leader discharge is triggered under the influence of the thundercloud charge [13,14], in the absence of a nearby descending lightning leader. The frequency of upward lightning initiation from a grounded object dramatically increases with height, especially when it exceeds 100 m [16]. However, upward lightning is influenced not only by the object height but also by the thunderstorm activity, the topographical conditions and the number of tall structures around [9,15]. It has also been recently shown that upward lightning can be either

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self-initiated by the structure or triggered by a nearby lightning discharge [13]. Self-initiated upward lightning takes place under the slowly increasing electric field produced by the thundercloud without any lightning discharge event occurring few minutes before. On the contrary, other-triggered upward flashes occur due to the fast changing electric field caused by nearby lightning discharges. Such discharges can take place several or several hundreds of milliseconds preceding the upward lightning initiation and can take place even several tens of kilometers away from the elevated object [17].

Since there is growing evidence that upward lightning plays an important role in the incidence of lightning to wind turbines, it should be considered when assessing the exposure and risk of wind farms [18]. Unfortunately there is no reliable method up to date to estimate the frequency of upward lightning from tall structures [4]. Even though empirical equations to estimate the fraction of upward flashes have been proposed [18], they are only a function of the structure height. However, there is clear evidence that the initiation of upward lightning depends also on several local conditions such as the cloud base height, the space charge layer, the occurrence of other lightning events, etc. [13,15]. For this reason, it is doubtful that empirical equations can be used for a generic risk assessment of any wind turbines in an arbitrary location. The incidence of upward lightning has also been calculated based on equations obtained from the historic data of hot-spot areas detected by sensitive lightning location systems [8,9]. However, such an approach is only valid at local/regional level and it can be applied to other conditions only in areas with turbines already installed and with several years of available LLS data.

In an attempt to assess the incidence of lightning flashes from a different perspective, this paper focuses on the physical evaluation of the conditions for attachment of downward lightning and the triggering of upward flashes by offshore wind power farms. Since numerous physical processes involved in the evaluation of upward lightning incidence are poorly understood or lack of sufficient experimental data, several rough approximations and assumptions are considered in this study. For this reason, the detailed analysis here described is only intended as a starting point to highlight which lightning processes need further investigation and which type of experimental data is relevant for improving the state of the art. Thus, the analysis introduced in the paper should not be considered as an engineering method to evaluate lightning incidence but instead as a scientific approach that needs to evolve as future research addresses those lightning processes that are unknown or have poor experimental data.

In order to compare the evaluation introduced in the paper with field observations, three different existing offshore wind power plants are analysed. These correspond to case studies with field observations related to lightning strikes. The first case corresponds to the Nysted wind farm, located in the Baltic Sea, close to the Rødsand sand bank in Denmark. It is in operation since 2003 with 72 wind turbines [19]. The other two cases correspond to the Horns Rev 1 and 2 wind farms, located in the east North Sea, about 15 and 30 km east from the coast of Denmark. The Horns Rev 1 park started operation in December 2002 with 80 wind turbines with total height of 110 m [20]. The Horns Rev 2 park consisting of 91 wind turbines (with total height of 114.5 m) is in operation since 2009 [21].

Although the lightning incidence to onshore wind farms can also be assessed with a similar approach, other influencing factors such as the terrain topography and the shielding effect of the near-ground space charge layer are not considered here. For this reason, the analysis of onshore turbines is out of the scope of this paper.

## 2. The Self-consistent Leader Inception and Propagation Model SLIM

In order to evaluate the lightning incident to wind farms, both downward and the upward lightning of negative polarity are analysed. Thus, the initiation and propagation of positive upward leaders is evaluated with the Self-consistent Leader Inception and Propagation Model SLIM [22–24]. In contrast to other leader propagation models, SLIM self-consistently calculated the properties of the upward leaders (e.g. velocity, current, potential gradient) launched from the wind turbine during the entire lightning attachment process. The evaluation of the lightning attachment in downward lightning is performed dynamically following the time variation of the ambient electric field produced by the stepped leader approach to ground [24]. Even though upward lightning has been generally evaluated assuming a static approach [25], the dynamic evaluation of SLIM is used here for both self-initiated and other-triggered flashes. In this manner, the physical properties of positive leader in upward lightning can also be estimated as a function of time.

The evaluation performed with SLIM follows the chronological sequence of discharges taking place from a grounded object under the influence of the downward stepped leader and/or the thundercloud. It includes the evaluation of the first and subsequent (precursor) streamers and the upward positive leader inception and propagation. In the case of downward lightning, the calculation also includes the final jump when the lightning attachment completes. For upward lightning, the evaluation at a given ambient electric field is performed until the upward leader either stops propagating or starts accelerating continuously with velocity higher than $3 \times 10^4$ m/s. For the detailed description of SLIM under dynamic conditions, the reader is referred to Ref. [24].

## 3. Attachment of downward lightning to wind turbines

In order to evaluate the general features of downward lightning attachment, the simulations are performed in this section for the wind turbines in the Nysted and Horns Rev 1 parks. These farms have turbines with total height of 110 m with nearly the same hub height (69–70 m) and blade diameter (80–82.4 m). It is assumed that the blades are protected with $n = 5$ lightning receptors each, connected internally with a down conductor. These receptors are assumed located only on one side of the blade, at the tip and in blade 37, 33, 28 and 20 m from the turbine axis.

Fig. 1 shows an example of the lightning attachment surfaces calculated with SLIM for each receptor at a blade angle of 60° and a prospective return stroke peak current of 10 kA. These surfaces are defined by the location of the downward leader tip at the moment it is intercepted by any of the upward connecting leaders initiated from a receptor on the blade.

A downward lightning flash is predicted to strike the receptor whose attachment surface is first touched by the descending stepped leader. In this manner, it is possible to define the lightning collection area $a_k$ for each receptor ($k = 1, 2, \ldots n$) as the exposed area for each attachment surface that can be reached by an approaching downward leader. However, these collection areas $a_k$ need to be calculated with care due to the overlap between the lightning attachment surfaces of receptors in all the blades (as seen in Fig. 1). After drawing the lightning attachment surfaces of all the receptors in the wind turbine, the lightning collection areas $a_k$ can be easily estimated as the zone of each attachment surface visible from the top view (Fig. 1b).

The simulations showed that the inboard receptors of the analysed wind turbine are exposed to downward lightning strikes only under prospective return stroke currents equal to or lower than