Upward Lightning Exposure Assessment for Wind Power Plants in Low Altitude Thunderstorms using Comsol Mulitphysics

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Introduction

Low altitude thunderstorms (often thunderstorms during the cold season) are a threat for wind turbines in several areas of the world because the charge of the thundercloud is much closer to the earth compared to warm season thunderstorms (Kitagawa & Michimoto, 1994). As a consequence, the electric field around the grounded wind turbine is much higher during these storms, triggering so-called upward lightning flashes (Wang, Takagi, Watanabe, Sakurano, & Hashimoto, 2008). Wind turbines being tall and pointy grounded structures are particularly affected, since the electric field around the tip of the blades can be several orders of magnitude larger than the ambient electric field (See Figure 1) , triggering the initiation of frequent upward lightning strokes.

Upward lightning flashes are typically characterized by lower peak current and specific energy compared to downward lightning. However, often the same wind turbines within a wind farm are affected and the accumulated exposure poses a significant risk for the receptors of a wind turbine blade (Diendorfer, 2015). An example of this so called “lightning cluster formation” can be seen in Figure 2, where Lightning Location System (LLS) data indicates that lightning exposure is unequally distributed within the wind farm and in particular two main discharge regions can be identified (red circles). Such lightning patterns can typically be observed in sites where frequent cold season thunderstorms or low altitude thunderstorms are apparent, for instance the north-western coast of Japan (Ishii M. , 2015), the north of Spain (Lopez, Hernaez, & Montanya, 2012) or the Mediterranean area.

A global overview of areas affected by winter type lightning was created by (Montanya, 2016). Wind turbine operators in related areas should be especially aware of the severe lightning activity. Notice that upward lightning flashes in Japan occasionally will transfer charge quantities exceeding the values of Lightning Protection Level (LPL) 1 parameters of the IEC61400-24 Ed.2 (Ishii M. , 2015).

In this paper, a methodology for assessing the distribution of upward lightning flashes inside a wind power plant during thunderstorms with a low cloud height is provided. Geographical and meteorological data is used to represent realistic lightning conditions for a specific site. The movement of the thundercloud is simulated by moving an equipotential plane at a certain altitude above the turbines, which will then expose the wind farm to varying electric field intensities.

Comsol 5.4 with a Livelink to Matlab is used to calculate the voltage distribution at the tip of each wind turbine blade (facing up) towards the cloud and a mathematical model of connecting leader inception and propagation determines which turbines have the highest risk to be struck by upward lightning.

The paper is structured as follows. Firstly, the essential parameters which impact the lightning attachment distribution are described in the theory section. Subsequently, the approach how to obtain and implement these parameters in the model is provided in the Methodology. Thereafter, the results are presented and are compared to measured lightning data. The last section presents the main findings and the conclusion of this paper.

Figure 1 – Illustration of electric field around wind turbine. The highest field is located at the tip of the upward facing blade (red), The mid-span part of the blade and the end of the nacelle are characterized by medium field areas (yellow). The tower and the inner side of the nacelle are characterized by low electric field magnitudes (white).

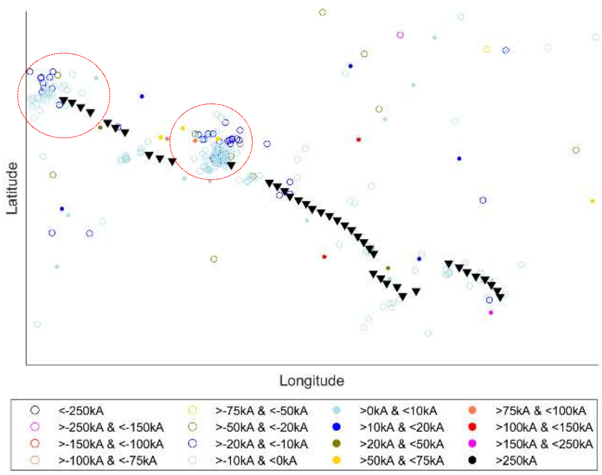

Figure 2 – Measured lightning exposure in a wind power plant during 10 thunderstorm days with low cloud height. Red circles show intensified lightning activity. Black triangles facing down resemble wind turbine location whereas circles and dots show stroke detections by LLS.

Theory

There are four parameters that impact the distribution and risk of upward lightning attachment with low cloud heights in a wind power plant. These are the topography, the wind direction, the height of the charge in the cloud and the magnitude of cloud charge. Firstly, the topography affects the overall electric field distribution where higher located turbines are affected by increased electric fields (Garolera, Vogel, Lopez, Madsen, & Bertelsen, 2015). Secondly, the wind direction determines the cardinal direction from where the storm approaches. Wind turbines facing the storm direction of approach are often the victim of an upward lightning flash and neutralize the cloud charge for the remaining turbines in the wind farm. Thirdly, the height and magnitude of the charge determines how the electrical field is distributed within the wind farm. By obtaining topographic information of a wind power plant and the meteorological parameters during thunderstorms, a valid input can be determined to create a simulation model based on realistic parameters. In Comsol, a thundercloud can be represented either as a plane with a certain potential or a volume with a certain charge density.

Methodology

This section describes the methodology how to estimate the upward lightning probability between different wind turbines. The model uses meteorological and geographical data from historic lightning events as an input. The simulation uses the Electrostatic interface of the AC/DC module with a stationary study step. The Livelink to Matlab enables to control the physical model and defines initial and termination conditions through a mathematical model.

Simulation Steps

The following approach has been created to build a representative model.

1. Elevation data has been downloaded for the wind farm under investigation.
2. Determination of date and time when previously lightning flashes during low-cloud altitude were observed in the wind farm. This data can originate from the wind turbine operators or from LLS data. In this investigation, 10 thunderstorm days were evaluated by utilization of Nowcast LLS data (Betz, 2014) which was acquired during the ELITE project (Madsen, Vogel, Lopez, Garolera, & Bertelsen, 2015).
3. Meteorological data (ERA5 dataset) was downloaded for the mentioned date/time period.

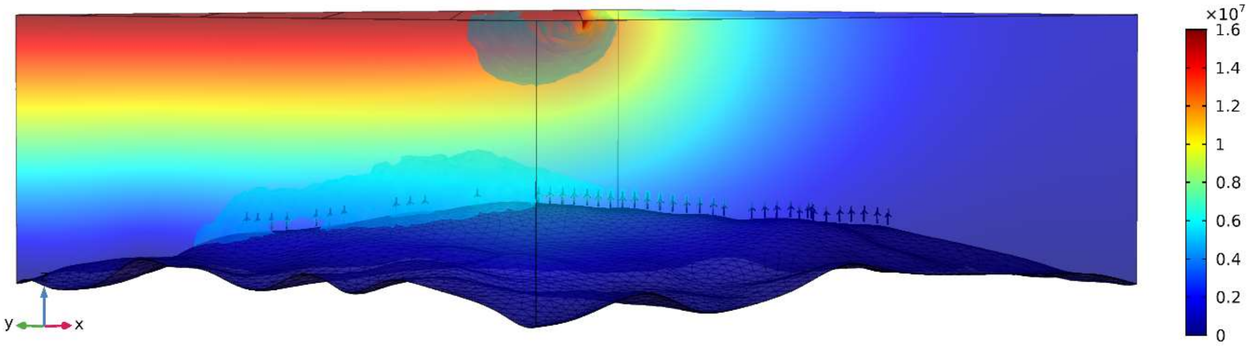

Figure 3 - The cold season thundercloud approaches the wind power plant from a certain direction and at a certain height. The electric field (Turquoise cloud) around the turbines is enhanced at the left side but it is insignificant at the right side.

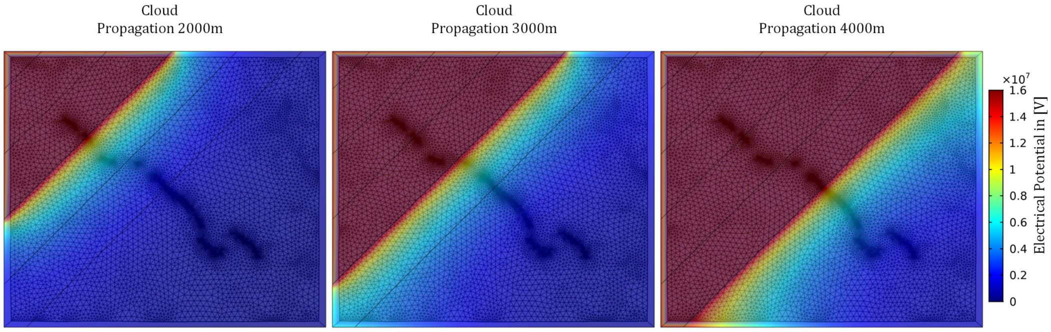

Figure 4 – Thundercloud propagation over wind farm with certain angle depending on wind direction.

Two key parameters are used in the investigation which are:

  a. Wind direction
  b. The height of the -10° Isotherm (This parameter is used to estimate the height of the charge concentration inside a cloud, which affects the likely type of lightning discharges being created).

The correlated parameters can be found in Table 1.

Table 1 – Simulated cases.

Cases	Date	Time	Wind direction	Height -10° Isotherm ASL
			[deg]	[m]
1	2012/01/29	14:00	0	2408
2	2012/11/28	22:00	352	2691
3	2012/11/29	06:00	347	2628
4	2013/01/23	12:00	322	2432
5	2014/02/02	16:00	341	2456
6	2013/02/08	08:00	332	2675
7	2013/02/11	07:00	299	2212
8	2014/02/11	03:00	297	3132
9	2014/02/25	23:00	290	2522
10	2014/11/05	10:00	324	3214

4. The Comsol model is built with the parameters from point 1 to 3. First, the elevation profile is built utilizing a parametric surface. Second, wind turbine outer geometries are placed at the exact location via GPS coordinates. Third, the height of the -10° isotherm (Often used as estimation of height of the charge in a thundercloud (Miki, 2015)) is implemented as the upper boundary of the air domain (See Figure *3*). Four, a work plane with the angle corresponding to the wind direction is created. This work plane simulates the thundercloud approaching from a certain direction and is coupled to a propagation parameter. The propagation parameter controls the location of the thundercloud in respect to the model as illustrated in Figure 4.
5. Afterwards, the thundercloud over the wind power plant is simulated by applying a voltage to a fraction of the upper boundary of the air domain which moves by adjusting the propagation parameter.
6. Three different voltage levels (low, medium and high) are applied to the potential plane. Low potential is defined as the potential when the first upward lightning leaders develop according to the model for leader inception. The potential in the medium and high level is determined as 133% and 166% of low threshold voltage, respectively. For each voltage and propagation level, the script evaluates whether the conditions for upward lightning development are met for each individual wind turbine. This simulation is repeated for each case.
7. The simulation for each case stops if:
   a. The potential plane (cloud) has propagated fully over the wind farm or
   b. More than 20% of the wind turbines in the wind farm develop an upward lightning leader
8. For each simulation, the charge of each developed upward lightning leader is saved.
9. From the charge of the upward lightning leader, the probability of lightning attachment is determined. The higher the charge level, the higher the probability that this wind turbine is affected by upward lightning. An upward lightning leader with a low charge magnitude may connect to a cloud charge pocket but with a lower probability.

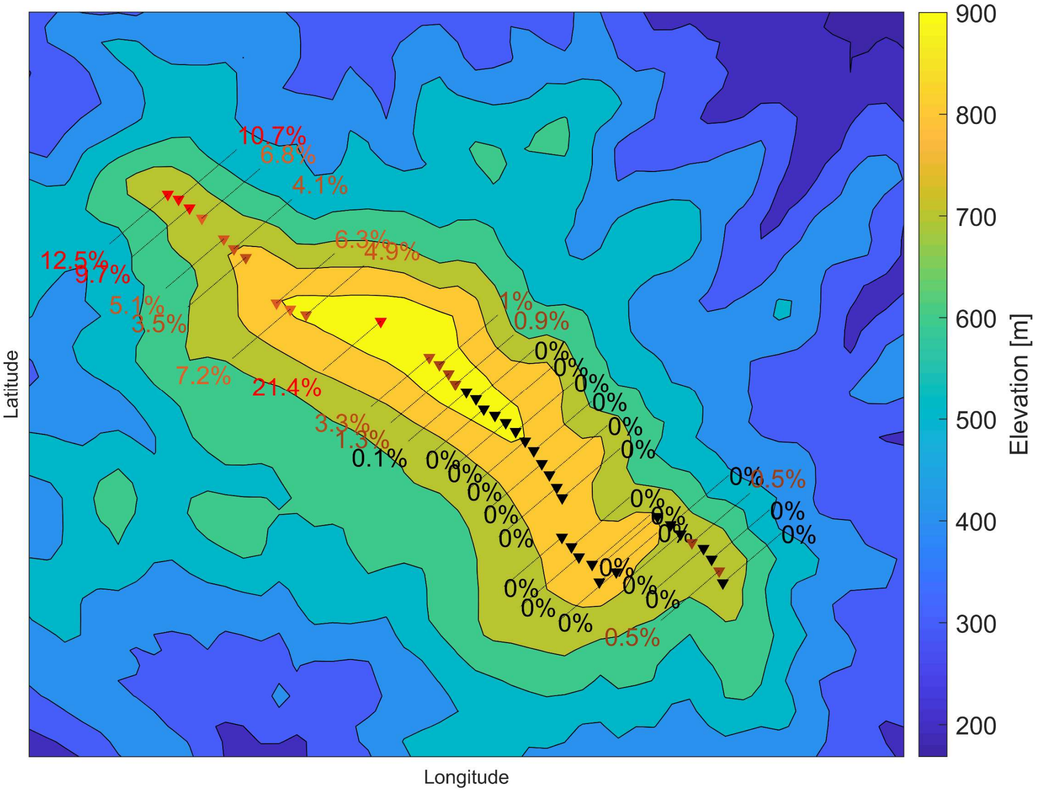

Figure 5 – Simulation Results from 10 low altitude thunderstorm events: The calculated lightning exposure is mainly focused on the north-west corner and on the wind turbine with the highest elevation. Turbines in the south-western area are less likely exposed to upward lightning. The determined risk of lightning attachment is in good agreement to the measured LLS data illustrated in Figure *1*.

Evaluation whether the electrical potential is high enough to trigger upward lightning

In order to determine whether sufficient potential is available to trigger an upward lightning flash, the upward lightning inception model developed by Goelian et al. (Goelian & Lalande, 1997) and simplified by Becerra and Cooray (Becerra & Cooray, 2006) is applied.

An example of the application of the model can be found in (Garolera, Vogel, Lopez, Madsen, & Bertelsen, 2015) and the description of the mathematical model is taken from this paper. The interested reader is referred to the papers above for more information.

After each simulation step, the voltage distribution U_1 from the tip of the turbine to the cloud is extracted and compared to the potential distribution after corona formation U_2. With this approach, a corona charge can be calculated:

$$\Delta Q = K_Q \int_{l_L}^{l_s} \left(U_1(l) - U_2(l)\right) * dl \qquad (1)$$

The condition for the leader inception is that the first corona charge ΔQ exceeds 1µC. Once this condition is fulfilled, an initial leader is triggered with an assumed length of 50mm. The potential at the tip of the leader is calculated as follows:

$$U_{tip} = l^{(i)} + E_\infty + x_0 * E_\infty * \ln\left[\frac{E_{str}}{E_\infty} - \frac{(E_{str}-E_\infty)}{E_\infty} * e^{\frac{-l^i}{x_o}}\right] \qquad (2)$$

$$x_0 = \nu * \Theta \qquad (3)$$

Where E_∞ is the quasi-stationary leader gradient, E_{str} is the streamer gradient and x_0 is a constant that depends on the ascending positive leader speed ν and the leader time constant θ.

A new potential distribution $U_2^{(i)}$ is recalculated considering the potential at the tip of the leader:

$$U_2^{(i)} = U^{(i)} + E_{str} * \left(l - l_L^{(i)}\right) \qquad (4)$$

The increase of the corona charge is calculated as defined in (1) with the new values of $U_2^{(i)}$ and $U_1^{(i)} = U_2^{(i-1)}$.

The calculation process is repeated for each new leader length in an iterative process. If the increase in the corona charge is higher than the charge per unit q_L necessary for thermal transition of the leader channel, the stable leader condition is fulfilled, and the iterative process continues. The simulation ends either when the length of the leader reaches 2m, where it is assumed that there is a stable leader development, or if the length of the leader does not increase, meaning that the leader extinguishes.

Simulation Results

As shown in Table 1, this evaluation considered 10 different thunderstorm cases. Each of these storms was defined with a characteristic cloud height and wind direction. The main wind direction of these storms is north to northwest meaning that wind turbines facing this direction will be exposed first to the electric field of the thunderstorms.

The results of the investigation are illustrated in Figure 5. The highest probability of lightning attachment is 21.4% at the structure placed on the highest elevation. This means that, according to this simulation, 21.4% of all lightning flashes in the wind farm attach to this structure. The second highest absolute probability of lightning attachment are located at the north-western corner of the wind power plant where the attachment probability of the first three wind turbines is spread with 12.5%, 10.7% and 9.7%, respectively. It can be concluded that the majority of lightning flashes will be discharged on these structures. Wind turbines in the south-eastern corner of the wind farm are not likely to be struck by upward lightning because the charge in the cloud is discharged on the wind turbines facing the thunderstorm and hence no cloud potential is available on these turbines.

Validation and Discussion

Comparing the simulation results depicted in Figure 5 with LLS measurements in Figure 1, it can be seen that there is a good agreement between the main cluster region from the measurement and the determined probability through simulation. It should be highlighted that in nature, charge distribution may not be as ideal as simulated and therefore discharge patterns may differ slightly. This can result in lightning attachment that cannot be foreseen with this simulation approach.

Furthermore, it should be noted that LLS data has certain location uncertainties up to several hundred meters. This has been reported in particular for low amplitude upward lightning discharges (Saito & Ishii, 2016).

Before erection of wind power plants, a process called wind turbine micro siting is executed. This process will determine the likely power output of the turbines, how the turbines and turbine blades should be configured depending on the mean wind speed and risk of turbulence, where the individual turbines should be placed to limit wakes and maximize Annual Energy Production (AEP), and basically de-risk the entire business case for the investment.

Modeling approaches like the ones presented in this paper is a valuable input to the *Lightning Micro Siting* conducted before turbine erection. Here the risk of lightning incidences and the distribution of lightning strikes within the wind plant are assessed, and the necessity of spare parts or where to place lightning monitoring systems can be identified.

The risk assessment is in good alignment with the latest IEC 61400-24 Ed2:2019, which also requires OEMs to consider the lightning environment on site and reflect the environment in the turbine design and validation process.

Conclusions

This paper presented a methodology to determine the most affected wind turbines within a wind farm which is exposed to low altitude thunderstorms. The resulting upward lightning discharges and their distribution within the wind farm is a valuable input for wind turbines because they are characterized by a high attachment frequency for the most affected turbines. Furthermore, discharges can lower substantial amount of charge to ground which wears the Lightning Protection System (LPS) of the wind turbine.

The approach can be used for existing or planned wind power plants. The only manual input required is the date and time of historic low altitude thunderstorms. This information can be obtained from meteorological services, LLS data or from historic records.

By determining which turbines in a wind farm are most likely struck by lightning discharges, the wind turbine operator may improve existing lightning protection, adjust maintenance schedules or install lightning measurement devices which supports the maintenance process.

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