International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Lightning Risk Assessment to wind turbines: methodology and guidelines

Victor March
Electrical Unit, Technology Department
Gamesa Innovation & Technology
Pamplona, Spain
vmarch@gamesacorp.com

***Abstract*—The paper deeps into the existing problem in industry for Lightning Risk Assessment on wind turbines. The method is based on current IEC standard but addresses the influence of lightning data quality, terrain influence, winter lightning activity and multiple ground strike terminations for downward and upward lightning. Guidelines and Recommendations for the assessment are deeply described in the paper. A validation of the method is described as well.**

Lightning risk assessment, wind turbines, winter lightning, IEC 61400-24

I. INTRODUCTION

Wind turbines are rotative tall structures erected in multiple environments such as flat terrain, mountain tops or offshore. Because of wind needs, these are always located in open areas with no other tall structures in the surrounding. Moreover, rotor diameter has highly increased during the last years from typically 40 meters up to 180 meters. These particularities make wind turbines to be very exposed to lightning in general (for both downward and upward). Another topic which seems to be very active in lightning exposure is the phenomena known as "winter lightning". This phenomenon has been highly reported in Japan [1] and recently described worldwide in [2].

IEC 61400-24 [3] describes a method to estimate the total number of lightning flashes to wind turbines in a wind farm during a certain time period. However, the information and methodology is based on building standards [4]. The basic equation of the method is:

$$N_D = N_g \cdot A_c \cdot C_d \qquad (1)$$

Where N_g is the ground flash density, A_c the collection area and C_d the environmental factor. Experience using this equation has shown that estimations underestimate the total number of lightning to wind farm turbines [5]. Therefore, for engineering purposes, it is necessary to develop and validate a method to reduce the associated uncertainty of these results. A deep description of this new method based on IEC standard is the objective of this paper. Guidelines and recommendations are given as well as results of method validation.

II. LIGHTNING RISK ASSESSMENT ON WIND FARMS: GAMESA METHOD BACKGROUND

Four years ago, Gamesa developed a method to estimate the total number of lightning strikes to wind turbines of a wind farm during a certain period. The method is based on IEC standard [3], as it defines the fundamentals of the analysis. However, the method described in the standard [3] needed to be reviewed, extended and validated. In this way, equation (1) was reviewed by Gamesa and main formula was updated to:

$$N_D = N_{sg} \cdot N_g \cdot A_c \cdot (C_{dc} + C_{wl} + C_{hasl}) \qquad (2)$$

Where N_D is the estimated total number of lightning flashes to a wind farm during a time period, N_{sg} refers to number of ground strike terminations, and the environmental factor was split into C_{dc} for terrain complexity, C_{wl} for winter lightning and C_{hasl} for the height above sea level.

Thus, the method is based on and close to the one established in IEC standard [3].

III. GUIDELINE TO ESTIMATE TOTAL NUMBER OF LIGHTNING TO WIND FARMS: DESCRIPTION

The total number of lightning to wind turbines in a wind farm can be estimated using (2). Using this equation, the user is able to estimate the total number of lightning without discerning between upward and downward flashes. The four parameters in (2) shall be estimated separately. In this section, for each parameter is described how to obtain and treat them, in order to reduce the uncertainty and errors associated to the different parameters. Additionally, it is also described the influence of the time period for which the analysis is performed.

A. Number of ground-strike terminations (N_{sg})

As it is widely known, a downward lightning flash is composed by multiple strokes. These strokes can attach in different blades or wind turbines. It means that it is possible that a lightning flash has different ground strike terminations. In terms of protection, the same flash is checking the performance of the lightning protection system (LPS) of two different structures or parts of the same structure. And this risk shall also be accounted. In literature, it is found that a factor of 1.6-1.7 could be adopted in order to take into account multiple ground strike points [6]. The author however, considers that in case of wind turbines, this value would be even higher due to the large number of tall structures in the same place.

But as (2) considers both upward and downward flashes, it is necessary to determine the value of this factor for upward lightning as well. Upward lightning can be triggered in winter or in summer involving completely different physical processes. In Japan, where winter lightning is very high and known, it has been found from field analysis a probability of 30% of having more than one upward flash from a wind turbine, involving in some cases more than two wind turbines.

In a similar way, in the US a probability of 46% was found in South Dakota for having multiple upward lightning from 10 telecommunication towers placed in a mountain top [7].

This factor should always be considered when more than one wind turbine is erected in the terrain. As seen, the probability in the different cases is high and cannot be neglected for risk assessment purposes. In the following Figure are described the different situations described above.

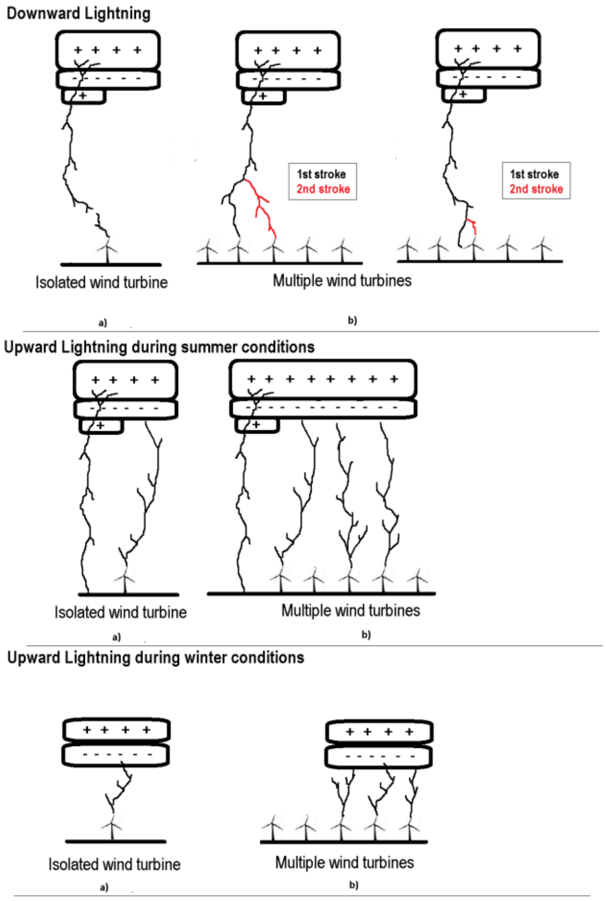

Figure 1. Situations in which multiple ground strike points on a group of wind turbines can occur.

B. Ground flash density(N_g)

Lightning activity in a specified area can be obtained from Lightning Location Systems (LLS). LLS detect the electromagnetic wave radiated from different strokes, and a non-experienced user could think that all lightning strokes and flashes are easily detected. But this is not the case, and usually the "quality" of lightning data differs from lightning data suppliers and location of the wind farm in the LLS Network. As the objective of this paper is to release standard guidelines to the users for an assessment, this paper only faces the basic outputs the user needs in order to manage the data. Therefore, the precision and the output value of the ground flash density is influenced by: Detection Efficiency (DE) of the lightning data in the specific location and the size of the grid used to obtain the ground density.

B.1) Detection Efficiency

DE is a direct measure of the quality of the lightning data in the location of interest. It can be defined as the fraction of strokes or flashes detected by the network from the total events. DE is a function of multiple parameters of the network, for example distance between sensors, location of the area of interest respect to the sensors, alignment of the sensors participating in the detection of an event or number of minimum sensors for detection. The sum of all these and other features can highly influence the performance of the network. So, the user shall determine the DE of the lightning data in the area where the wind farm is erected in order to precisely estimate the flash density to be introduced in (2). In [6] it is described an engineering method to determine the DE of the network in a specific region respect to a reference curve from a region in which DE is expected to be 100%. The author described and tested the method for two different LLS in Catalonia (Spain), and found good agreement with theoretically expected results [8]. For example, and from a qualitative point of view, both LLS presented a lower DE peripheral regions and for the LLS with less number of sensors and shorter baseline, DE highly decreased respect to the central point. Figure 2 represents the basis of the method, with a "test" curve which is to be scaled ("adjusted") respect to the "reference" curve in order to determine DE of the LLS in the "tested" region.

The ground flash density to introduce in (2) shall be corrected applying the engineering method described in [6], and is defined as:

$$N_g = \frac{N_{gLLS}}{DE} \qquad (3)$$

Where N_{gLLS} is the flash density measured from LLS data and DE the fraction of the detection efficiency.

This kind of correction is always needed and even more important in case that the user wants to use the output data to determine lightning activity in a wind farm. It is necessary to perform this analysis to have a realistic estimation of the quality of the network in the location of the wind farm.

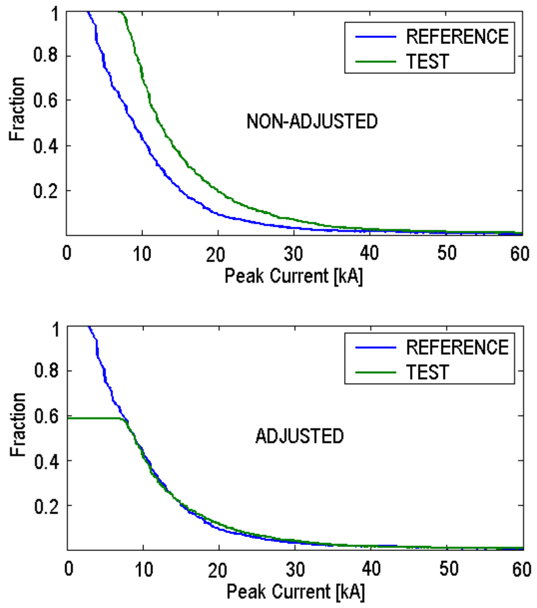

Figure 2. Representation of DE correction method with non-adjusted curve (top) and adjusted curve (bottom), resulting in a fraction of 0.59 (DE=59%).

An analysis of the lightning data close to the wind farms was performed by the author in [5]. Figure 3 depicts the percentage of negative peak current flashes (not all strokes!) close to 700 meters from 18 wind farms in the north of Spain. As seen, the percentage of peak current of flashes lower (in amplitude) than 7 kA ranges from 35% to 66%, while in case of 10 kA ranges from 55% to 85%. It means that in case that t the LLS would not be able to detect less than 7kA, we would be missing 35 to 66% of the lightning events. In US, Warner [7] reported that NLDN was not able to detect 66% of the total upward lightning flashes from 10 telecommunication towers as the threshold value was -7.1 kA. This is in agreement with the results in Figure 3.

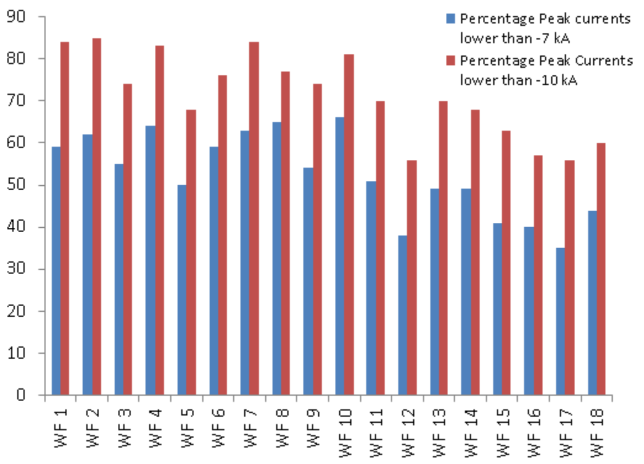

Figure 3. Percentage of negative peak currents for flashes with absolute values lower than 7 kA (blue bars) and 10 kA (red bars) close to 700 m from the wind turbines for 18 wind farms analyzed in [5].

From the above figure it can be extracted a very important conclusion regarding the detection of lightning flashes in wind turbines: statistical parameters for flashes detected close to wind turbines are closer to sub-sequent strokes and to upward flashes [6]. It means that DE for strokes would be more precise than DE for flashes when checking the quality of LLS to detect lightning events in a wind farm. In other words, user should use stroke DE instead of flash DE to compensate the number of detected flashes close to a wind farm with methodology described in Figure 2. As modern commercial LLS are designed to detect downward flashes, detection of upward events and local "hot spots" close to wind turbines is not expected in general for commercial LLS. A method to compensate DE can be found in [6] and field examples of this method for two operational LLS can be found in [8].

B.2) Grid size

The size of the grid has an influence in the obtained ground flash density in the site. The standard does not fix a size of the grid to obtain the ground flash density. In [5] the author obtained for 10 wind farms and 5 different time periods (a total of 50 cases), the percentage difference of the ground flash density for mesh sizes of 10x10, 20x20 and 30x30 km respect to a reference case of 5x5 km. Figure 4 shows the average percentage difference (blue points) and the standard deviations as a function of the different grid size. Thus, any methodology must take into account the variation of the N_g for different grid sizes.

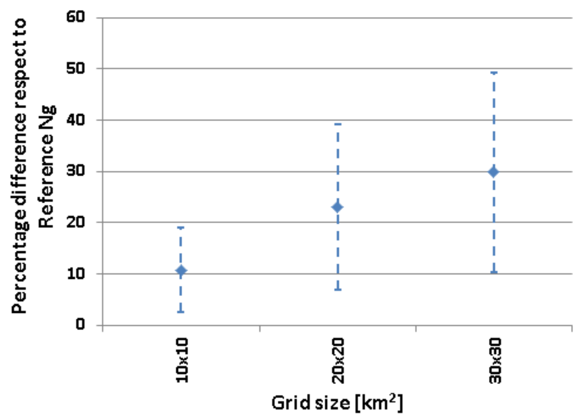

Figure 4. Average percentage difference of N_g value as a function of the grid size respect to reference grid of 5x5 km.

C. *Collection area (A_c)*

Collection area is defined in IEC standard [3] as a circumference with a radius being three times the height of the wind turbine [3]. This parameter has been adapted to wind turbines from buildings standard [4]. In case of single wind turbine this is defined as a circle with a radius being three times the height of the structure. However, wind farms are composed by multiple wind turbines in which the collection areas of these usually overlap. IEC standard [3] establishes that in such cases, the collection area should be the resulting from the total 1:3 slope intersections. This situation is depicted in next Figure 5:

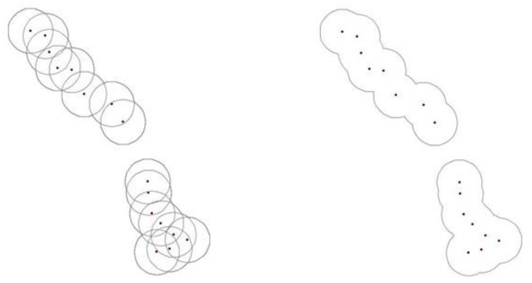

Figure 5. Collection area of a wind farm without overlapping and with overlapping (black points represent wind turbines).

The simplest way to obtain the total collection area is representing the wind turbines to be placed in the same ground plane and with its own height (as different turbine models may be found in the same wind farm). An easy algorithm can be developed to calculate the total collection area as represented in the right side of Figure 5.

Of course, the user could adopt the proposal in [3], in which the collection area could be obtained from the projection on the terrain of the 1:3 slope from wind turbine tip. An example of the problems related using this method can be found in [9].

D. *Environmental factor(C_d)*

Environmental factor is probably the most difficult parameter to estimate and to understand in this kind of assessments. This factor collects all the influences from the environment. However, these influences vary widely from different sites and are also submitted to yearly variations. For example location of wind farm is fix and does not vary throughout years but the degree of winter lightning can highly change in two consecutive years.

According to IEC standard [3], the environmental factor shall consider:

- Influence of the terrain, being C_d=1 for flat and C_d=2 for mountainous terrain.
- Wind turbines placed at location known to be very exposed to lightning in general and to winter lightning in particular may be assigned a higher environmental factor to consider upward lightning being triggered under such conditions.
- Wind turbines placed off shore may have to be assigned an environmental factor of 3 to 5 to get a realistic estimate.

These are the three rules the IEC standard [3] gives to the user. But these rules are confusing the user, as for example it makes no sense that offshore wind farms have from 3 to 5 times higher exposure than an onshore wind farm in flat terrain. And also, that all mountainous terrains have the same shape and same effect to lightning activity to a wind farm. From these assumptions, Gamesa decided to divide the environmental factor in three different sub-factors to consider all environmental effects:

- Complexity of local terrain
- Height above sea level
- Winter lightning activity

The first term, considers the shape and height of the location where the wind farm is erected. The degree of complexity of a mountain or hill must be quantified. As known from research in instrumented towers and in lightning research in general, the shape of the mountain has a high influence in the local electric fields ("sharp effect"). In this way the proposed approach is to measure the terrain slope at the vicinity of the wind farm and use tabulated values for its quantification.

Figure 6 shows an example of a wind farm composed by 8 wind turbines. As seen, front and side views lead to different slopes h1/d1 and h2/d2. This slope is related with this sub-factor, which could be understood as local "sharp effect" of the terrain. There are multiple ways to quantify C_{dc}, as usually each wind turbine is submitted to different slopes, which is related to the local electric field each wind turbine experiences.

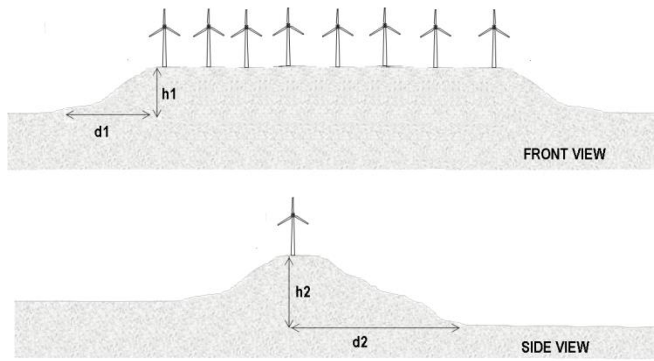

Figure 6. Terrain complexity by means of terrain slopes of the wind farm.

The second sub-factor is the height above sea level. Again the height of the terrain has an influence in the local activity on the wind farm. In Brixton tower (South Africa) [10], multiple upward events have been reported in summer conditions triggered by nearby IC or CG flashes. The tower is placed on flat terrain but at a height of 1780 meters above sea level. The height above sea level of a wind farm can also be tabulated to determine its influence.

Finally, many years ago winter lightning was identified in Japan as one of the major causes of increase in lightning activity in the west coast [1]. In recent years, winter lightning signatures have been identified in different locations such as the north of Spain [11]. A global distribution of winter lightning has been recently released in [2]. For example, the east of US and Mediterranean Sea have been identified as areas with winter lightning activity. Users are referred to [2] to determine the existence of winter lightning close to a wind farm. However, it is a very difficult task to quantify the activity of winter lightning in places where there is not a high performance LLS. LLS have been designed to detect downward lightning. Upward lightning triggered under winter lightning activity have very low peak current values, and are thus difficult to detect. For example, the Author reported winter lightning activity in North of Spain using data from Linet LLS [12]. Four evidences of winter lightning were identified close to the wind turbine:

- High percentage of events close to tall structures occurring during winter season, from October to March in the North hemisphere (Figure 7).
- Statistical parameters of detected negative peak currents close to tall structures similar as direct measurements on tall structures.
- "Hot spots" identified plotting events on a map.
- Multiplicity of lightning events in short time periods without any activity in the surroundings. In this way, 9 flashes were recorded in less than two hours [11].

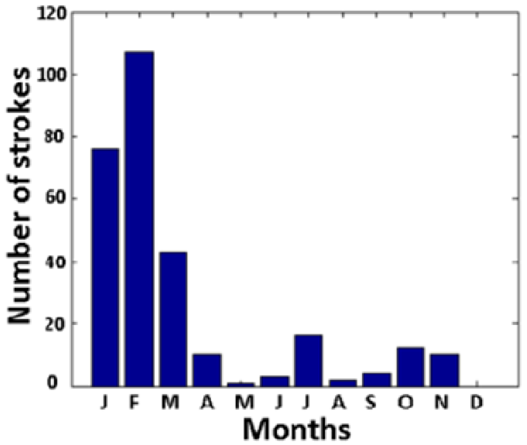

Figure 7. Number of CG strokes detected during the period 2006-2013 located less than 500 m from the wind turbine.

It is also important to remark that the first two sub-factors are constants for a given wind farm. However, winter lightning activity it is not constant in two consecutive years. For example, the Author reported an increase of 4 times of lightning flashes to a wind turbine during one year with high winter lightning activity respect the previous year with few winter lightning activity [11].

E. Time period

The duration of the analyzed period also has an influence on the expected results. Time period is not included in (2) but it has an influence on the results and for this reason its influence must be described.

Estimations of lightning activity in wind farms can be used for different purposes in different times of a project. For example, in preliminary project phases, an engineer can use these predictions to determine the expected lightning activity the wind farm may have. With other purposes, these predictions can be used to determine the lightning activity an operational wind farm has. In all these predictions, there are two basic concepts the user may have in mind:

- Complete years will lead to more realistic estimations
- Long-time predictions will be more accurate than short-time predictions.

Complete years are preferred because in those cases, the effect of seasonal particularities is avoided. For example, in case that wind farm is submitted to winter lightning, the activity during those months may be much higher than during other seasons. As a minimum, it is recommended a minimum time period of one year.

On the other hand, time duration of the analysis also impacts the precision of the prediction. In [5] an analysis of the impact for cumulative years seems to benefit when degree of winter lightning is reduced. Winter lightning may be a big inconvenient when trying to estimate activity in short periods.

IV. GUIDELINE TO ESTIMATE TOTAL NUMBER OF LIGHTNING TO WIND FARMS: SUMMARY

From previous section, a summary of the guideline and recommendations can be extracted:

- Ground flash density:
    - Use lightning data from a known and analyzed LLS. Determine DE and use "stroke DE" instead of "flash DE" due to big percentage of low peak current events.
    - Select and use a constant grid size.
- Collection area: use method described in Figure 5 considering overlapping and neglecting terrain complexity.
- Environmental factor: divide environmental factor in three sub-factors:
    - Terrain complexity (C_{dc}): Value shall be a function of terrain slope close to the wind turbines (Figure 6).
    - Height above sea level (C_{hasl}): Value as a function of the height above sea level of the wind farm.
    - Winter lightning (C_{wl}): Value shall be a function of the winter lightning activity in the area. Use

- Time period: use complete years, minimum 1 year. High winter lightning activity may affect predictions.

V. METHOD VALIDATION

Any methodology adapted from the IEC standard or own developed by any engineering team or company must be validated in order to check the precision of the predictions. However; it is very complicate to validate any method because the high percentages of low peak current events, continuous currents from upward lightning and multiple ground terminations. As said before, commercial LLS and even more scientific LLS such as LMA are not able to detect all lightning flashes to a wind farm. And any method needs to be developed and validated in different environments and wind farm characteristics.

Validation of the method developed by Gamesa based on IEC standard [3] was performed in [5]. This validation was done using 18 wind farms located in the north of Spain, using 4 years data from Linet LLS. Linet was chosen in this region, as this LLS demonstrated its ability in detecting low peak current upward lightning events recorded in this area in a monitored wind turbine [11]. In order to compensate the non-detected lightning events or multiple ground terminations, some hypothesis were performed based on existing field data from other researchers.

So, 90 cases (18 wind turbines with 5 time periods) were analyzed. The number of wind turbines in wind farms ranged from 15 to 142. The results showed that there was a possible influence of the winter lightning activity in the average errors. For this reason, Table I shows the percentiles of the average errors in four different cases: all data, cases with low WL activity, cases with medium WL activity and cases with high WL activity. For example, for cases with low WL activity in 52.9% and 73.6% of the cases the error is lower than 20% and 30% respectively, while for the cases with medium and high WL activity average errors increase.

TABLE I. PERCENTILES OF AVERAGE ERRORS DURING METHOD VALIDATION IN DIFFERENT CONDITIONS

Percentiles of average Errors	**Percentage of cases [%]**			
	All 90 cases	***Single year Low WL (34 cases)***	***Single year Medium WL (27 cases)***	***Single year High WL (11 cases)***
P_{10}	20	26.5	18.5	9.1
P_{20}	40	52.9	37	18.2
P_{30}	60	73.6	59.2	18.2
P_{40}	71	82.3	70.4	36.4
P_{50}	80	85.3	81.5	54.5

In the same way as Table I, and in order to determine positive and negative deviation of the predictions, Table II presents for the same cases described in Table I, the probability of positive and negative deviation higher than 20% and 30%. As seen from the results, the method shows good correlation for the total 90 cases and only for high WL the method seems to highly underestimate the total number of lightning. This happens in cases where there is a combination of high WL with high terrain complexity.

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TABLE II. PROBABILITY OF UNDERESTIMATING AND OVERESTIMATING MORE THAN 20% THE PREDICTED RESULTS

Percentiles of percentage errors	**Percentage of cases [%]**			
	All 90 cases	***Single year Low WL (34 cases)***	***Single year Medium WL (27 cases)***	***Single year High WL (11 cases)***
$P_{OVERESTIMATE\ >30\%}$	16.6	23.5	18.5	18.2
$P_{OVERESTIMATE\ >20\%}$	22.2	35.3	18.5	18.2
$P_{UNDERESTIMATE\ >20\%}$	25.5	11.7	37.0	63.6
$P_{UNDERESTIMATE\ >30\%}$	15.5	2.9	10.8	63.6

VI. DISCUSSION

The paper has described a method to estimate the total number of lightning flashes to a wind farm during a certain time period. As known from previous experience, this is not an easy task and there is a lot of controversy in the industry on how to perform those estimations and the associated uncertainties of any methodology. In previous paper [5], the Author found that using current IEC standard [3] the results are non-acceptable as the errors are really high (only 1% of the analyzed predictions in [5] have errors less than 20%).

The method described here is a result of a deep revision of the method described in the standard. From this revision it was found the need of compensating LLS DE or splitting environmental factor in three sub-factors. The reader may observe that the three sub-factors are not tabulated in the paper. This is because in any attempt to quantify the method, environmental factor values are influenced by: a) the method to compensate DE (the reference curve, and use of stroke or flash DE) and the grid size. Therefore, the flowchart to determine the values of the environmental factors is composed by two steps as shown in Figure 8. In the first step it is necessary to adjust lightning data from LLS to a certain number of wind farms. Once lightning data is adjusted, it is possible to perform an algorithm to determine tabulated values for the environmental factors. Of course, in this process the number of wind farms and time period for lightning data and properties of the wind farm has a high influence in the final tabulated values. For example, for the same wind farm and different time periods with different winter lightning percentages can be used to adjust winter lightning sub-factor.

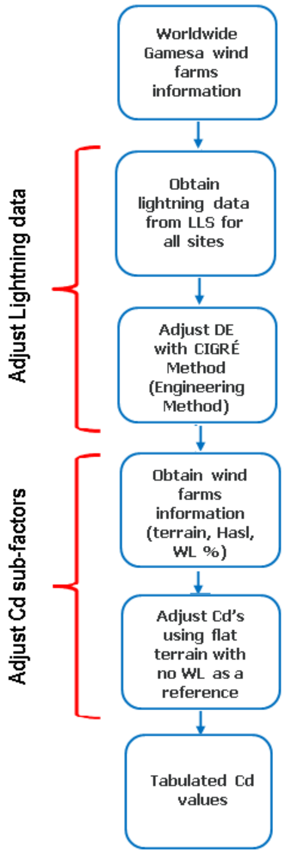

Figure 8. Flowchart to determine tabulaed values for the environmental factors.

Validation of the method shall be performed using cases that have not been used for Cd tabulation. In the case of the present Method, this was done using 90 cases, with different terrain conditions (flat or mountainous) and for 4 years in which winter lightning activity in wind farms highly varied. As released in the paper, in case of low or non-existent winter lightning activity in the wind farm the method predicts the 73.6% of the cases with an error less than 30%, while with high winter lightning the error increases and it is mainly due to an underestimation in the total number of lightning (the probability of underestimating with error higher than 30% is 63.6%). The method showed some disagreement in extreme winter lightning cases together with high terrain complexity. In those cases the method is highly underestimating the total number of lightning flashes to a wind farm.

VII. ANNEX – PERCENTAGE OF UPWARD LIGHTNING

One of the aspects which has an influence on the risk assessment concerning to tall structures such as wind turbines is the total number of upward lightning, or in other words applied to this method, the percentage of upward lightning from the method described in this paper. Using LLS data is not possible to discern between downward and upward lightning. However, with this approach, it is possible to determine a range of upward lightning from the total number of flashes to the wind farm (referred as N_D). Investigations on tall structures in places where winter lightning is not observed has resulted in equations such as the one from Eriksson which applied to typical wind turbines height of 100 to 150 meters lead to upward lightning percentage ranging from 13% to 34% [9]. This could be the percentage of upward lightning in wind farms placed in flat terrain and with no winter lightning and low height above sea level. Data presented in [5] supports this percentage. However, when winter lightning activity increases, several reports in Japanese west coast in flat terrain indicate that the percentage of winter lightning can reach to values close to 95-100%.

There are factors such as the degree of winter lightning, height above sea level and complexity of terrain that will increase this percentage of upward lightning. Additionally, with the presence of multiple wind turbines in the same area, there is also a high probability of having more than one upward lightning from two different wind turbines. In this methodology, the increase of upward lightning is related with an increase of the total environmental factor. As a general rule, the higher the total C_d the higher the percentage of upward lightning is. It is important to remark that even very accurate systems installed in blades may not be able to detect a large percentage of upward lightning. As an example, Figure 9 shows a detection which has not been detected by the LLS analyzed in [11], which demonstrated to be accurate in detecting upward events. For this case, in which we monitor 3 wind turbines, approximately 20-30% of the events have not been detected by the LLS.

Figure 9. Upward lightning from the tip of the central wind turbine analyzed by Author [11]. The flash was not detected by LLSwhich has a peak threshold of 2.3 kA.

From the analysis of the terrain together with the winter lightning activity, the following table could be adopted for the percentage of upward lightning in any site.

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TABLE III. PROBABILITY OF UPWARD LIGHTNING BASED ON RELATIONSHIP WITH ENVIRONMENTAL FACTOR

Percentiles of percentage errors	**Percentage of upward lightning [%]**		
	No winter lightning	***Moderate winter lightning***	***Extreme winter lightning***
Flat terrain	15-40%	40-80%	>80%
Moderate hill	20-45%	45-80%	>80%
Mountainous terrain	25-50%	50-90%	>90%
High height above sea level	20-45%	45-80%	>80%

These values have been widely ranged, as the purpose is only to give a qualitative idea of the percentage of upward for generic conditions. Each mountain, winter lightning degree and own local conditions differ from site to site. However, the values released in this Table III can be used for lightning protection system engineers in order to take decisions relating to the protection of the wind turbines in specific wind farms. For example, for an engineer it is not important to determine if upward percentage is 40% or 60%, but it is highly important to determine whether the upward percentage is 20% or 90%, as the design, performance and maintenance of lightning protection system may be affected by high differences in this percentage. In the same way, the method presented in this paper is important to estimate if the risk is 1 or 5, not if it is 3.2 or 3.5 in imaginary levels.

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