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Lightning Attachment Estimation to Wind Turbines by Utilizing Lightning Location Systems

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***Abstract*— The goal of a lightning exposure assessment is to identify the number, type and characteristics of lightning discharges to a certain structure. There are various Lightning Location System (LLS) technologies available, each of them are characterized by individual performance characteristics. In this work, these technologies are reviewed and evaluated in order to obtain an estimation of which technologies are eligible to perform a lightning assessment to wind turbines. The results indicate that ground-based mid-range low frequency (LF) LLS systems are most qualified since they combine a wide coverage with a good accuracy for downward lightning. Furthermore, advances in the technology indicate the detection of certain upward lightning events. A correlation between the size of the uncertainty ellipse and the peak current of the lightning detections is presented. Furthermore, lightning data from three different wind power plant locations are analyzed and the impact of varying data qualities is evaluated regarding the ability to detect upward lightning. This work provides a variety of background information which is relevant to the exposure assessment of wind turbine and includes practical examples regarding different LLS data qualities.**

Keywords—Wind Turbine, Lightning Location System, LLS, Upward Lightning, Downward Lightning, Exposure Assessment

I. Introduction

In this paper, the purpose of a lightning exposure assessment is to determine the characteristic properties of lightning which may affect the condition of the wind turbine during the lifetime. The information obtained is used to improve the Lightning Protection System (LPS) of the wind turbine or to calculate risk of economic or human loss. Ideally, measured current parameters in wind turbines or instrumented towers provide the most reliable information about a lightning environment. However, since direct measurements are expensive and allow only the evaluation of a specific location, the exposure assessment of wind turbines is usually conducted with Lightning Location System (LLS). A wide variety of such systems exist in the market. The performance of each system depends on the used technology and the type of discharge. The result of an exposure assessment of wind turbines with different LLS technologies can therefore vary vastly and wrong conclusions can be made if the limitations of the technology are unknown to the user. Various lightning density maps are available which indicate flash densities for certain areas of the world, however, these maps show only the events a particular technology has identified.

In this paper, the newest findings regarding the lightning exposure of wind turbines in respect to the type and current properties of the discharge are revised. Different types of LLS are reviewed and their applicability to an exposure assessment to wind turbines is evaluated. Special attention is attributed to upward lightning, which has an increasing ratio in the overall exposure on wind turbines, and emits only low Lightning Electromagnetic Pulses (LEMP). The consequences of the limited applicability of LLS data are applied to the exposure assessment defined in IEC 61400-24:2010 Ed. 1.0 – Wind turbines – Part 24: Lightning protection [*IEC 61400-24*, 2010]. Since the performance characteristics of LLS may vary with the investigated location, the impact of increasing uncertainty ellipses to the peak current distribution is investigated, and finally, conclusive statements are made in order to define which technology is suitable for exposure assessments of wind turbines

II. Exposure of Wind Turbines

As the first step of the evaluation, the concept of lightning exposure of wind turbines shall be reviewed. Wind turbines are exposed to both downward and upward lightning. Observations show that the ratio of appearance of these two types may vary drastically depending on the wind farm location. The background processes for the initiation of upward lightning are still considered as ongoing research, however, a classification of other-triggered and self-triggered lightning discharges is frequently used [*Diendorfer*, 2015]. Four factors are observed to affect the ratio of downward and upward lightning experienced by a wind turbine. First, the height of the structure has an impact, where taller objects are more frequently exposed to upward lightning [*Eriksson*, 1987]. Second, the topography of the wind power plant and its environment, where elevated terrain such as mountain ridges promote the appearance of upward lightning [*Rizk*, 1994][*Garolera et al.*, 2015]. Third, the meteorological conditions and local effects, as seen at the west coast of Japan [*Kitagawa and Michimoto*, 1994][*Fujii et al.*, 2013] [*Zhou et al.*, 2014] [*Ishii*, 2015]. These three factors refer to an increase of electric field at ground level due to either elevated objects on ground or low cloud base height which contains sufficient charge. These factors enable the formation of an upward leader from ground before the initiation of the downward lightning process is possible. The fourth factor relates to the local ground flash density which may, together with the characteristics of the structure, be responsible for upward lightning triggered by nearby cloud-to-ground (GC) or intra-cloud (IC) activity [*Warner et al.*, 2012].

In this work, the classification of upward lightning according to current waveforms characteristics are adapted from the work of Diendorfer et al. [2009] who divided upward lightning into three types: initial continuous current without pulses or return strokes ICC_{Only}, initial continuous currents and pulses ICC_P, and initial continuous currents with a return stroke ICC_{RS}.

The characteristic current waveforms of the downward and upward lightning are substantially different. This has also a distinct impact on the resulting failure modes of wind turbine LPS. A summary of reported lightning current parameters can be found in [*Cigre Wg C4.407*, 2013].

Downward lightning consist of 1st return stroke, eventually subsequent return strokes and/or continuous currents. They are characterized by a peak current I, charge Q, action integral W/R, flash duration T, and the average steepness of the current di/dt, which are defined as the five lightning threat parameters of a LPS [*IEC 62305-1*, 2013]. These parameters may cause damage to the wind turbine due to several factors such as: erosion at the attachment point, ohmic heating, mechanical effects, a combination of physical effects (thermal, mechanical, arcing) and indirect effects to electrical components.

Upward lightning, on the other hand, consists of initial continuous current which may or may not be superimposed by pulses, and a possible return stroke which is reported to have similar properties to subsequent return strokes from downward lightning [*Diendorfer et al.*, 2009]. The main threat parameters of upward lightning are characterized by charge Q, average steepness of the current di/dt, and duration T. Very high action integrals W/R>10 MJ/Ohm were only reported in 0.3 % of all cases measured in the extensive research on upward lightning performed within the Japanese NEDO project [*Ishii et al.*, 2013]. Furthermore, peak currents above 50 kA are only observed in 0.7 % of all cases. As a result of the possibly high charge content of the initial continuous current, the main failure modes due to upward lightning for wind turbine with modern lightning protection according to [*IEC 61400-24*, 2010] are melted tip receptors and possibly indirect effects due to fast subsequent return strokes. This limits the immediate threat of upward lightning to wind turbines which may be controlled to a certain extent by introducing regular maintenance intervals to check for degradation of arc entry points and the integrity of the LPS.

III. LLS DATA FOR THE EVLAUALTION OF RISK TO WIND TURBIENS

The technology for geo-location of lightning can be divided into two major categories: ground-based and satellite based LLS. Ground-based LLS are divided into time-of-arrival (TOA), direction finding (MDF), or a combination of both technologies. Satellite-based LLS utilize optical imaging to locate lightning. The performance characteristics for the networks are usually defined with Detection Efficiency (DE), Location Accuracy (LA), polarity and peak current estimation accuracy, and lightning type classification accuracy. A thorough review of the technologies was performed by *Cummins et al.* [2009]. When evaluating the risk of a wind turbine to be struck by lightning, ground-based LLS technology should always be preferred compared to satellite-based LLS. Reasons against satellite-based LLS are general inferior performance characteristics, the inability to differentiate between GC and IC lightning, and the limited spatial and temporal resolution. The DE of a low-earth orbiting satellite varies from 38% to 88% percent, depending on the instrument and time of day. LA ranges from ten to several tens of kilometers which is not sufficient to correlate a distinct lightning event to a wind turbine site [*Nag et al.*, 2015]. For this reason, this evaluation of the usability of LLS data for lightning exposure of wind turbines is focused on ground-based LLS. Since the ability of ground-based LLS to detect and allocate downward lightning is substantially different from upward lightning, the topic is divided into two parts which address first the downward lightning and then the upward lightning.

A. Performance characteristic of ground-based LLS for downward lightning

Ground-based LLS are divided by the frequency ranges in which they are able to detect the radiated lightning electromagnetic pulses (LEMP). They can be classified into long-range, medium-range, short-range, and very short range systems. A comprehensive state of the art summary about the LLS technologies with performance indicators can be found in the work of *Nag et al.* [2015]. From his work, the performance characteristics from different ground-based LLS are listed by different frequency bands in Table 1. Three main observations can be made when evaluating the usability of different LLS technologies:

- With increased frequency band, the DE and LA is increased
- With increasing frequency band, the necessary sensor baseline is decreased
- With increasing frequency band, the CG stroke peak current error decreases

1) Long range LLS

The DE of long range LLS like the World Wide Lightning Network (WWLN) is strongly depended on peak current and polarity. Current amplitudes bigger than ±35 kA are detected in 10% of the events. Current amplitudes in between 0 and -10 kA are detected in 2% of the events [*Abarca et al.*, 2010]. These performance characteristics indicate that the data from these networks are too inaccurate to perform risk assessment for wind turbines. They provide global information of high peak current amplitudes events.

2) Medium range LLS

Medium range LLS, which normally operate in a LF frequency band (approx. f= 1 – 350 kHz), are the best choice to evaluate the lightning incidences to wind turbines. They cover a big part of the frequency spectrum of lightning which is not biased by propagation effects. Low frequency electromagnetic signals (<100kHz) are able to propagate over conductive ground without major losses of amplitude. The high frequency components (>100kHz) in a lightning current waveform are subjected to propagation effects due to soil conductivity. The radiated amplitudes of those waveforms loose power while propagating over soil with finite conductivity. This effect is important for users which are particularly interested in fast subsequent strokes. Globally, there are over 60 VLF-LF LLS networks operating which provide commercial lightning detection data. Examples of major networks are the National Lightning Detection Network (NLDN) covering North America, the European Cooperation for Lightning Detection (EUCLID) and LINET covering Europe, the Japan Lightning Detection Network (JLDN) covering Japan, the Brasilian National Network (BrasilDat) covering Brasil, the Canadian Lightning Detection Network (CLDN), and the South African national network [*Cummins et al.*, 2009]. It needs to be highlighted that performance characteristics of such networks can vary vastly, especially for small peak current amplitudes. According to *Betz* [2009], the five most important parameters that influence DE are:

- Sensor baseline and network geometry
- Sensor sensitivity, noise handling, thresholds, and dead time
- Signal treatment and discrimination
- Procedures for correlation of signals belonging to on and the same stroke
- Numerical location software

State of the art commercial ground-based mid-range LLS are able to detect peak currents > 20 kA of downward lightning very reliably within their interior boundaries. LA varies between 100m and 1000m where lower peak currents are usually associated with higher location uncertainties. Depending on the network properties, also current magnitudes lower than 10 kA are detected. Looking at the peak current distribution from Section V, however, it becomes apparent that the majority of detected lightning discharges are below 20 kA and often below 10 kA. Therefore, it is crucial to verify the mean LA and DE of the network at location (x,y) with the LLS data provider in order to quantify the exposure of lightning strikes to wind turbines. Subsequent strokes are characterized by 5 – 10% lower DE and LA compared to the first return strokes, due to lower mean current amplitudes and higher impulse frequencies which increases attenuation of LEMP due to propagation effects [*Cooray et al.*, 2000]. The lowest possible first return stroke peak current amplitude which can occur in nature was previously determined to be within a range of 1.5 - 3 kA [*Cooray and Rakov*, 2012].

TABLE 1: CHARACTERISTICS AND PERFORMANCE OF DIFFERENT GROUND-BASED LLS FOR CLOUD-TO-GROUND LIGHTNING(FROM [*Nag et al.*, 2015], [*Cummins et al.*, 2009])

			Detection Efficiency				
Range	Frequency Band	Sensor Baseline	CG Stroke	CG Flash	IC Flash	Median Location Accuracy	CG Stroke Peak current estimation error
Long range	VLF (1 – 12 kHz)	Several thousend kilometers	3 – 40 %	10 – 70 %	< 10 %	2 km to more than 10 km	25 – 30 %
Medium range	ELF-HF (3Hz – 3 MHz)	150 – 400 km	70 – 90 %	85 % to greater than 95 %	About 50 %	About 100 m to less than 1 km	15 – 20%
Short range	ELF-HF (3Hz – 3 MHz)	50 – 75 km	Greater than 90 %	Greater than 95 %	About 75 %*	About 100 m to few hundred meters	15 – 20%
Very short Range	VHF mapping (30MHz – 300 MHz)	10 – 40 km for TOA, 150 km or less for interferometry	Total flash DE greater than 95 %			Several tens to few hundred meters	N/A

CG=Cloud-to-ground,TOA=Time of arrival, DE=detection efficiency, N/A=Information not available, ELF=extreme low frequency, VLF=very low frequency, LF=low frequency, HF=high frequency, VHF= Very high frequency

* =Estimated performance characteristics derived from the characteristics of sensor, associated instruments, and algorithms

3) *Short range and very short range LLS*

For the purpose of defining the risk of lightning to a wind turbine, of course, the high DE, the low LA, and a low stroke peak current estimation error are advantages. Therefore, short range and very short range LLS data may be optimal to investigate a location. Unfortunately, these systems have a short sensor baseline and do not cover large areas. They are used to study the individual breakdown process of virgin air and provide lightning information for research purposes for designated locations [*Rison et al.*, 2015]. Furthermore, due to their high operating frequency range, large amount of data are collected for each lightning discharge which makes the data processing tedious. HF and VHF LLS need to be located within a short distance to the observed object due to the propagation effects of the LEMP.

B. *Performance characteristic of ground-based LLS for upward lightning*

In this section, recent research regarding the ability of mid-range LLS to detect upward lightning is stated. Recently, few publications evaluate the performance of VLF-LF LSS to detect upward lightning. In the work of *Diendorfer et al.* [2015a], the author stated a local DE of 42% to detect upward lightning which was derived from 713 upward lightning events measured in the Gaisberg tower in a time period from 2000-2013. This low percentage is a result of the low efficiency of LLS to detect the most common characteristic upward lightning current waveform which is ICC_{Only}. Out of 713 upward lightning events, 338 were of the type ICC_{Only} which is 47%. The probability of an LLS to detect upward lightning ICC_P and ICC_{Rs}, are 58% and 96%, respectively. The author does not provide information about LA of detected upward lightning events. A similar study was performed for the Säntis Tower in Switzerland by Azadifar et al. [2015] where an overall DE to detect upward lightning is stated to be 97%. However, ICC_{Only} events were removed from the scope of the study which limits the usability of the evaluation in respect to the lightning exposure of wind turbines. The publication included an analysis of LA for upward lightning events. The author reported a strong correlation of larger location errors for peak currents below 10kA, which most of them are associated with ICC_P waveforms. On the other hand, the current rise time does not influence the LA with a clear tendency; however, current rise times larger than 8us are reported to be detected by the network in only 3% of the cases. Furthermore, the LA decreases with an increased number of reporting electromagnetic sensors. Both studies mentioned previously use the EUCLID network in the alp region for performance evaluation which consists of about 150 lightning detection sensors. Other parts of Europe which are also covered by EUCLID may vary in performance characteristics due to different sensor technologies [*Poelman et al.*, 2014], varying sensor baselines, and the geographic region being considered [*Nag et al.*, 2015]. Another commercial European lightning detection networks is the LINET system which is comprised out of 130 crossed-loop antennas which measure variation in the magnetic flux due to lightning [*Betz*, 2014]. The network has a capability to detect lightning events with currents well below 5 kA within the central part of the network according to [*Betz et al.*, 2009]. *March* [2015] documented the process of data quality improvements due to an increase of nearby sensors close to two wind power sites in Spain. Throughout the observation period from 2006-2013, the stepwise increase in the amount of nearby LINET sensors showed improvements of DE and LA for the LLS. Furthermore, lower peak-current magnitudes were able to be detected after more sensors were installed. The median, mean, and first percentile peak current magnitude around the wind turbines after the sensor update in 2010 as detected with LINET data were ranging from: 5.9 – 7.8 kA, 6.1 – 10.2 kA, and 2.2 – 2.4 kA, respectively. These values were recorded in the years 2010-2013. For comparison, in 2006, before additional sensors were installed in the area, the median, mean, and first percentile peak current magnitude was: 15.9 kA, 19.2 kA, and 9.5 kA, respectively. This study highlights the importance of low baselines between sensors in LLS in order to detect low peak current amplitudes. A comparison between measurements conducted with Rogowski coils in 16 wind turbines in Japan and LLS data from the JLDN revealed DE of 18 % for lightning currents with less than 100C and 23% for lightning currents above 100C [*Saito et al.*, 2012]. The performance of the NLDN in respect to upward triggered lightning was investigated in [*Warner et al.*, 2012] during a time period from 2004-2010. Time-stamped optical sensors of ten tall towers revealed that due to nearby lightning activity observed by the NLDN, upward lightning was triggered in 83% of the cases. The analysis further showed that 44% of the upward flashes were reported by the NLDN as subsequent negative CG strokes or IC events.

The following observations can be made regarding the DE of upward lightning by ground based VLF-LF LLS.

- ICC_{Only} events are not detected due to their very low frequency electromagnetic fields and their weak peak current amplitude. According to measurements performed by Diendorfer et al. [2015b], 47% of all upward initiated lightning's are of type ICC_{Only}.
- ICC_P events are detected in 58% of all cases. A high amount of reporting sensors, a high peak amplitude, and low rise times promote the DE and LA for this type of upward lightning. 21% of the lightning strikes measured in *Diendorfer et al.* [2015b] were of type ICC_P .
- ICC_{RS} events feature similar characteristics like subsequent return strokes in natural downward lightning and the DE is reported to be above 95%. 32% of the lightning strikes in *Diendorfer et al*. [2015b] are of type ICC_{RS}. LA follows similar patterns like ICC_P.
- *March* [2015] reported direct improvements of DE and LA for upward lightning by LSS by reducing the sensor baseline in the network.

IV. IMPLICATIONS OF VARYING LLS DATA QUALITY ON LIGHTNING EXPOSURE ASSESSMENT ACCORDING TO IEC 61400-24

A procedure for the lightning exposure assessment for wind turbines is defined in IEC 61400-24:2010 Ed. 1.0 – Wind turbines – Part 24: Lightning protection [*IEC 61400-24*, 2010]. In this international standard, the average number of dangerous events to the wind turbine N_d is assessed through the annual average ground flash density N_g of the environment, a so called "collection area" A_d around the structure which has the same annual frequency of lightning ground flashes as the wind turbine and is approximated as a function of the total height h of the turbine, and an environmental factor c_d which may be adapted to the environmental conditions of the wind farm.

$$N_d = N_g A_d c_d \qquad (1)$$

Following observation can be made from this definition regarding the average number of dangerous events to the wind turbine N_d derived with LLS data:

- LLS data needs to be grouped into flashes in order to get the flash density N_g. A stroke is added to a flash event if the occurrence is less than or equal to 1 s after the first return stroke, the stroke location is less than or equal to 10 km from the first return stroke, and the time interval of the previous stroke is less than 500 ms [*Bouquegneau*, 2014].
- Only first return-strokes are accounted for. Subsequent strokes or other-triggered upward lightning events which may start from the turbines following the first return stroke are excluded.
- On the other hand, a fraction of self-triggered upward lightning (ICC_P, ICC_{RS}), which may be detected with LLS in particular areas with good coverage, are included in the estimation and are treated with the same impact as the first return stroke. If several events start simultaneously, only one is detected. The events detected are often characterized by small peak current amplitudes which result in a lower LA compared to first return strokes events.
- The environmental factor c_d is used as a universal factor to account for topography effects, winter lightning areas or offshore locations. This factor is intended to account primarily for the probability of upward lightning. The factor would be expendable for accurate LLS.

The data quality has a direct impact on calculated value of dangerous events. Depending on the performance characteristics of LLS networks, very different lightning exposure rates can be calculated for the same site. N_d is comprised out of both downward and upward lightning estimations which are mixed together and are eventually used as a general number. Since the immediate consequences of downward lightning and upward lightning are substantially different, as described in Section II, it may be wise to consider both estimations separately in an exposure and risk assessment for wind turbines and tall structures. This could lead to dedicated maintenance schedules according to actual exposure and a standard which is truly international.

It needs to be mentioned that the standard currently undergoes a revision and a new version is expected being circulated in the second quarter of 2016. One of the main changes planned regarding exposure assessment is a revision of the environmental factors which intend to improve the lightning environment definition. Furthermore, the implementation of the strike point density N_{sg} is planned which replaces the average flash density N_g in equation 1.

$$N_{sg} = f N_g \qquad (2)$$

The factor f is defined in the newly published, IEC 62858 - Lightning density based on lightning location systems (LLS) - General principles [*IEC 62858*, 2015], and accounts for multiple ground terminations which may be misclassified by LLS systems. The Factor *f* varies between 1 and 2 depending on the LLS network performance. This adds another degree of freedom to the equation. The factor does not relate to upward lightning.

V. PRACTICAL LLS DATA EVALUATION TO WIND TURBINES

A. The influence of the uncertainty ellipse r_s

As an example to highlight the differences in LLS data for an exposure assessment, the lightning detection data for 13 random wind power plants are used. The data were obtained from a major VLF-LF LLS network. The purpose of the analysis is to examine only the data quality differences and the effect to the peak current distribution. This analysis can provide information regarding the differences of LA and may imply some tendencies for DE. The wind power plant locations are scattered within a rectangular area with the longitudinal and latitudinal distance of approximately 2400 and 2900 kilometers, respectively. The lightning data covers a spatial distance of 10 kilometers around the wind power plants and is recorded in a timeframe of 5 years. Intra-cloud lightning detections were removed from the dataset. For each lightning stroke detected, the network provided an uncertainty estimation r_s which defines the semi-major axis of the elliptical confidence region of the detected lightning stroke. This confidence region is a measure that the detected lightning stroke is within the boundaries of the radius r_s with a probability of p. Usually, but not exclusively, the reference probability level p of a LLS network is 50% [*Cummins et al.*, 1998].

In Figure 1, the detected peak current distribution of the 13 sites is illustrated. The data are sorted with increasing semi-major axis of the uncertainty ellipse. Furthermore, the amount of detected strokes is presented. The following observations can be made:

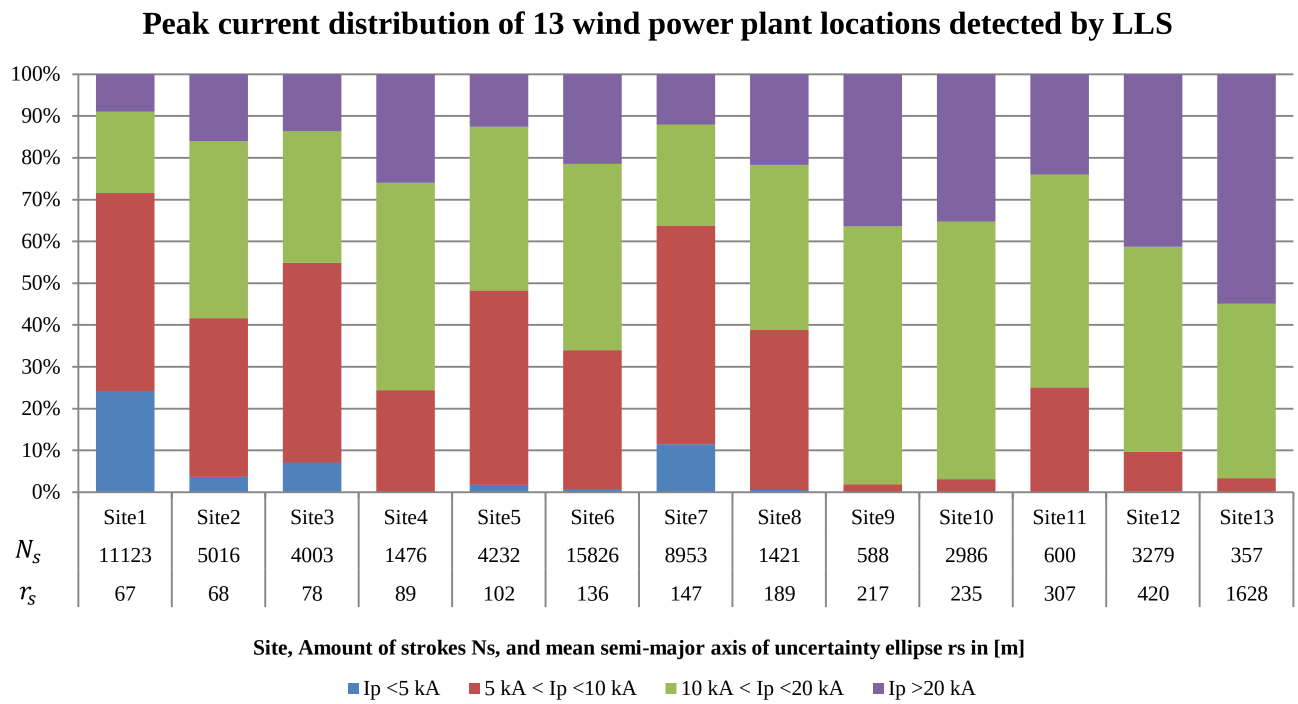

Figure 1: LLS Data of detected peak currents from 13 wind power plant locations sorted by increasing semi-major axis of uncertainty ellipse rs

- The calculated mean uncertainty estimation r_s from all detected lightning strokes within one sites varies from 67 – 1628 meters. This is a considerable difference of LA.
- With increasing r_s, the absolute percentage number of detected lightning strikes above 20kA is increasing (purple color).
- With increasing r_s, the ability to detect small current amplitudes below 5 kA is decreasing. From Site 9 – Site 13, no lightning currents below 5 kA are detected.
- With increasing r_s, there is a trend that the absolute percentage of lightning strikes between 5 and 10 kA is decreasing.

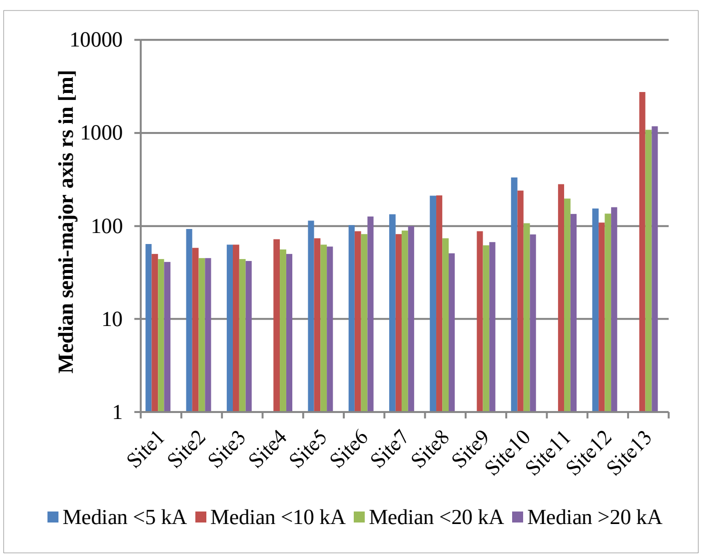

Figure 2: Median error ordered by detected peak current amplitude. Usually lower peak currents are associcated with lower location accuracy.

A smaller uncertainty ellipse is generally combined with improved LLS network properties. This can be due to smaller sensor baseline, more reporting sensors, and improved sensor technology. The sites 1 – 7 are characterized by a mean stroke LA error of less than 147 meters. At site 1, 3, and 7, 5 % or more of the total detected lightning strokes are characterized peak currents magnitudes below 5 kA; however, at sites 2, 4, 5, and 6, no or very few peak currents below 5 % are detected. Without more details about the properties of the LLS, no definite conclusions can be made if there are simply no lightning currents below 5 kA in this area or if the network is not able to detect them, however, the later seems more likely. Several studies report observations of triggered or self-initiated upward lightning leaders with low peak currents starting from wind turbines blades which seldom are detected by LLS [*Candela Garolera et al.*, 2015][*Cummins et al.*, 2014][*Montonaya et al.*, 2014]. At sites 8 – 13, the mean LA is bigger than 190 meters. The majority of detected lightning discharges are above 10 kA. At site 13, very high location accuracies are detected and the majority of detected lightning amplitudes are above 20kA. There is a high probability of missed lightning detections with small peak current amplitude / low current rise time at sites 8 – 13.

In Figure 2, the median error is illustrated for the individual peak current interval with a logarithmic scale. Low peak currents are generally characterized by the highest uncertainty value r_s and hence, the LA is lowest. With increasing peak current the LA is increased. This result follows observations reported in *Azadifar et al.* [2015]. Site 6, 7, 9, and 12 do not follow clear trend in this perspective.
The example given above emphasis the differences which are attributed to different local LLS performances even within the same network.

B. *Hot spot formation due to low current ampltide strokes with high quality LLS data*

As observed in the previous example, the mean semi-major axis of the uncertainty ellipse r_s can be used as an indicator if low peak current amplitudes are able to be detected by a LLS network. In this example, five years of LLS data from three different wind power plants are compared. Two sites are characterized by low r_s, whereas one site is characterized by a high mean r_s. For all three sites, the average flash density N_g and the average stroke density N_{st} are illustrated in Figure 3 to Figure 8. Wind turbines positions are marked with a black triangle facing down and lightning detections are marked with a colored dot or circle related to the peak amplitude and polarity.

TABLE 2: THE CALCULATED AVERAGE FLASH AND STROKE DENSITIES FOR THE THREE INVESTIGATED SITES ILLUSTRATED IN FIGURE 3 - FIGURE 8. THE TERM AREA REFERS TO THE GENERAL LIGHTNING ENVIRONMENT OF THE SURROUNDING OF THE WIND POWER PLANT WHEREAS A_d REFERS TO THE LIGHTNING ACTIVITY IN THE CLOSE VICINITY OF THE WIND TURBINES INSIDE THE COLLECTION AREA DEFINED BY IEC 61400-24

	$\overline{r_s}$ [m]	Average Flash Density Ng [1/km2yr]		Average Stroke Density Nst [1/km2yr]	
		Area	A_d	Area	A_d
Site 1	111	3.0	5.0	5.0	11.0
Site 2	78	1.4	1.1	2.5	2.6
Site 3	420	0.6	0.9	0.8	1.5

In Figure 3, the lightning flash detections for the first windfarm are illustrated and hence strokes are removed from the observation. The lightning detections in the map are fairly distributed in the map with a slight intensification around certain turbines. The intensification can be attributed to either

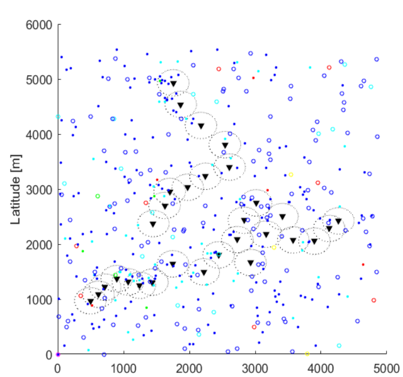

Figure 3: Flash detections for a wind power plant which is influenced by upward lightning. LLS data with high accuracy. Small intensification of lightning discharges around wind turbines.

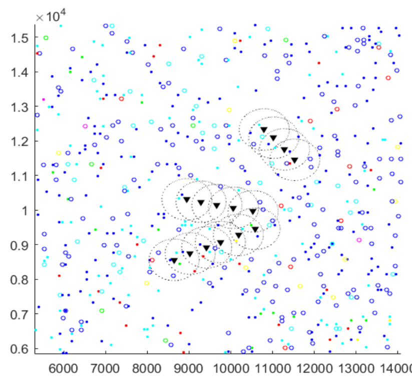
Figure 4: Flash detections for a wind power plant which is not affected by upward lightning. LLS data with high accuracy. No intensification of lightning discharges around wind turbines.

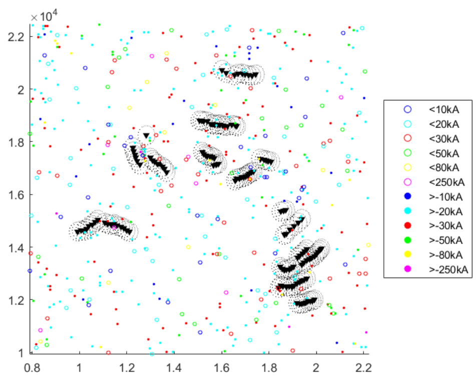

Figure 5: Flash detections for a wind power plant which is may be affected by upward lightning. LLS data has low accuracy, so low amplitude flashes are maybe not recorded.

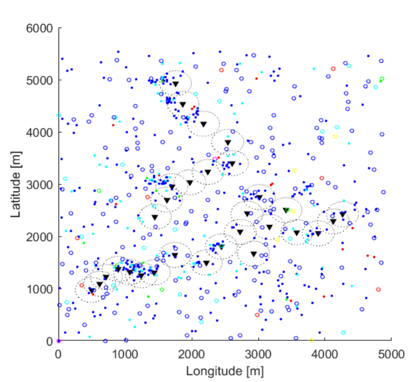

Figure 6: Stroke detections for a wind power plant which is exposed to upward lightning. LLS data with high accuracy. Distinct intensification of lightning discharges around wind turbines.

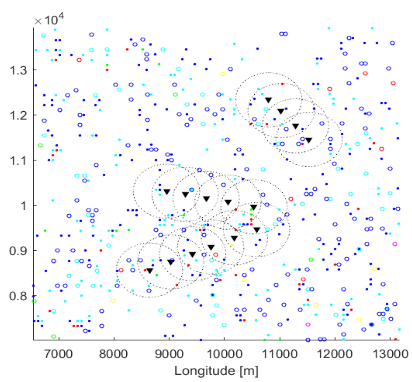

Figure 7: Stroke detections for a wind power plant which is not affected by upward lightning. LLS data with high accuracy. No intensification of lightning discharges around wind turbines.

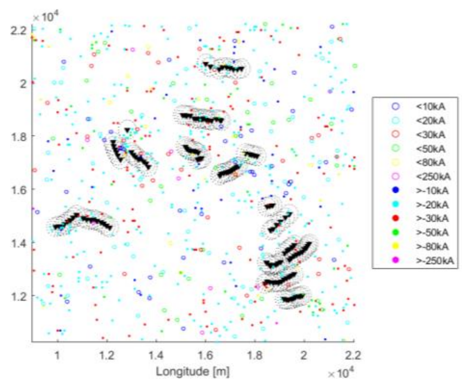

Figure 8: Flash detections for a wind power plant which is may be affected by upward lightning. LLS data has low accuracy, so low amplitude flashes are maybe not recorded.

intercepted downward lightning or upward lightning. On the contrary, Figure 6 shows the same dataset for lightning stroke occurrences. It can be observed that cluster formations are more prominent compare to Figure 3 and subsequent events do influence the exposure. These events can be attributed to triggered upward lightning, repeated self-initiated events or to subsequent strokes.

The second wind power plant is also characterized by a good LA. In this example, the lightning environment is different. In Figure 4 and Figure 7, the flash density and stroke density are illustrated, respectively. It can be observed that no intensification of lightning events around the wind turbine are apparent. It appears that the wind turbines are mainly influenced by downward leaders in this location.

The third wind power plant is characterized by a high r_s and hence low DE and LA. In this example, it is not possible to predict the effect of upward lightning to the wind power plant based on Figure 5 and Figure 8. Similar to the second study, no or only limited cluster formation around the wind power plants can be identified from the Figure. However, in Table 2, it is apparent that the lightning density inside the collection area A_d is higher than the surrounding area for both flash and stroke occurrences. This is an indication that the wind turbines at this location are exposed to a certain enhancement in lightning activity, however; due to the limited data quality, it is difficult to conclude to which extend the site is really exposed. In this example, three different locations are investigated and two main conclusions can be obtained. Firstly, there are wind turbine sites which are affected frequently by subsequent lightning activity and upward lightning, and there are other sites which are not influenced. Secondly, the data quality of a LLS has a big impact in the DE and LA. From the performance characteristic review of Section III.A, it can be assumed that in all three cases the high peak currents of downward lightning strikes are detected and located with a high percentage. The biggest unknown of lightning exposure of wind turbines based on LLS data is attributed to low peak amplitudes which are often related to upward lightning events. These, on the contrary, are not very problematic for modern LPS in wind turbines. Even though, hot spot formation is apparent in Site 1 and partially in Site 3, only a fraction of upward lightning discharges are able to be detected and hence, an even higher lightning density is expected in reality due to ICC_{Only} events which cannot be detected by any LLS.

VI. Conclusions from the performance characteristics of different LLS technologies

This paper reviewed information which is important if a detailed exposure assessment for wind turbines shall be conducted with LLS data.

From the evaluation of performance characteristics of different LLS technologies of downward, upward lightning, several characteristics of LLS in respect to lightning exposure of wind turbines can be concluded.

- Due to the low DE, especially for low peak current amplitudes, very **long range LLS** are not suitable to provide LLS data for exposure assessment of wind turbines. They are able to detect mainly high peak current return strokes.
- **Satellite LLS** are characterized by a low DE and LA. A classification between upward and downward lightning is not possible. Furthermore, only certain parts of the world are currently observed with low earth orbiting satellite. Therefore, an exposure assessment is not recommended.
- **HF / VHF LLS** cover only limited area and generate high amount of data which may require long time to evaluate; however, the technology records lightning processes in a very high detail. In general, the technology may be seen as research technology to investigate the individual breakdown processes during lightning formation or to benchmark other LLS.
- Downward lightning: Benchmarks of **VLF-LF LLS** to towers with measurement equipment indicate very good flash DE of 85 % till over 95 %. Stroke DE vary from 70 – 90% depending on the network. Often low peak currents < 10 kA are missed by LLS. The median LA of flashes and strokes can be estimated in a range of 50 meters – 2000m depending on the sensor network.
- Upward Lightning: Upward lightning performance characteristics vary vastly among **VLF-LF LLS**. Approximately 50% of upward lightning strikes are of type ICC_{Only} which cannot be detected by any VLF-LF LLS. For the remaining 50% of type ICC_P and ICC_R, the DE and LA of the strokes depend on the sensor baseline, peak current, current rise-time, and evaluation algorithm. From the numbers in the studies, a DE of 0-40 % with a possible LA accuracy of 100 m – 5 km may be assumed for all lightning events, depending in the location and the type of LLS.

The evaluation of the LLS data to the exposure assessment defined in IEC61400 – 24 resulted in the knowledge that the amount of dangerous events to wind turbines N_d accounts for both downward and upward lightning. These lightning strikes types are characterized by distinct different current waveforms and imply different failure modes to a LPS of a turbine. A separate estimation of both lightning events would improve the significance of the exposure assessment. Each exposure assessment should be performed together with an evaluation which percentage of upward lightning may already be included in the average flash density N_g.

The factor c_d in the lightning exposure assessment is introduced to account for the inability of LLS to detect upward lightning, however, since network technology steadily improves, upward lightning events may be included already in LLS data nowadays. A careful investigation need to be conducted before an exposure assessment to avoid the overestimation of the total number of estimated strokes to the turbine.

The fact that also first return-strokes can have low peak current amplitudes which are not detected by an LLS may induce to overestimate the current peak amplitude of lightning strikes attaching wind turbines which has implications on the LPS design.

The performance characteristics of the LLS data have a distinct impact in the ability to detect small current amplitudes. Furthermore, the occurrence of upward lightning to wind turbines depends heavily on the location observed.

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