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Field Performance Assessment of Wind Turbine Lightning Protection Systems

Uncertainty due to Upward Lightning and Other Factors

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***Abstract*— Modern wind turbines are typically equipped with lightning protection systems (LPS). Internationally recognized standards require that the LPS should intercept and conduct the vast majority of strikes without damage to the turbine, yet insurance companies are reporting 20% of all wind project claims are due to lightning damage. While international standards cover the design, testing and risk assessment of lightning protection systems, there is no standardized approach to evaluate the field performance of wind turbine lightning protection systems. Without a standardized approach to evaluating LPS performance on operating turbines, it is challenging to determine whether LPS are operating as designed and assess the site-specific risks. To address this challenge the authors have developed a method of assessing the field performance of wind turbine LPS. This paper presents the current state of the challenge and our approach to assessing risk of damage and LPS field performance, and in particular identifies topics requiring further research and direction from the lightning community.**

Keywords—wind turbine; lightning protection systems; field performance; force majeure; detection efficiency

I. Introduction

Production of electricity by wind turbines has grown to become a major U.S. and international industry. As of the end of 2013, 318 GW of wind generation capacity was installed around the world [GWEC 2014], 69 of which was in North America.

World-wide installed wind powered generation capacity has experienced rapid growth, as shown in Fig. 1 and currently represents approximately $70-80 billion in annual capital investment.

Amongst a number of factors that add risk to investment in wind energy is unexpected turbine downtime and associated costs. Many sources of downtime can be predicted with high confidence, such as routine maintenance. Lightning has become a significant source of higher than expected costs and downtime in the U.S. operation of wind farms. This often results in not only disputes over who is responsible for repairs but also has likely led to higher insurance premiums and higher costs of financing across the industry.

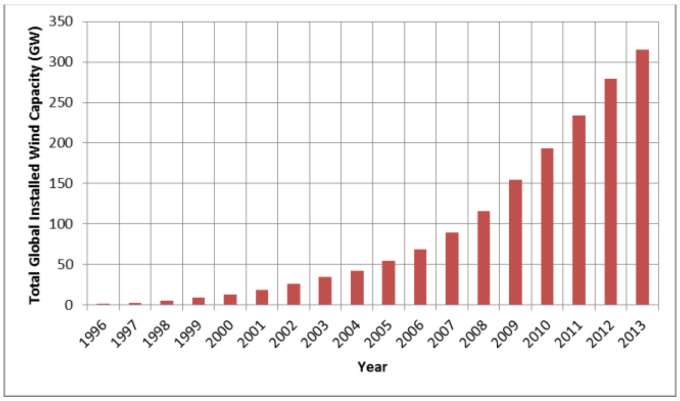

Fig. 1. Cumulative Global Installed Wind Capacity by Year

Most modern wind turbines are equipped with an LPS, which is designed to intercept lightning strikes to the blades through receptors (air termination systems) and conduct the lightning through the turbine to the grounding system. Internationally recognized standards require that the LPS should intercept and conduct the vast majority of strikes without notable damage to the turbine. Extreme strikes can occur that the LPS is not expected to resist without damaging the turbine. However, there is no standardized approach to the evaluation of field performance of wind turbine LPS. The absence of a standardized approach to evaluation of LPS performance complicates the determination of who is responsible for the costs to repair lightning damage and assessing lighting risk at a project. In response to the industry need and lack of standard guidance, the authors have developed a method of assessing the field performance of wind turbine LPS and identified several areas where additional research is needed to decrease uncertainty in performance and risk assessments.

II. Lightning Interaction With Wind Turbines

A number of factors combine to make wind turbines uniquely exposed to lightning strikes:

- To capture the strongest winds, wind turbines are commonly sited on a region's most prominent land features: on tops of ridges, hills or in exposed flat areas.
- Wind turbines are almost always the tallest objects in the vicinity; common tip heights range from 100 to 150 m.
- As noted by Rachidi et al. [2008], and Wilson et al. [2013], there is some evidence that the upward movement of the rotor blades during half of the rotation may stimulate more lightning strikes than a stationary object.

Additionally, wind turbines are more prone to damage from lightning if struck compared to some other tall structures such as steel towers. Wind turbine blades are susceptible to lightning damage if strikes do not attach to the metal LPS receptors (also called air terminations). Blades are typically constructed of fiberglass-reinforced plastic materials, with carbon fiber-reinforced plastic becoming more prevalent as blade lengths increase. These materials are more susceptible to impairing damage than steel or concrete structures. Major damage can occur due to burning or splitting bonded joints due to rapid thermal expansion. Even small damages, such as punctures, create the risk that damage will propagate to complete blade failure because much of the blade is fatigue designed and small damages can propagate under fatigue loading.

A. *Applicable Design Standards*

Wind turbine LPS are designed to the International Electrotechnical Commission (IEC) standard 61400-24:2010, which contains normative references to IEC standards 61305-1:4, amongst others. IEC 61400-24 includes requirements for protection of wind turbines against lightning damage. Testing methods are also recommended. IEC 61400-24 also provides informative guidance on lightning exposure assessment. However, there are no standards providing guidance or requirements for assessing the field performance of a wind turbine LPS.

B. *Expected Performance*

Per IEC 61400-24, an LPS should be able to effectively intercept and conduct all lightning strikes that are within design limits without sustaining function-impairing damage to the turbine. The authors interpret function-impairing damage as damage that requires the turbine to be shut down until repair; damage that can be tolerated until the next normal maintenance period is not considered function-impairing.

The primary LPS design parameters are: peak current, total charge transfer, specific energy and rise time. The design limits of these parameters vary by Lightning Protection Level (LPL). Most wind turbines are designed to LPL I. For LPL I, the standard specifies a maximum peak current of 200 kA and maximum total charge transfer of 300 C for any flash.

The IEC design limits are based on likelihood of exceedance, which is understood through measurements made by the International Council on Large Electrical Systems (CIGRE) [Berger, 1975] on two towers on Monte San Salvador in Switzerland (San Salvador Towers). IEC 61400-24 specifies that an LPL I LPS should intercept and safely conduct all lighting that is within the design limits; it is expected that 98% of all lighting experienced will be within the design limits.

It is commonly assumed that the San Salvador Towers' measured lightning environment will be matched around the globe, with some notable exceptions, when considering data covering a long enough period of record. To the extent that the lightning characteristics at a site differ from the San Salvador Towers lightning environment, the probability of experiencing lighting that exceeds the design limits will vary from site to site.

In areas subject to winter lightning storms, particularly in the presence of tall objects such as wind turbines, upward lighting may be a concern. However, the lightning environment, which is used in the standard to develop the likelihood of exceedance discussed above, is based only on the downward lightning statistics from the San Salvador Towers. This is not likely a concern with respect to peak current because the mean peak current for upward lightning has been found to be only a third of that for downward lightning [Diendorfer 2010, Diendorfer, et al., 2011]. However, there are some data to support the claim that upward lightning is more likely to exceed the total charge transfer design limit than downward lightning. IEC 61400-24 does suggest increasing the durability of some aspects of the LPS with respect to total charge transfer for sites with exposure to upward lightning. However, a new design limit for total charge transfer is not provided.

Data from the Gaisberg Tower suggest that approximately 1% of upward lightning will have a total charge transfer exceeding the 300 C LPL I design limit [Diendorfer, et al., 2011]. Thus it is important to fully understand the site-specific lightning environment in order to have realistic expectations for the amount of damage turbines at a site may experience even with a properly functioning LPS.

C. *Observed Field Performance*

Despite the use of an LPS designed to IEC standards on most modern wind turbines, the rate of lightning damage is far exceeding the expectations of the wind industry. In 2012, a major U.S. wind insurer reported 23.4% of claims were due to lightning [GCube 2012].

The authors have observed hundreds of instances of lightning damage to wind turbines in the US; and in our experience, blades are most commonly damaged by lightning over any other component. Blade damage occurs in the form of broken blades, localized burned or charred blade material, torn fiberglass, delamination, split trailing edge bonds, and/or pin holes puncturing the blade structure. As previously mentioned, wind turbine blades are subjected to a very high number of structural fatigue cycles, and as such small areas of damage may grow and lead to eventual blade failure. Further, damage to blade structures creates the potential for water ingress to the blade structural materials. Water ingress can lead to damage growth in freeze-thaw cycles. Fig. 2 shows an example of lightning damage to a wind turbine blade.

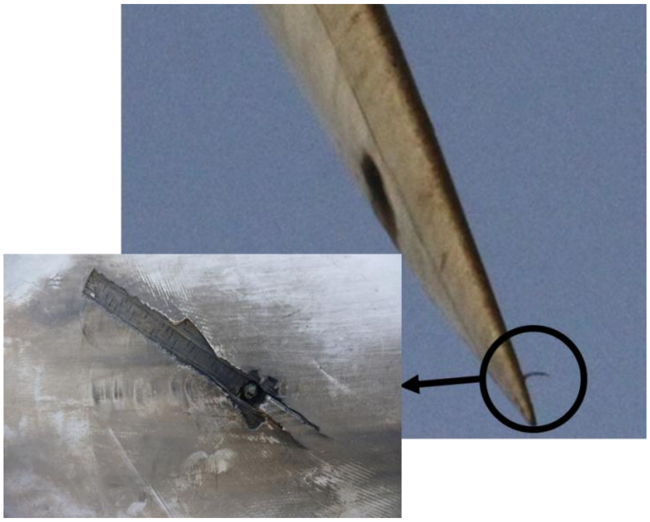

Fig. 2. Example of Lightning Damage to a Wind Turbine Blade

Blades are commonly damaged by lightning, other parts of the turbine, however, are susceptible to lightning damage as well: LPS receptors and down conductors can melt, power electronics can be damaged, and fires can initiate.

The majority of wind turbine lightning damage the authors of this paper have observed in the U.S. was due to poor interception (which is a function of LPS design) or due to poor LPS maintenance. Strikes with a total charge transfer higher than the design limit are likely to cause mechanical damage to portions of the LPS, such as the air termination and down conductor, by heating.

In the opinion of the authors, wind turbine lightning damage we have observed is not primarily due to upward lightning and associated high total charge transfer. However, this opinion is not based on a comprehensive study of an independent sampling of damage events, and may not prove to be representative of the wind industry's experience at large.

As the wind energy industry matures, there is lower tolerance for dismissing lightning damage as force majeure. Turbines are designed with LPS that are intended to prevent function-impairing damage to the turbine for all lightning strikes within the design limits. Owners, manufacturers, and insurance companies need a better understanding of lightning interaction with wind turbines in order to ensure state of the art LPS design and accurate high confidence field performance assessments.

III. Field Performance and Risk Assessments

The objective of a field performance assessment is to determine, within the accuracy of the calculation, the efficacy of the system in relation to the expected efficacy per the relevant standards and design statement of the system. The field performance of an LPS can be quantified by considering the site lightning environment, the LPS design standard, and the record of lightning damages. There is no standard for how to use the available information to assess the efficacy of an LPS and the available lighting data typically do not fully characterize the site conditions. Additionally, a simple comparison of actual and expected LPS performance is challenging because lightning is a stochastic process, and thus the LPS field assessment needs to be a probabilistic assessment, yielding a probability that the system is achieving the expected performance.

Drawing from applicable IEC standards when possible, the authors have developed an approach to assessing field performance of wind turbine LPS. The basic steps are:

a) Determine Site-specific Flash Density: Using available lightning data from a lightning location system (LLS) such as the National Lightning Detection Network (NLDN) in the U.S., and estimated detection efficiency (DE) for the site (further detailed in Section IV), calculate the site-specific flash density for the period of record.

b) Determine Number of Strikes to Turbines: Using the site specific flash density and the equivalent collection area (further detailed in Section V) of the turbines, calculate the number of strikes expected to turbines over the period of record.

c) Determine Number of Expected Damages: Using the number of strikes to turbines, the LPS design criteria, and the site-specific estimate of probability of any strike remaining within the LPS design levels (probability of non-exceedance), P_{NE}, (further detailed in Section IV), estimate the number of function impairing damage events expected if the LPS were performing as expected.

d) Quantify Damages: Review inspection and repair reports from damage events, interview site personnel and, using criteria for function-impairing damage, determine the number of damages over the period of record.

e) Determine the Binomial Probabilities, Confidence Intervals and Bayesian Probabilities: Using the available data, perform statistical analysis to develop binomial probabilities, confidence intervals and Baysian probabilities to provide a statistical picture of the LPS field performance.

A similar approach can be used during the feasibility and planning phase of developing a wind farm to understand the risk of lightning related damage to the turbines. Such a risk assessment would be informative for setting insurance premiums and allocating budget for repairs.

Because the approach utilizes statistical methods, sources of uncertainty, particularly with respect to the number of samples observed, are reflected in the results. However, as with any statistical approach, if the uncertainties on the inputs are too large, the uncertainty in the results may reduce the usefulness of the results. One potentially large source of uncertainty is in the estimates of DE utilized to determine flash density, where research has shown that upward lightning may be undercounted but could be a significant contributor to the lightning environment experienced by a wind turbine.

IV. Detection Efficiency and Upward Lightning

DE is the percent of flashes or strokes that a lightning detection network can be expected to detect. For example, a 95% flash DE implies 95% of all flashes in an area are detected and correctly identified by the detection network. It is not uncommon for networks to report a regional DE of 95% for all (upward and downward) lightning. However, as shown by Diendorfer et al., [2011], some types of upward lightning are very difficult to detect with modern LLSs. Wind turbines, or other tall objects, initiate upward lightning. This implies that reported DE in the area of a wind farm (or other tall objects) may need to be adjusted downward to account for upward lightning that was not detected.

A. Upward Lightning in IEC Standards

IEC 61400-24 addresses upward lightning in three ways: it identifies a need to bolster the durability of air termination systems when exposure to upward lightning is significant; it indicates the flash density in an area may need to be scaled up if upward lightning is present through the use of an environmental factor; and it describes the phenomenon of upward lightning in an informative annex.

IEC 61400-24's guidance for risk assessments for sites with upward lightning leaves many issues open to interpretation. The design limits provided in IEC 61400-24 are for downward lightning only. Upward lightning has been found to have different characteristics [Diendorfer 2010, Diendorfer, et al., 2011] than downward lightning.

Thus there is a need to (1) understand how to estimate the incidence of upward lightning at any particular site and (2) define the parameter distributions and probability of exceedance of the design limits for sites prone to upward lightning. Section IV.D of this paper describes an approach to address both needs until more research can be done. This approach builds on current research on upward lightning, including research conducted in Japan.

B. Review of Experiences in Japan

Research reports unusual lightning characteristics specific to the winter season on the west coast of Japan [Miki et al., 2010, Shindo et al., 2012 and Rakov and Uman 2003]. This lightning environment is defined by: (1) a high number of upward strokes, (2) a low DE (as low as 62% reported by Honma [2010]), and (3) high frequency of events with high total charge transfer. Shindo [2012] noted 4-7% of observed strikes exceeded 300 C of total charge transfer, which is the design limit specified in IEC 61400-24.

The prevalence of such lightning environments elsewhere in the world is still a topic of research. Initially, Rakov and Uman [2003] suggest that this lightning environment has not been observed outside of Japan, but later Shindo et al., [2012] noted similar lightning environments have been reported in other geographic areas. Additionally, as noted earlier, upward lightning with high total charge transfer has been observed at the Gaisberg Tower [Diendorfer, et al., 2011]. Because modern LLSs do not detect the majority of upward flashes, the prevalence of upward lightning at other sites is difficult to determine. This is an active area of research; CIGRE is currently convening a working group (C4.36) on the topic of winter lightning and engineering consequences for wind turbines.

The Japanese experiences are relevant to the assessment of wind turbine LPS and associated risks because they suggest that at some locations there may be a higher than specified incidence of strikes with a total charge transfer that is more likely to exceed the design standard for wind turbine LPS. Further, these experiences also identify environments where there is a high incidence of upward lightning which may be undercounted if traditionally reported DE values are used to define the lightning environment.

C. Impact of Detection Efficiency on Field Performance Assessment

Having a correct DE is integral to an accurate field performance assessment of a wind turbine LPS or a risk assessment to assist in planning a wind farm because DE directly scales the expected number of damage events. If, for example, the DE were overestimated by 20% then the expected number of damage events would be underestimated by 20%.

A further complication is the role that upward lightning plays in understanding the distribution of lightning parameters at any specific site. Upward lightning has been found to have different distributions of peak current and total charge transfer than downward lightning. This implies P_{NE}, the expected probability of lightning at a specific site being within the design limits, should be adjusted to account for the presence of upward lightning. P_{NE} also directly scales the expected number of lightning-caused damage events at a wind farm: if the P_{NE} were underestimated by 10%, then the expected number of damage events would be underestimated by 10%.

To accurately estimate the number of damage events to be expected, site-specific upward lightning must be understood and included in the calculation.

D. Proposed Method of Addressing Site-Specific Upward Lightning

Until further guidance is provided by the IEC committee or additional research is completed, the authors propose the following method to addressing upward lightning in risk assessments or field performance assessments of wind turbine LPS.

a) Determine Downward Detection Efficiency

The agency managing the LLS often can provide a regional DE for cloud-to-ground lightning, supported by documentation and validated. This DE generally does not consider a significant concentration of tall structures such as at a wind farm. As such, the DE provided by the LLS is a good estimation of downward DE. Alternatively, there are methodologies for calculating DE (for example, CIGRE Working Group C4.404 2009 or Diendorfer 2007).

b) Determine Upward Detection Efficiency

Many campaigns to measure lightning to towers have been undertaken, but available literature on upward DE is limited. Diendorfer et al., [2011] has published on upward lightning DE measured at the Gaisberg Tower, indicating that approximately 40% of all upward lightning was detected. As previously reported the detection efficiency for all flashes at a site in Japan with substantial upward lightning was reported to be as low as 62%. References such as these can be used to estimate an upward lightning DE.

c) Determine Percent Upward and Downward Lightning

Determination of percent upward and downward lightning can be made by determining winter and summer seasons and assuming all winter lightning is upward and all summer lightning is downward. Alternatively, the percent of upward lightning can be calculated based on an empirical equation using effective height, shown below.

Investigation of locally sourced weather information and inspection of lightning data can inform the determination of site-specific winter (non-convective season) and summer (convective season). Holle and Cummins [2010] monthly cloud-to-ground flash density maps may be useful in understanding the winter storm propensity in any particular region of the U.S. The basic assumption underlying the approach is that upward lightning is most likely to occur in the winter, when storm clouds tend to form much closer to the ground than in summer, providing conditions conducive to upward lightning. This assumption is a simplification: upward lightning has been observed in other months; however, it is understood to be the most frequent in winter months.

Alternatively, percent of upward lightning can be estimated through the effective height concept. Objects with an effective height (H) taller than 100 m initiate upward lighting, and as the effective height increases, a greater percentage of strikes are upward. It has been reported that objects with an effective height taller than 500 m receive only upward cloud-to-ground flashes [Eriksson 1987]. This relationship has been summarized by Eriksson [1987] in (1).

$$P_{upward} = 52.8 * \ln(H) - 230 \quad (1)$$

This equation can be used instead of seasonal differences; however, determination of effective height is subjective and introduces uncertainty in the assessment of LPS performance.

d) Estimate Site-specific Detection Efficiency and P_{NE}

Site-specific DE is the weighted average of the downward DE and upward DE, shown in (2).

$$DE = P_{upward} * DE_{upward} + P_{downward} * DE_{downward} \quad (2)$$

Where P_{upward} is the percent of strikes expected to be upward initiated and $P_{downward}$ is the percent strikes expected to be downward initiated.

The site-specific P_{NE} is the weighted average of the upward and downward P_{NE}, shown in (3).

$$P_{NE} = P_{upward} * P_{NE,upward} + P_{downward} * P_{NE,downward} \quad (3)$$

Where $P_{NE,upward}$ is the probability of upward lightning exceeding the design limits, and $P_{NE,downward}$ is the probability of downward lightning exceeding the design limits. Various reference papers include statistics for upward lightning parameters (e.g., Diendorfer 2011 and Peesapati 2009).

V. Equivalent Collection Area and Environmental Factor

The concept of equivalent collection area (Ac) is integral to the determination of the number of strikes to turbines. The equivalent collection area of a structure is defined as the ground surface area that would have the same number of annual lightning flashes if there were no structure there as there would be to the structure itself. The methodology for calculating the equivalent collection area for a wind turbine specified in IEC 61400-24 is ambiguous regarding treatment of terrain surrounding the turbine. The authors propose the following interpretation, based on content in withdrawn standard IEC 61024-1-1, to calculate equivalent collection area for wind farms.

For each turbine, a 1:3 slope line is intersected with and rotated around the maximum blade tip height, forming a cone that intersects with the surrounding terrain. The intersection of the cone and the terrain, projected vertically to a horizontal plane, is the boundary of the equivalent collection area for each turbine. The union of equivalent collection areas for all turbines on the site is the total area used in calculation of flash density for the site.

The above method of calculating equivalent collection area can be used to estimate the effective height of an individual wind turbine or tower by applying (4).

$$H = \sqrt{Ac/\pi} /9 \quad (4)$$

The Gaisberg Tower effective height was calculated as 682 m using the approach described above and in equation 4. The tower is a 100-m tall tower on an 800-m high hill near Salzburg, Austria. The calculated effective height is within the range of the effective heights calculated by Zhou [2010] using different methods:

- 1,000 m by the Pierce method
- 450 m by the most current Eriksson method
- 274 m by the Rizk-model method.

The above method does not necessarily reduce the uncertainty in effective height; however, this method is based on information found in standard references.

An environmental factor can be included in calculation of flash density to account for terrain effects and upward lightning; however, guidance in the standard on the appropriate values for this factor is limited. Terrain effects are accounted for in the approach presented here by equivalent collection area, and upward lightning is accounted for in calculation of DE; therefore the environmental factor is set to a value of one.

In the opinion of the authors, further research and guidance are needed on the accuracy of the equivalent collection area approach as applied to wind turbines.

VI. Conclusions

The wind industry is currently suffering from poorly understood interaction of lightning and wind turbines, resulting in increased risk for investments in wind energy projects and increased insurance premiums for all wind turbine owners, regardless of actual exposure to lightning damage.

The IEC 61400-24 approach to lightning damage risk assessment focuses on downward lightning, and lacks direction for accounting for upward lightning, which is increasingly suspected to be a major contributor to wind turbine lightning damage. Additionally, the concepts of equivalent collection area and effective height are necessary and relevant to wind turbines, but IEC 61400-24 leaves much up to interpretation.

The authors' experiences with hundreds of lightning damage events to wind turbines in the U.S. challenges the assertion that upward lightning is largely responsible.

Existing standards do not include a clear methodology for assessing the field performance of an LPS. The authors have proposed methods for performing LPS field performance assessments and lightning damage risk assessments, but they rely on assumptions that require confirmation or correction as the industry gains knowledge.

This work has highlighted significant gaps in the existing lightning protection standards for wind turbines and the need for substantial further research and development in the following areas:

- Capability to detect upward lightning by modern LLS.
- Understanding of the prevalence and seasonal distribution of upward lightning in the vicinity of wind turbines.
- Improved understanding of how wind turbines attract or initiate lightning, in particular, understanding if wind turbines have larger equivalent collection areas than towers with identical effective height and surrounding terrain.
- Guidance on field performance assessment of wind turbine LPS by the IEC.
- Guidance on accounting for upward lightning by the IEC for wind turbine risk assessments.

The potential benefits of better understanding of lightning interaction with wind turbines includes aligning expectations of LPS performance with actual experience, improvements to LPS design, and siting of wind turbines that considers the appropriate details of the lightning environment.

VII. Acknowledgements

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