Lightning Damage to Wind Turbine Blades From Wind Farms in U.S.

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***Abstract*--This paper presents statistical data about lightning damage on wind turbine blades reported at different wind farms in the U.S. The analysis is based on 304 cases of damage due to direct lightning attachment on the blade surface. This study includes a large variety of blades with different lengths, laminate structure and lightning protection systems. The statistics comprises the distribution of the lightning damage along the blade and classifies the damage by severity. In addition, the frequency of lightning damage to more than one blade of a wind turbine after a thunderstorm is assessed. The results of the analysis show that the majority of the lightning damages are concentrated at the tip of the blade. Furthermore, all the blades involved in the study show a great similarity in the distribution of damages along the blade and the characteristics of the damages, even concerning the significant differences in the blades geometry and materials.**

***Index Terms*-- Lightning, lightning damage, wind turbines, attachment distribution, lightning zoning**

I. Introduction

THE increasing height of wind turbines and their location often in open areas make them very exposed to direct lightning strikes. According to field observations, wind turbines experience a significant number of lightning strikes during their lifetime [1] - [4], mostly to the rotor blades. The lightning current causes severe damage to the blade structural materials and involves considerable costs of repair - materials, labor and downtime. Therefore, lightning protection of blades is a very important issue often addressed as one of the two largest environmentally caused concerns for wind turbine blades, the other being leading edge erosion. The requirements for an efficient blade lightning protection system (LPS) are specified in the standard IEC 61400-24 [5]. However, lightning damage still occurs in blades equipped with lightning protection systems, in particular due to interception failure of the air termination system during direct lightning attachment on the blade surface.

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The standard [5] proposes a procedure to design the blade LPS based on the threat of direct lightning attachment to the blade, which is evaluated according to the Lightning Protection Zones (LPZ). High voltage tests simulating the lightning events expected in field are also recommended to validate the LPS. Wind turbine blades are classified in the standard as Lightning Protection Zone 0_A, which implies that the entire blade is exposed to direct lightning strikes, the full current and the un-attenuated magnetic field. This classification of the blade has been questioned by several authors, including Peesapati et al. [6] and Madsen et al. [7]. They point out that, according to their field observation and numerical calculations, the majority of the lightning strikes occur at the last few meters of the blade tip. Furthermore, Madsen et al. [7] suggest a new zoning concept for the blade based on more realistic assessment of the lightning attachment points along the blade, where only the outermost tip of the blade are exposed to the full amplitude of the lightning current while inboard radii are only partially exposed or not exposed to direct strikes at all.

The analysis of the lightning damage on blades in the field is the most direct and reliable tool to validate the LPS effectiveness and evaluate the methods of risk assessment proposed in the standard. Unfortunately, there is very little of such information available. The published research mainly concerns blade damage caused by winter lightning in Japan reported by Yokoyama and Yasuda [8], [9], which has also been used in the CIGRE TB 578 to exemplify the different types of lightning damages on blades [10].

This paper presents general statistics of lightning damages on blades reported at different wind farms in U.S. The damage has been classified according to the location along the blade and the severity. Finally, the results are compared with the expected damage according to the standard [5] and the existing literature [6]-[9].

II. Description of the Analysis Data

The analysis presented in this paper is based on 304 lightning incidences causing damage to wind turbine blades that required significant repair. The lightning damages analyzed correspond to wind farms with a total installed power of 997 MW, located in the states of Texas, Kansas and Illinois, where the lightning flash density is within 2 and 8 flash/km2/year. The analysis was performed for a period of approximately 5 years, with a total population of 508 wind turbines. Therefore, on average each wind turbine experienced blade damage due to lightning every 8.4 years. This accounts for 2-3 blade damage incidences due to lightning during an estimated wind turbine life time of 20 years.

The analysis includes burns, punctures, delamination of the blade structure, debonding of the shells and detachment of part of the blade, but not cosmetic damages such as peeling paint, superficial marks or slight melting of the air termination system. The analysis comprises only lightning damages associated with the lightning attachment process, when the air termination fails in intercepting the strike. Consequently, it does not include damage occurred during the current transmission to ground, such as burns and melting of the down conductor and connectors due to lack of proper equipotential bonding.

The analyzed damages occurred in a varied population of blades, with lengths over 35 m. The structure of the damaged blades includes fiberglass only (64.8% of the blades), and mixed structures of fiberglass and carbon fiber (35.2% of the blades). Regarding the load carrying structure of the blade, it consists of a box beam spar in 76% of the damage blades and a structural shell in the remaining 24 %. All the damaged blades were equipped with lightning protection systems, which included an air termination system, a down conductor and a connection system to transmit the lightning current to the nacelle. The blade models had different types of air termination systems, including a single pair of receptors at the tip, several discrete receptors along the blade, a metallic tip, a metallic band over the caps and metallic mesh covering part of the shell. It is noted that all the wind turbine blades were designed and manufactured prior to the publication of the IEC 61400-24 [5]. In the 304 cases of lightning damages analysed in this paper, it is observed that the efficiency of each type of air termination system is not so closely related to the configuration of the system (number of discrete receptors, band, mesh, etc.), but to the proper insulation or shielding of the conductive elements inside the blade, such as the internal parts of the protection system (receptor holders, down conductors) or the carbon fiber laminate.

III. Location of the Lightning Damage

This section presents the statistics of the blade damage with respect to the location of the damage along the blade. The statistics for all the blades are compared with the specific cases of fiberglass blades and blades including carbon fiber in the structure. The position of the damage with respect to the trailing and leading edges is also analyzed, as well as the severity of the damage. Figure 1 shows the distribution of the lightning incidences along the blade including all blade damages, and Figures 2 and 3 illustrate the distribution of lightning incidences in fiberglass blades and blades with a mixed fiberglass and carbon fiber structure.

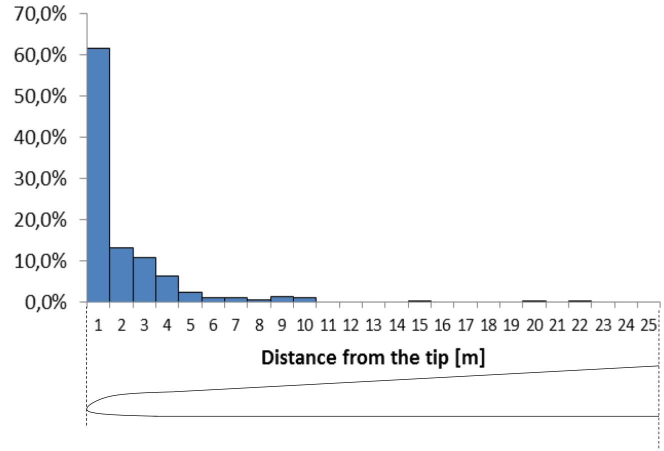

Fig. 1. Location of the lightning damage (in percentage) for the total population of damaged blades

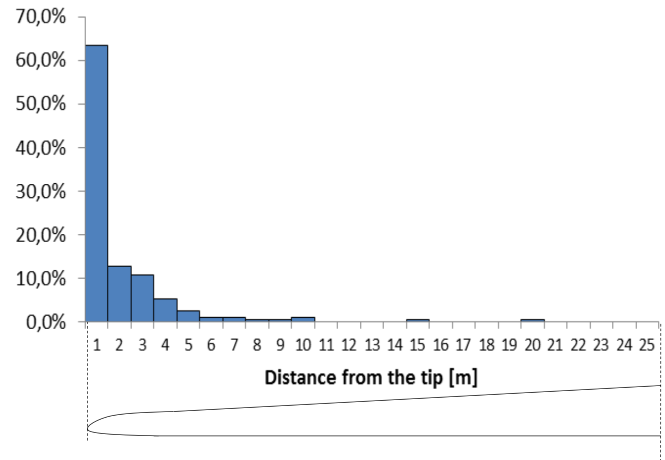

Fig. 2. Location of the lightning damage (in percentage) in damaged blades with fiberglass structure

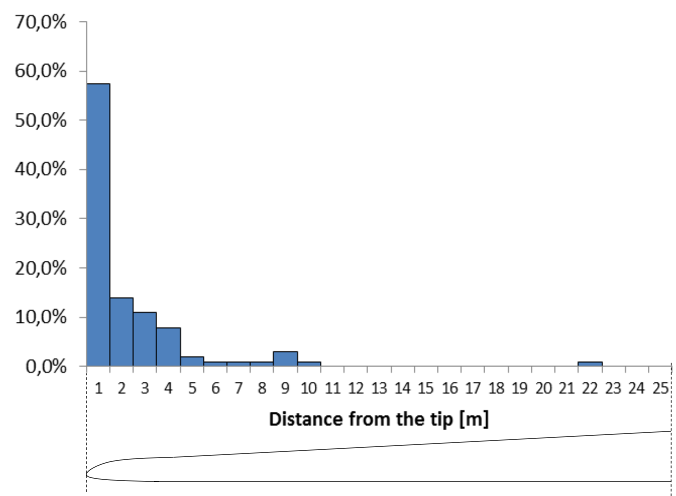

Fig. 3. Location of the lightning damage (in percentage) in damaged blades with mixed fiberglass and carbon fiber structure

It is observed in Figure 1 that more than the 60% of the total damage occurred at the last meter of the blade, and 90% of all damages are located at the last 4 m. The remaining 10% of damages are found mainly at 5 to 10 m from the blade tip.

There are only three lightning incidences further inboard, at 15, 20 and 22m from the tip.

Interestingly, both types of blade with and without carbon fiber experience very similar lightning distribution along the blade, with the largest percentage at the tip of the blade. The number of damages at 1 to 4 m from the blade tip is slightly higher in blades with carbon fiber in the structure.

The lightning damage on the blades has also been classified according to whether the lightning attached the blade surface adjacent to the spar caps, the trailing edge, the leading edge or the area covering the last 0.5 m of the blade tip. Figure 4 reveals that 58.6% of the damage occurred at the very tip of the blade, followed by 23.6% of the damage on the shells over the spar caps (attachment to carbon fibre structures or the down conductor for pure fibreglass blades) and 17.8 % on the trailing and leading edges.

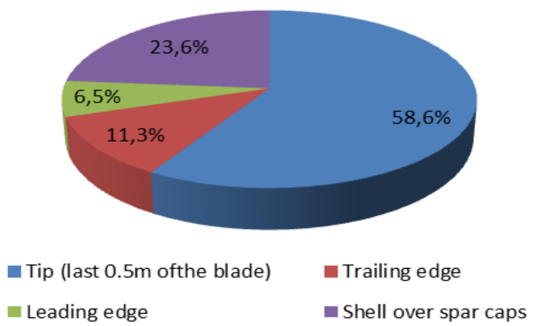

Fig. 4 Distribution of the lightning damage (in percentage) in the tip, shell over the spar caps, trailing and leading edges

It is noted that many of the incidences included in the 'tip location' (last 0.5 m of the blade) are likely due to direct strike to the edges, but the small area of the tip made it difficult to determine the exact location of the lightning attachment.

The location of the lightning damage with respect to the blade cross-section is of great significance not only to determine the most vulnerable areas of the blade, but also because it is closely related to the characteristics and severity of the damage, as explained in Section IV.

IV. Characteristics of the Lightning Damage

The lightning damage experienced on the wind turbine blades has been classified in four types, according to the appearance and severity. The types of damage comprise delamination, debonding, shell detachment and tip detachment.

Damage type 1: Delamination. The delamination consists of damage on the blade structure, where the plies of the laminate are detached from each other (Fig. 5 and 6). It is normally caused by local pressure and rapid expansion of the lightning arc column combined with incineration of the resin between the laminate plies due to the temperature of the lightning channel. Usually, delamination is accompanied with punctures and burns on the laminate at and around the point where the lightning struck the blade. The examination of the damaged blades shows that delamination is the most common type of damage and can occur at any location of the blade (upper and lower shells, trailing and leading edges) from the tip to 22 m inboard.

The extension of delamination is strongly determined by the location of the strike point and characteristics of the laminate. Delamination at the tip of the blade, where the laminate is thinner, often has a larger extension than delamination in the shell further inboard where the laminate is thicker. When delamination affects not only the shells but also the structural spar caps, the damage is severe and in the worst case may lead to the tip detachment (damage type 4).

Fig. 5 Burn and delamination on the shell at about 3m from the blade tip due to lightning direct strike.

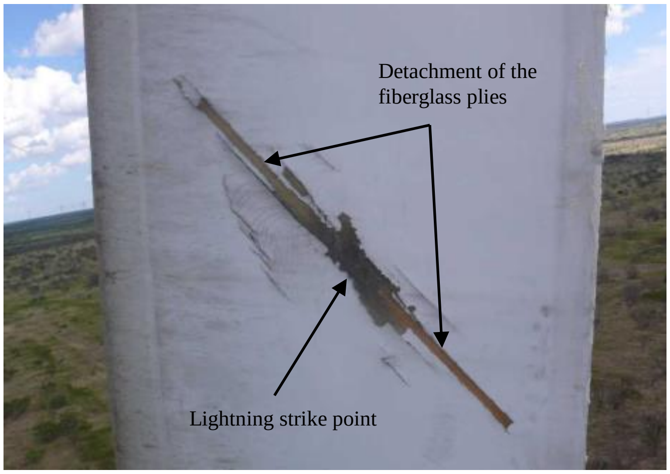

Fig. 6 Delamination on the shell at about 2m from the blade tip due to lightning direct strike. It is observed how the fiberglass plies of the shell are detached around the strike point.

Damage type 2: Debonding. Debonding of the shells consists of a localized separation of the upper and lower shells, usually at the tip of the blade or at the trailing edge in the last few meters of the blade (Fig. 7). The lightning strike point is often located close to but not at the debonded area, which suggests that the cause of the debonding is the expansion of the air inside the blade due to the heat generated by the lightning channel, possibly combined with vaporization of condensed moisture trapped inside the blade. All the examined blades that suffered debonding were accompanied with a certain degree of delamination.

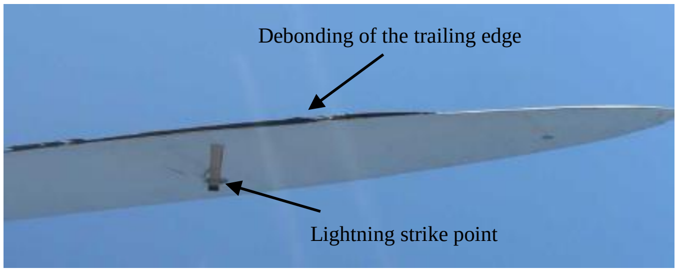

Fig. 7 Delamination on the shell over the cap and debonding of the trailing edge likely due to the expansion of the air caused by the lightning current.

Damage type 3: Shell detachment. The shell detachment consists of several meters of one or both shells completely detached from the load carrying structure (Fig. 8). The examination of the affected blades suggests that the damage started with a shell debonding (damage type 2). The rotation of the blades combined with the strong wind gusts during the thunderstorm generates mechanical forces to the debonded area, eventually causing shell detachment. This type of damage did not occur frequently. It is noted that in the cases of shell detachment analyzed here, the lightning attachment point was located within the last 3m of the blade tip, even if the damage affected several meters of the shell.

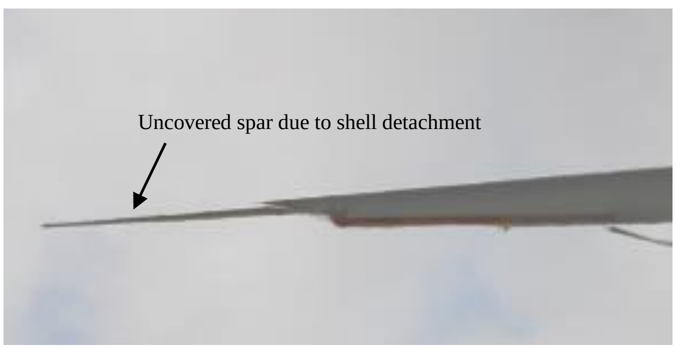

Fig. 8 Shell detachment of the last meters of the blade most likely initiated with a shell debonding due to direct attachment to the blade, aggravated by the strong wind conditions.

Damage type 4: Tip detachment. The tip detachment is the most critical case of damage, where several meters of the blade tip are detached from the rest of the blade (Fig. 9). This type of damage occurs when the lightning current severely damages the structural laminate, to the extent that the laminate cannot support the mechanical load and breaks. Tip detachment does not occur frequently, and it is mainly associated with blades having a carbon fibre structure. In the case of a direct strike to the carbon fibre, the current can flow through the conductive carbon fiber laminate and extend the damage. In the cases analyzed here, lightning struck the cap laminate a few meters inboard from the blade tip, where the spar cap laminate is relatively thin but supports certain mechanical loads.

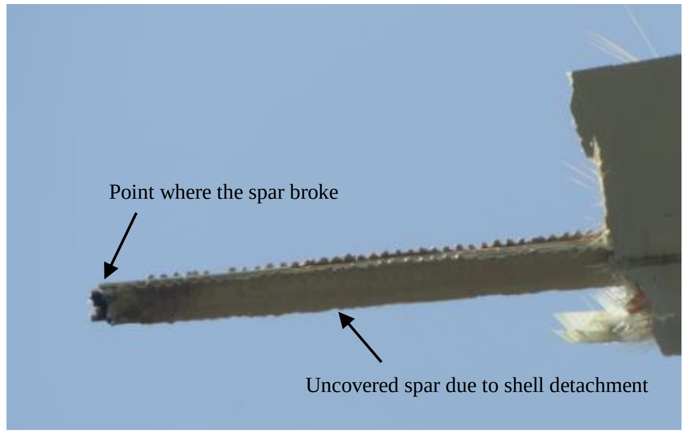

Fig. 9 Tip detachment due to direct lightning strike to the carbon fiber laminate of the spar (load carrying structure). The spar broke at several meters from the blade tip and the shells where detached several meters further inboard.

Figure 10 shows the distribution of the lightning damages according to the damage types described above. It is observed that the most common type of lightning damage is delamination, followed by debonding of the shells. The shells and tip detachment occurred only in 2.8% of the cases.

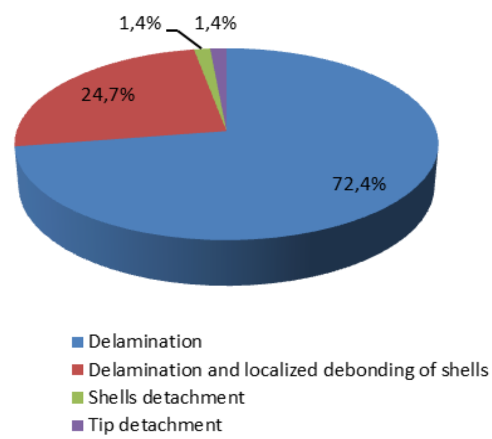

Fig. 10. Distribution of the damage according to the type, including delamination, debonding, shell detachment and tip detachment

It is important to point out that the costs associated with the damage vary significantly with the type of damage and type of blade. Considering the amount of time needed to repair a blade, with the consequent down time and lost revenue, the less severe type of delamination may take a couple of hours of repair, while most severe damage may involve 2 to 5 days to repair. Therefore, taking into account only the lost revenue, the total cost due to shells and tip detachment (2.8% of occurrence) may be comparable to the total cost due to delamination (72.4% of occurrence).

Figure 11 shows the distribution of the different types of damage along the blade length. It is observed that delamination occurs in all radius from the blade tip to 11 m inboard, and punctual cases further inboard up to 22 m from the tip. The localized debonding of the shells is mainly located at the tip of the blade, there are only few cases between 2 and

6 m from the tip and none further inboard. The distribution of the debonding can be explained by the fact that the blade is more robust in inboard radius, and therefore the expansion of the air due to direct strike on the blade surface does not cause the separation of the shells. Regarding the shell detachment, it is observed that in all the reported events the lightning strike was located at the last meter of the blade, even if eventually a shell section of several meters was detached from the load carrying structure. This would support the assumption that the shell detachment is initiated by a localized shell debonding and aggravated by the rotation of the blades and strong wind conditions. Finally, the tip detachment is located within 2 and 7 m from the blade tip, where a direct lightning strike can be critical for the integrity of the relatively thin laminate of the load carrying structure.

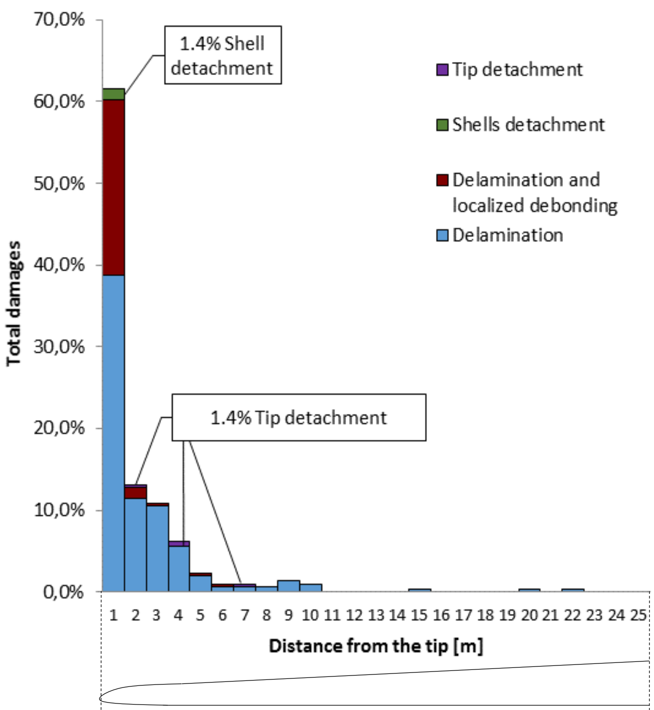

Fig. 11. Distribution of the different types of damages along the blade length.

V. Lightning Attachment to More than one Blade

The analysis of the damaged blades revealed few cases where a wind turbine suffered damages in more than one blade. Figure 12 shows the percentage of lightning incidences including one, two or all three blades of a wind turbine.

Since the inspections at the wind farms were carried out after thunderstorms, it is not possible to determine with certainty the cause of every damaged blade. There are several likely scenarios, including a single lightning stroke sweeping from one blade to another due to the blade rotation, different branches of a single lightning stroke attaching the blades, lightning subsequent strokes attaching to the blades, or different lightning events during the thunderstorm. In any case, the statistics here show that damage to more than one blade of a single wind turbine is a rare event.

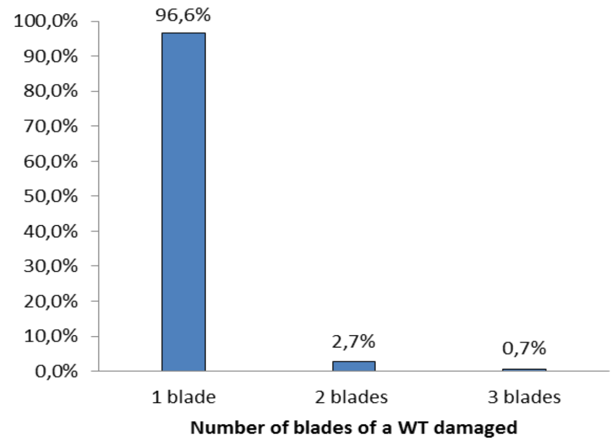

Fig. 12. Number of damaged blades of a WT reported after a thunderstorm

VI. Discussion

The analysis of the data shows that in 60% of cases, lightning damage to wind turbine blades occurs in the last meter of the blade, and in 30% of cases, lightning damage occurs in the area from 1 to 4 m from the blade tip.

The remaining events occur mainly on the area 5 to 10 m from the blade tip, although there are few events further inboard. The distribution of the damage along the blade length is similar for blades with and without carbon fiber laminate. The damage is more concentrated at the blade tip area than expected according to the risk assessment tools provided by the standard [5]. There are possible reasons for the disagreement. First of all, the electrogeometric method considers only downward lightning, while field observations have shown that tall structures like wind turbines experience a large percentage of upward lightning [11], which are typically initiated at the blade tip. Furthermore, tall structures also originate longer upward connecting leaders that may direct the downward lightning to the tip of the blade. Also, since only lightning events that caused damage are considered in this analysis, it is possible that lightning with low current peak attached the blade at inboard radii without producing significant damage. In any case, the distribution of damage along the blade obtained in this study agrees with the previous research performed by Peesapati et al. [6] and Madsen et al. [7], where in all cases the majority of the lightning strikes are concentrated at the last few meters of the blade tip and almost no strikes occur more than 10 m inboard. This suggests that the risk of direct lightning strike is much higher at the last few meters of the blade tip than at the rest of the blade, which agrees with the results of numerical models to determine the lightning strike points in wind turbines [7]. Therefore, considering the entire blade in the lightning protection zone $LPZ0_A$ as proposed by the IEC 61400-24 [5] may be inaccurate and lead to oversized lightning protection at inboard radii of the blade and too severe validation tests.

Regarding the characteristics of the damage, most of the lightning incidences resulted in delamination, in some cases accompanied by debonding of the shells. The fact that most of the damage occurred at the blade tip suggests that the efficiency of the air termination system should be improved. Since the delamination is worse where the laminate is thinner and the debonding of the shells is likely due to the air expansion during the lightning attachment, a more robust tip with less air volume may reduce the extent of damage. The damage involving shell and tip detachment is fortunately very uncommon. It consists of severe cases of delamination and debonding at critical locations made worse by the blade rotation and strong gusts of wind during the thunderstorm or simply due to continued operation after damage. The characteristics of the damage (Damage types 1 to 4) experienced in U.S are similar to the damage reported by Yokoyama et al. [8],[9]. Both studies in US and Japan show a comparable classification of the damage from reparable damage with different degree of severity (delamination, debonding) to catastrophic damage (shell or tip detachment), regardless of the configuration of the lightning protection or the blade geometry. Additionally, the pictures illustrating each type of damage for the study in US and Japan show many similarities both in the way the structural materials of the blades are damaged and in the extent of the damage. Unfortunately, the analysis performed in Japan does not include the frequency of occurrence of each type of damage, and therefore it is not possible to determine if the probability of severe damage is higher in Japanese wind farms exposed to different meteorological conditions including winter lightning.

The analysis of lightning attaching to wind turbines performed by Wilson et al. [1] shows that a significant percentage of lightning has relatively low peak current, under 30 kA and there are only few events with a peak current higher than 50 kA. This suggests that lightning with average current parameters may cause severe damage in some cases, depending on the location of the attachment, characteristics of the blade laminate and wind conditions at the moment of the lightning damage. Unfortunately, this study does not include the measurement of the lightning current parameters attaching the blade to correlate with the extent of the damage.

VII. Conclusions

This paper presented an analysis of lightning damage on wind turbine blades in the U.S. The analysis revealed that most lightning strikes to wind turbine blades are concentrated at the outermost 4 m of the blade, in particular at the last 0.5 m of the tip, regardless the blade geometry and material. The damage presented similar patterns in all the blades and could be classified in four types, including delamination, debonding, shell detachment and tip detachment. The delamination and debonding are the more common type of damage and may show different degrees of severity. The shell and tip detachment are critical for the blade integrity but are also very infrequent. The results of this study performed in the United States agrees with other studies carried out worldwide regarding the damage distribution along the blade and characteristics of the lightning damage.

References

[1] N. Wilson, J. Myers, K. L. Cummins, M. Hutchinson and A. Nag "Lightning attachment to wind turbines in Central Kansas: Video observations, correlation with the NLDN and in-situ peak current measurements", European Wind Energy Association, Vienna, 2013

[2] K. L. Cummins, D. Zhang, M. G. Quick, A. C. Garolera, J. Myers, "Overview of the Kansas Windfarm2013 Field Program", International Lightning Detection Conference, March 2014, Tucson, Arizona, U.S.A.

[3] D. Wang, N. Takagi, T. Watanabe, H. Sakurano and M. Hashimoto, "Observed characteristics of upward leaders that are initiated from a windmill and its lighting protection tower", Geophysical Research Letters, vol. 35, 2008, DOI: 10.1029/2007GL032136

[4] M. Ishii, M. Saito, D. Natsuno, A. Sugita "Lighting current observed at wind turbines at winter in Japan", International Conference on Lightning and Static Electricity, Seattle, U.S.A., 2013

[5] "IEC 61400-24 Ed.1.0: Wind turbines – Part 24: Lightning protection", IEC, June 2010

[6] V. Peesapati, I. Cotton, T. Sorensen, T. Krogh, N. Kokkinos, "Lightning protection of wind turbines – a comparison of measured data with required protection levels" IET Renewable Power Generation, vol. 5, Iss. 1, pp. 48-57, 2010

[7] S.F. Madsen, K. Bertelsen, T.H. Krogh, H.V. Erichsen, A.N. Hansen, K.B. Lønbæk, "Proposal of new zoning concept considering lightning protection of wind turbine blades", Journal of Lightning Research, vol. 4, pp. 108-117, 2012

[8] S. Yokoyama, Y. Yasuda, "Proposal of lightning damage classification to wind turbine blades", 7th Asia-Pacific International Conference on Lightning, pp. 368-371, 2011

[9] S. Yokoyama, Y. Yasuda, M. Minowa, S. Sekioka, K. Yamamoto, N. Honjo, T. Sato "Clarification of the mechanism of wind turbine blade damage taking lightning characteristics into consideration and relevant research project", International Conference on Lightning Protection, pp. 1-6, Vienna, 2012

[10] CIGRE TB 577 "Lightning protection of wind turbine blades" WG C4.409, June 2014

[11] V. Rakov and M. A. Uman, "Lightning, Physics and Effects", Cambridge Univ. Press, 2003, Cambridge, U.K.

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Søren Find Madsen received the M.Sc. degree in electrical engineering from the Technical University of Denmark (DTU) in 2001.
From 2003 to 2006 he did his PhD thesis on lightning protection of wind turbine blades (DTU), investigating numerical methods as well as high voltage and high current test techniques to verify protection concepts. He is Co-founder and Co-owner of Global Lightning Protection Services A/S, where he holds the position as CTO and is responsible for the specialist group on numerical modeling. Søren is participating actively in CIGRE and IEC work as secretary for the WG C4.36 and IEC 61400-24 maintenance process respectively.

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Jackson D. Myers received a BS degree in physics from McGill University, Canada, in 2006, and a M.S. in nanoscale physics from Rice University in 2008, USA. He is currently working as a performance data analyst for EDP Renewables North America, a developer, owner, and operator of renewable energy projects based out of Houston, Texas (USA). Jackson has been heavily involved in EDPR's lightning detection and reporting program, and has lead multiple research studies on the topic of lightning in wind farms.

Joachim Holboell is Associate Professor at the Technical University of Denmark (DTU) with many years of experience within electric power components, their properties and high frequent equivalents plus methods for condition assessment of these components. Past years focus has been on high voltage transformers and cables and, in general, components performance under AC, DC and transients. The work is now concentrated on wind turbine components, materials and high voltage research with respect to the future power grid. J. Holboell has been visiting researcher at Ontario Hydro Research, Canada, Royal Institute of Technology in Sweden and Monash University, Australia. J. Holboell is Senior Member of IEEE and member of Cigré Study Committee D1.