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Overview of lightning interaction and damages to wind turbines

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I.   Introduction

It is well known that tall structures such as telecommunication towers can be exposed to numerous lightning incidence. Wind turbines are in this group, but two particular characteristics distinguish wind turbines from the rest. The first peculiarity is that a substantial part of the structure is rotating. That corresponds to the rotor blades. The second, is also related to the rotor blades and corresponds to the intensive use of composite materials. Due to these two factors, protection against lightning requests very special attention.

Tall structures including wind turbines are exposed to downward lightning flashes and, in certain conditions, they can initiate upward lightning flashes. This is one of the reasons because a particular design of a lightning protection system (LPS) can show different efficiency in different regions depending on the thunderstorm climatology. For example, turbines affected by winter thunderstorms such as in Japan and Europe (e.g. [1-2]) suffer severe damages. The charge regions in these storms are found at significantly lower altitudes compared to ordinary thunderstorms associated to deep convection (e.g. [3]). As result, tall objects at ground have favorable conditions for upward lightning initiation. For risk assessment purposes it is very important to know the types of the storms that a wind turbine will be exposed.

The most exposed part of a wind turbine are rotor blades. Blades are typically simplified as two shells enclosing a spar. Composite materials such as glass fiber (GF) are extensively used. In addition, some blades have carbon reinforced plastics (CFRP) because its high strength to weight ratio. Carbon reinforced plastics are electrically conductive. A typical lighting protection system (LPS) of a blade consists of an air termination system and a down conductor system. Air terminals are located in the areas where lightning attachments are expected such as the tip. These air terminals, or also named as receptors, are connected to the down conductor system that brings lightning currents to ground (e.g. *IEC 61400-24, 2010*). The insulation provided by the shells is not perfect and it is possible to experience lightning attachments in areas outside of the air terminals. Since separation distance is not possible, all conductive elements in a blade must be bonded to the lightning protection system. That is the case of blades that use carbon fiber reinforced plastics (CFRP), these components shall be bonded to the lightning protection system (*IEC 61400-24, 2010*). CFRP laminates are anisotropic and poor electrically conductive. In addition, electrical connections to CFRP can be very complex since in most of the cases it is not possible to use bolted connections. Failures of the air termination system or the down conductor system cause the most dramatic lightning damages to wind turbines.

In the path to ground, lightning currents find different components. From the blade to the nacelle several elements such as pitch and shaft bearings, hydraulic actuators, main shaft and the gearbox might be affected by lightning currents. The transfer from the nacelle to the tower needs to consider the yaw system of the turbine. Tubular metallic towers are appropriate down conductors of lightning currents to ground. In the case of reinforced concrete towers, continuity of the rebar needs to be ensured. In addition to physical damages to the mentioned components, transient overvolatges might be produced due to the flowing of lightning currents through the wind turbine or induced by a nearby lightning strike.

In the first part of this work lightning interactions to wind turbines are described according to the types of thunderstorms. The effects of the different type of interactions to the calculation of risk assessment is

discussed. In the second part, lightning damages are treated. This include a review of the mechanisms of damages and statistics. The case of incidences to rotor blades, protection to CFRP components and transient overvoltages are highlighted. Finally, an overview of our current investigations is presented.

2. Lightning interactions to wind turbines

2.1 Summary

General circulation in the atmosphere determines Earth's climate and global thunderstorm distribution resulting in geographical dependence of thunderstorms and lightning. That is of importance for general lightning protection and specially of wind turbines [2]. Risk assessment is performed before the installation of a wind turbine in order to estimate the number of lightning events that it will experience in a particular location. To do that it is necessary to understand the interactions between lightning and the struck object.

Wind turbines can receive downward lighting strikes as any other structure, but due to its considerable height, turbines can efficiently initiate upward lightning. Downward lightning to wind turbines (Figure 1a) can be more common in relation to deep convective storms (e.g. summer storms in the northern hemisphere and tropical storms). Downward lightning is the most frequent type of lightning and it is a threat to wind turbines because its high frequency of occurrence. The number of downward lightning events to a particular wind turbine will depend on the height of the turbine, exposure (e.g. located on flat terrain or on a hill) and the regional ground flash density (N_g). Although downward lightning is frequent, in Europe, instrumented tall towers show that most of their events are upward.

In the case of upward lightning two situations can be distinguished: induced (Figure 1b and 1c) and self-initiated (Figure 1d and 1e). An induced upward lightning flash is related to the occurrence of a nearby flash (e.g. CG or IC). In such case, a nearby CG (Figure 1b) flash or an IC flash (Figure 1c) can produce the electric fields necessary for initiation and stable propagation of an upward leader. Upward induced lightning is more likely to occur during deep convective storms because the high occurrence of lightning. Beneath thunderstorms, the intense electric fields produced by the cloud's electrical charge can initiate corona discharges at the tips of wind turbines at ground. Corona discharge will produce some space charge (positive for a typical dipole or tripolar charge structure as discussed in [4]. As pointed out in [5], this space charge accumulates at the tip screening and thereby preventing the initiation of a leader. In order to produce a stable leader, it is convenient a temporal increase of the electric field at the tip of the turbine [6]. This increase can be produced thanks to the fast neutralization of charge in a cloud-to-ground CG lightning flash (e.g. [7-8]) or an intra-cloud IC lightning flash. Because of the slow ion mobility of the space charge at the tip of the turbine, the electric field is not screened and it is increased. In the case of wind turbines, the most favorable conditions for induced triggered lightning will be the case of a fast and large charge neutralization in nearby CG and IC flashes and with enhanced electric fields due to the terrain height (close to the cloud charge) and orography (e.g. on hill tops). In the case of self-initiated upward lightning, the most convenient situation is present in winter thunderstorms (Figure 1d to 1f). The high temperature lapse rates and the dependence of the thunderstorm electrification processes on temperature (e.g. [9-10]) in winter, cloud charges can be found at lower altitudes compared to ordinary thunderstorms. Although the lower height of the cloud charges, winter storms are not prolific generators of downward lightning (e.g. [11]). That can be explained because of the lack of opposite polarity charge under the mid-level charge region that is necessary to initiate a leader in the cloud [12]. In the case of winter storms in Europe, the authors in [3] showed that, because the low altitude of the freezing level (even at ground), the lower positive charge center in the cloud might not be accumulated and then downward lightning may not be initiated. But prominent objects on the ground or at mountain tops have favorable conditions to initiate an upward leader (e.g. [13,8]).

Upward lightning is characterized by continuing currents that can last for several hundreds of milliseconds. Long continuing currents with amplitudes of few hundreds of amperes can have more specific energy than typical return strokes with peak currents of several tens of kilo-amperes. Over continuing currents, current impulses can be found, but those usually have amplitudes of few kA. In some upward flashes return strokes are also produced, but statistics in Europe shows that the amplitudes rarely exceed few tens of kA. A more critical situation occurs in positive CG flashes. Those shows both high amplitudes of return strokes followed by continuing currents. Intense positive lightning flashes are produced in relation to stratiform regions of Mesoscale Convective Systems (Figure 1g), (e.g. [14]).

Most of the winter lightning strikes to wind turbines are upward type (e.g. [1]), the effect of rotation on the enhancement of lightning to wind turbines has been discussed and investigated (e.g. [15-16,5, 17-18]). However, there is no clear evidence that the number of lightning flashes increases significantly with the effect of rotation. In the studies in Japan [16], the authors noted slightly larger number of strikes to rotating wind turbines than to a close protecting tall tower. Recently in [5] it is shown corona/leader activity associated with rotating wind turbines (Figure 1g). This activity can last for more than an hour, especially when the turbines are under an electrically charged stratiform region of a thunderstorm. This periodic activity might stress the insulation of the rotor blades and have some future repercussion to the efficiency of attachment during lightning.
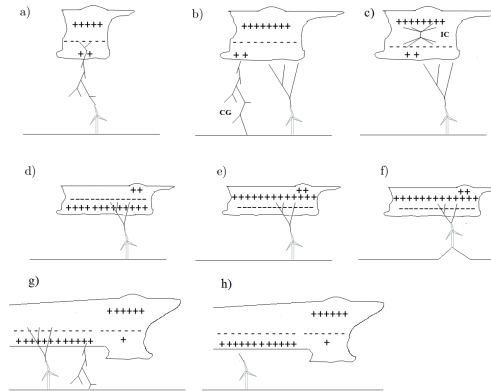

Figure 1 a) Downward lightning stroke to a wind turbine; b) Upward lightning initiated by a nearby CG flash; c) Upward lightning initiated by a IC flash; d) Self-initated wind turbine t in a winter storm (charge distribution as observed winter storms in Japan); e) Self-initated wind turbine t in a winter storm (conventional charge structure); f) Situation of a very exposed turbine to self-initiated lightning;   g)Upward and downward positive flashes in the trailing stratiform of MCS; h) Repetitive corona/leader emissions from wind turbines under storms. Proportions in these diagrams are not to scale. Adapted from [2].

Experience in tall instrumented towers in Europe has shown that they receive (actually produce) mostly upward lightning. Upward lightning is characterized by a continuing current and, in some cases, with superimposed current pulses followed by return strokes. In the case of the Gaisberg tower in Austria [19], 93 % of the flashes are negative upward initiated, 3.5 % upward positive and 3.1 % upward bipolar. A 46 % of the negative upward flashes only presented continuing currents. The median peak currents of the negative return strokes is 9.2 kA, which is much lower than the 33.3 kA found in standards (*IEC 62305-1* and *CIGRE ELECTRA no 41*). In the case of the Morro do Cachimbo's tower in Brazil [20] the situation is significantly different. In this tower, a 77 % of the events are downward flashes whereas only 23 % are upward. In this situation the majority of upward flashes might be induced by nearby flashes (personal communications) showing durations much lower than the typical upward flashes in Europe or Japan. The median peak current of the downward flashes is 45 kA which is much higher than the median peak currents found in standards. Finally, in the measurements done in Japan [1], show significant high median peak currents (>100 kA) for bipolar flashes measured in wind turbines during winter thunderstorms. In addition, a 5 % of the total measured flashes show charge larger than 300 C.

Lightning protection standards of wind turbines (e.g. *IEC 61400-24*, *2010)* base the estimation of the number of lightning events on the ground flash density N_g, the total height of the wind turbine H and a coefficient called environmental factor C_d. The effect of upward lightning is included within the C_d coefficient. But this method is not completely realistic since N_g is dominated by deep convection storms that is not representative for winter lightning. So, this method only considers the downward lightning activity. A realistic risk assessment should treat separately the estimation of downward and upward lightning. Recently, in [21] presents an engineering approach to include all the scenarios described above and produce realistic results based on observations. One of the important parameter for the estimation of the lightning events is the occurrence of winter thunderstorms in the point of interest. In order to identify areas that can be affected winter lightning, the authors in [2] have presented global maps of winter

lightning (e.g. Figure 2). The maps show how winter lightning is distributed outside of the intertropical converge zone (ITCZ). Japan, Europe and the east offshore of north of America present the highest activity.
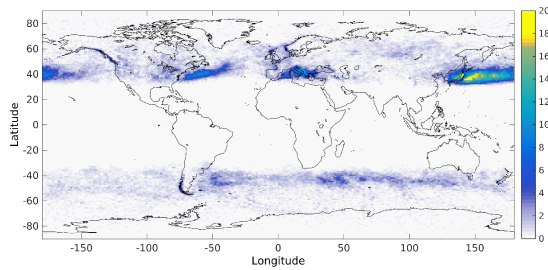

Figure 2. Global map of the average number of winter thunderstorm (TWL) days (adopted from [2]).

3. Lightning damages to wind turbines

3.1 Statistics of damages

Early comprehensive statistics in Europe of lightning damages to wind turbines during 1990-1998 ([22-23] and *CIGRE WG C4.409, 2014*) showed that control systems, electric systems and sensors were the most frequently damaged components by lightning (Figure 3a to c). Some of the turbines included in that study had rated powers <450 kW, which would correspond to blade lengths ~20 m or less. In this group (<450 kW), failures related to blade damages were ranked at the third position. The analysis for the high power wind turbines (>450 kW) brought rotor blade failures to the first (Germany) and second (Denmark) position of the typical damages. Of course, for all types of wind turbines blade damages represented the highest repair costs.
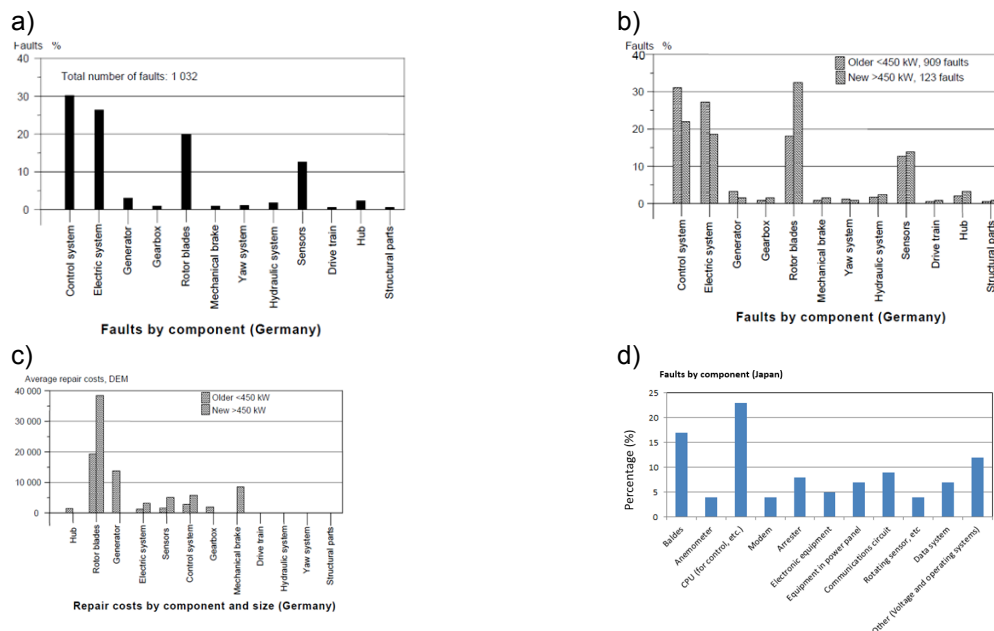

Figure 3. Faults for the period 1991-98 (see, *IEC TR-61400-24, 2002* and references therein): a) Faults caused by lightning; b) Faults distinguishing low and high power wind turbines. c) Average

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repair costs of lightning related faults. Experience in Japan: d) Faults caused by lightning in Japan ([24]).

More recent statistics (e.g. [24]) present similar behavior (Figure 3d). In Figure 3d, the number of damages to electronics of control systems competes with damages to rotor blades. However, the number of outage days and repair costs are significantly higher in the case of damages to rotor blades. Nevertheless, there is significant dependence on the thunderstorm climatology in relation to the number of failures. For instance, failures related to lightning represent about 3.7 % in Europe compared to the 22.2 % in Japan [25]. In Japan, the *CIGRE WG C4.409* report concluded that the outages of blades are 75 % of the total outages for wind turbines over 1 MW. The total outage period due to blade damages in winter is three times as much as that in summer. In addition, winter lightning damages tend to be more severe than in summer.

3.2 Mechanisms of lightning damages

First of all, the mechanisms of lightning damages are classified:

- Arc root thermal damage and heating effects, which are produced due to the contact of the lightning channel (e.g. with the air termination system). This damage is characterized by melting and vaporization of the involved components (Figure 4a). The direct plasma heat flux is due to conduction, electronic or ionic recombination and radiation flux. Also the Joule heating of the material.
- Shock wave (pressure wave): because the energy is delivered in a very short time by the return stroke, the channel pressure will exceed the pressure of the surrounding air. That will produce an expansion which takes place at supersonic speed producing a shock wave. The shock wave expansion of the channel may last less than 10 µs. As an example, a return stroke current of 30 kA would produce about 30 atm at a distance of 1 cm (Figure 4b).
- Current conduction: there are several effects due to the conduction of lightning currents (Figure 4c).
    - The first is related to electrodynamic forces. In wind turbines several paths can conduce lightning currents (e.g. down conductors and CFRP spars) which can experience electrodynamic forces.
    - The second effect is related to the overvoltages. These overvoltages are typically due to voltage drops (resistive and inductive) along conductive parts and couplings (magnetic and electric) between conductive parts. That includes overvoltages in the electric power system of the wind turbine.
- Indirect effects due to nearby lightning due to the electromagnetic fields and/or incoming currents from lines (Figure 4d).
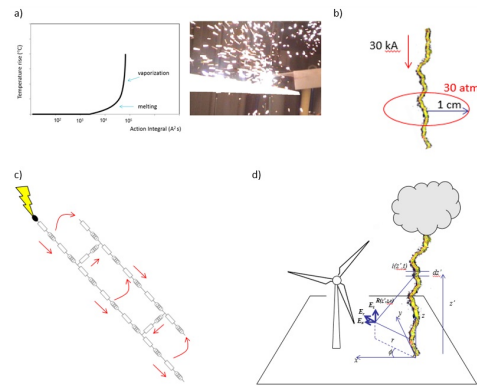
Figure 4. Lightning damage mechanisms. a) Arc root thermal; b) overpressure; c) current distribution in a blade; d) induced effects. (Adapted from [26]*).*

3.3 Summary of damages to wind turbines

Figure 5 summarizes the typical lightning damages to different components. In the figure, indirect effects represent those effects not related with the direct attachment of the lightning channel (e.g. effects derived from the current conduction).

The most exposed component of a wind turbine are the rotor blades. Blades are equipped with an air termination system that usually consists of one or several discrete receptors. It is desired that lightning will attach to these receptors and do not to another uncontrolled location. In the case of an attachment to a receptor, the most common damages are melting and vaporization of the receptor. Receptors need to be replaced during blade's lifetime, so the degradation of the receptors should still allow replacements. Experience has shown that not all the attachments occur at the receptors, in some occasions lightning produce punctures in the shells attaching uncontrolled parts such as straight to down conductors, receptor blocks, drain tubes, etc. In such cases, different damages can occur ranging from pure cosmetic to severe damages that need repair o reconstruction of the blade tip. Statistics have shown that most of the damages happen in the last meters of the blade (e.g. [26-27]). The worst scenario is when lightning channels penetrate the blade cavity. As described in the previous section, the portion of a hot lightning channel (30000 K) within the blade cavity produces an overpressure able to debond the shells.

Nevertheless, even with an efficient air termination system, severe damages to blades might occur. Once lightning currents are flowing through the down conductor system, connection components of the LPS are stressed. Blades equipped with CFRP components such as spars, those must be bonded to the LPS. Special care must be paid to electrical bonding connections between the LPS to CFRP because those connections are usually restricted to surface contacts. Due to the lower conductivity of CFRP electrodes suffer intense current densities at their edges resulting in high potential differences and arcing. The different conductive paths that lightning currents can find inside a blade, can produce high potential differences between them. In the tip area, conductive components cannot be separated and insulation results complex. If potential differences are too high, dangerous sparks can happen within the blade producing serious damages. If those sparks involve CFRP components delamination will happen. Conduction of lightning currents inside the blades can also induce overvoltages electrical circuits such as signalization, sensors and actuators.

Direct impacts to the nacelle are not common. Meteorological instruments and warning lights are protected against direct attachments by means of air terminals. Most nacelles made with glass fiber and some manufacturers protect by means of a mesh. Another component that it is rarely struck by direct lightning but needs to be protected is the spinner.

Lightning currents from rotor blades are transferred to the nacelle by means of several techniques. Some designs use spark gaps, brushes or simply allow currents to be transferred through the main shaft and its bearings. Bearing damages are still under consideration in wind turbine standards. Pitting of

bearings have been found in helicopters but there are no many evidences or reports belonging to wind turbines. On the other hand, inside the nacelle and rotor hub lightning currents can produce intense magnetic fields that can induce overvoltages to the electrical wiring. Overvoltages to electronic control systems, sensors and communications are common and produce frequent damages.

There are not many evidences of direct strikes to towers. Towers provide convenient paths to lightning currents from the nacelle to the ground. Steel towers are continuous and provide good conductive paths and shielding. Concrete towers are built with precast elements. Rebars of the elements are part of the down conductor system and suitable connections are required (e.g. according to *IEC 62561-1*). In addition, precast elements shall be interconnected to produce a continuous path to ground. The use of tall precast towers is relatively recent in the wind energy industry and there are not many evidences of damages produced by lightning.

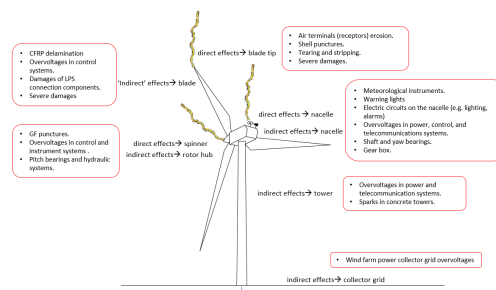Finally, propagation of overvoltages along the wind farm collector grid have been identified.

Figure 5. Distribution of lightning damages in a wind turbine (adapted from [26]*).*

3.4 Classification and examples of lightning damages to wind turbine blades

The *CIGRE C4.409* working group proposed a classification of the lightning damages to wind turbine blades according to the severities. Damages are classified as catastrophic, serious, normal and minor. Catastrophic damages are those that require and immediate turbine shutdown. Some of these damages are blade breakdown and collapse (Figures 6a and 6c), burnout and melting of the down conductor (Figure 6b), etc.
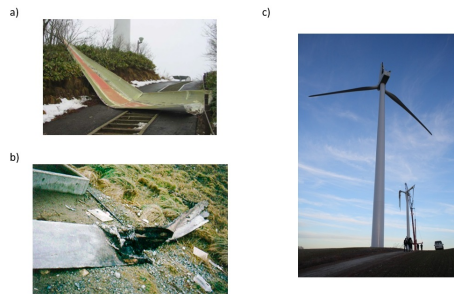

Figure 6 a) Blade breakdown (from *CIGRE WG C4.409, 2014*); b) Blade burnout and wire melting (from *CIGRE WG C4.409, 2014*); c) Blade collapse and destruction (from [5]).

Serious damages require immediate repair. These damages include surface cracking (Figure 7a), tearing (Figure 7b) and receptor loss (Figure 7c).
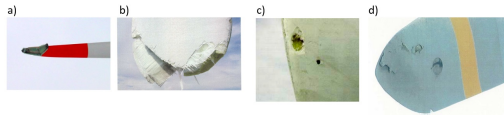
Figure 7 a) Cracking along bond weld; b) Surface tearing; c) Receptor loss; d) surface stripping. All images are adopted from *CIGRE WG C4.409, 2014* and references therein.

Damages classified as normal are those that require repair as soon as possible such as stripping of the blade surface (Figure 7d). Damages that do not imply immediate fix are grouped as minor. Some of these damages are receptor vaporization (Figure 8a), surface scorching (Figure 8b), punctures (Figure 8c), erosion (Figure 8d and e) and other minor damages.
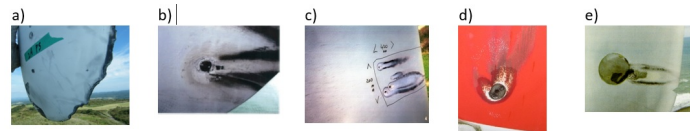

Figure 8 a) receptor vaporization (adopted from *CIGRE WG C4.409, 2014*); b) surface scorching (adopted from *CIGRE WG C4.409, 2014*); c) Shell punctures (*Adopted from [28]*); d) and e) Receptor and surface (adopted from *CIGRE WG C4.409, 2014*).

3.5 Particularities of CFRP components

Some wind turbine blades use CFRP because their good mechanical strength properties with a reduced weight. CFRP can be found as part of spars and in other structural elements. Unidirectional type of CFRP is the most commonly used in blades. This type of CFRP have the carbon fibers aligned in one direction. From the electric point of view this results in a very anisotropic properties. As example, a unidirectional CFRP can present a conductivity of 40 kS/m in the direction of the fibers and conductivities of 4 kS/m and 0.4 kS/m along the other perpendicular axis. This anisotropy produces that currents will not distribute easily along all directions (Figure 9). Despite large cross-sections can be available, currents can be confined in small sections (e.g. Figure 9c)
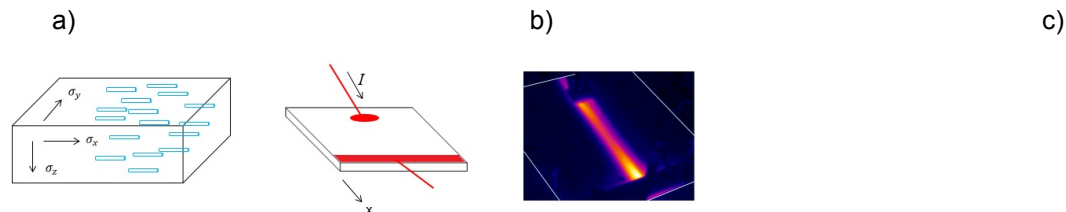

Figure 9. a) Sketch of a unidirectional CFRP; b) Illustration of a test of a CFRP coupon; c) Thermal image of the test described in b. (Adopted from [29]).

In order to distribute lightning currents efficiently in CRFP components, connections shall be designed considering the particularities of these components. Connections shall have an appropriate size in order to spread lightning currents over the available width. Due to the low conductivity of the CFRP compared to copper (~three orders of magnitude), high current densities might be present at the edges of the connections (Figure 10a). Intense current densities can produce high potential differences at the contact resulting in electric arcs. This situation is highly dangerous because delamination can occur weakening

seriously the area. In addition, efficient connections to CFRP are not trivial since in most of the cases those cannot be bolted being limited to surface contacts. In addition, sometimes connections are only possible in one side of the CFRP laminate. In that case, in [30] the authors studied the potential distribution in the sides of a CFRP coupon and its potential differences (Figure 10b).

a)

b)

Figure 10. a) Current density in a simulated electrical connection to a CFRP coupon (adopted from *Romero et al., 2014*); b) Distribution of the potential difference between two faces of the coupon in Figure 10 (adopted from [30]).

In some blades, CFRP occupies large portions (e.g. caps in spars) providing a long parallel path for lightning currents from the tip to the root (Figure 11). In such cases, dangerous sparks shall be avoided between the down conductor system and the CFRP.
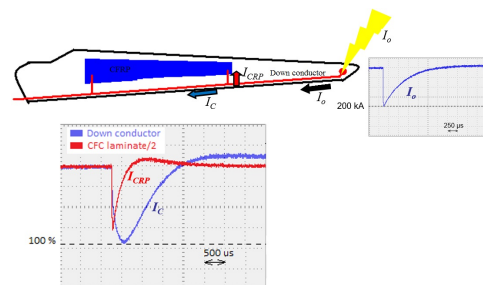

Figure 11. Example of test results of a wind turbine blade. Current I_o was injected at the tip. Current distribution to down conductor I_{CRP} and to CFRP spar I_{CRP} are plotted in the lower graph. (Adopted from [29]).

In [29] it was presented experimental and simulation results of current distributions in a full scale experimental CFRP blade (Figure 11). In that blade, CFRP laminates formed the caps of the spar. At the tip the width was less than 20 cm whereas at the root it was more than a meter. The thickness also varies along the blade axis. At the tip the thickness was just few millimeters whereas at the root was several centimeters. Test results show how higher frequency components (during the rise) of the current preferred the high resistive but low inductive path of the CFRP whereas low frequency components preferred the low resistive down conductor. This effect is convenient because the energy to the CFRP is reduced, but it has the risk that high peak currents are present in the CFRP. These high peak currents can produce high voltage drops at the connections.

3.6 Overvoltages on the electric power systems of wind turbines

Not all wind turbines have the same configuration of the electric power system, that will depend, among other factors, on the type of generator and the location of the power transformer. Figure 12 presents a typical diagram of a wind turbine with a doubly-fed induction generator (DFIG). In the diagram, the stator of the generator is connected to the low voltage side of the power transformer. The rotor of the generator also feeds the low voltage side of the transformer by means a power converter. The low voltage side of the transformer is typically wye connection with the neutral connected strait to the nacelle (in this case). The high voltage side is typically delta connected. Overvoltages are typically limited by means of the

installation of surge arresters at the high voltage side of the transformer and shielding. Of course surge protective devices are also present in the low voltage circuits.
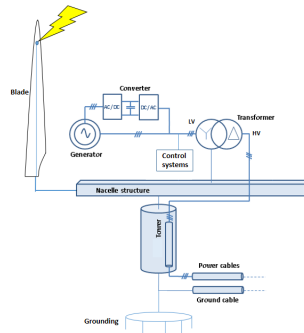

Figure 12. Electric power diagram of a wind turbine with a doubly-fed induction generator and its power transformer at the nacelle (based on IEC 61400-24). Surge arresters are not included.

When lightning strikes a wind turbine current flows to ground through its down conductor system. That comprises several natural elements such as the nacelle and the tower. In order to investigate the overvoltages all those elements need to be included and modelled. As an example, even the nacelle is a massive metallic structure an electric model is needed because the distribution of the currents affects to the magnetic fields that in turn induce voltages to electrical conductors. Beside the down conductor system, the electric system shall be modelled in such way to represent the transient (or high frequency) behavior. Many works have considered the high frequency behavior of power transformers (e.g. [31]). As summary, transfer overvoltages in a transformer are mainly governed by the capacitances between primary and secondary and between ground (Figure 13a). In many wind turbines, power transformers are dry-type which typically presents lower capacitances compared to liquid-cooled transformers. Another element to consider is the power converter. The high frequency behavior of a power converter in the overvoltage investigations has been poorly treated. In [32] and references there in, a model has been presented (Figure 13b), however a converter is highly non-linear. At lower frequencies the semiconductors and the DC-link capacitors governs the behavior of the transfer overvoltages whereas at higher frequency the transfer is mostly due to capacitive effects and becomes more linear.
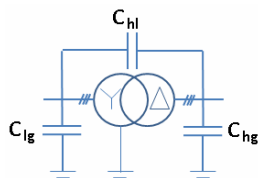
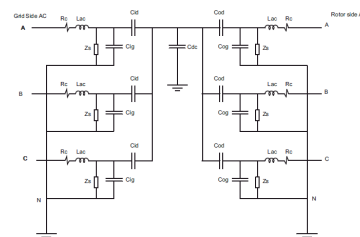a)   b)

Figure 13. a) Basic high frequency model of a transformer. b) Example of high frequency model of a AC-AC converter (adopted from [32]).

The grounding system of a wind turbine is well defined in the IEC 61400-24 standard. The response of the grounding system against lightning currents influences the overvoltages in the power electric system of the wind turbines. Modern wind turbines have appropriate designs of the grounding system but, in some cases, installations in highly resistive soils need special consideration.

Since lightning currents can present different components that shall also be considered in order to estimate the transients. Figure 14 shows the simulated potential of the nacelle due to different lightning components (1st negative return stroke IEC, 2nd or subsequent negative return strokes IEC, 1st positive return stroke IEC and superimposed impulses associated to upward lightning flashes).
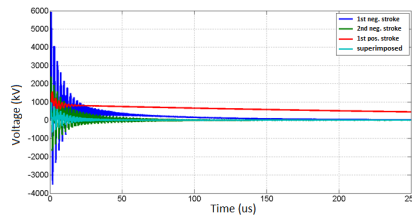
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Figure 14. Simulated transient potential at nacelle frame for median values of different types of lightning transients (1st negative return stroke IEC, 2nd or subsequent negative return strokes IEC, 1st positive return stroke IEC and superimposed impulses associated to upward lightning flashes). Ground system is type B of IEC 61400-24 with a resistivity of 750 Ωm.

And Figure 15 presents an example of the overvotlages in the absence of surge arrestors at both sides of the power transformer for a lightning current corresponding to the first return stroke in negative flashes defined by IEC.
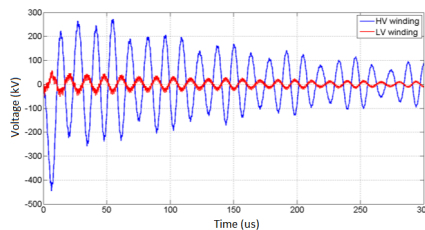

Figure 15. Simulated transient overvoltage at both sides of the power transformer in the absence of surge arrestors. Lightning current is represented by the first return stroke defined by IEC.

The design of the overvoltage protection of wind turbines includes the establishment of the lightning protection zones (LPZ) defined in IEC. These zones are characterized by their shielding of the lightning electromagnetic fields, their limitation of the currents by means of sharing and the use of surge protective devices (SPD).

4. Current investigations

Our current investigations are related to the induced charge of rotor blades and its consequences to control and electronic systems of wind turbines. In [5] periodic discharges from wind turbines were found for long periods under the influence of electrically charged clouds. Later in [33] it was found that these emissions were also present during fair weather conditions. This discharges are assumed to be corona but the fact that are detected by distant Lightning Mapping Array stations means that are highly energetic compared to regular coronas from power lines. One of the object of the research is to understand how blades are charged. In [32] the authors assumed that the mechanism of charging is triboelectric, but the lack of relatively large particles (e.g. water or ice) interacting with the blade are not present in clean air. In

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[34] the autohrs argued that the charging mechanism of a blade during fair weather in clean air shall be due to electrostatic induction due to the fair weather atmospheric potential. In fair weather, a 200 m wind turbines picks up about 50 kV of atmospheric potential. That will stablish a charge distribution on a wind turbine by virtue of electrostatic induction.

a)

b)

Figure 16. a) Simplified geometry of a wind turbine. b) Induced charge in a wind turbine under fair weather. (Adopted from [34]).

  With the resulted induced charge [24], it was obtained that a 200 m tall wind turbine will experience an electric field ~100 kV/m close to the tip during fair weather (Figure 17). This electric field could enable the intense corona discharges detected by means of the Lightning Mapping Array.
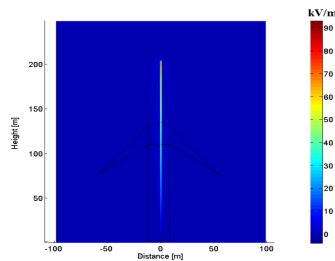

Figure 16. Electric field at the wind turbine during fair weather simplified by a vertical thin wire (Adopted from [34]).

Although the induced charge and electric fields during fair weather are not a threat to the current wind turbines, future designs with more control and sensor systems within blades can be affected by intense electrostatic discharge. Of course, this effect is highly enhanced when turbines are beneath or at the vicinity of electrified clouds.

5. Conclusions

    First, the thunderstorm climatology and the exposure of a wind turbine determine the lightning environment that a wind turbine will be exposed. That is of importance in order to perform the risk assessment. The guidelines of a method to evaluate the number of lightning events to a wind turbine has been discussed. A convenient method shall take into account independently both downward and upward flashes. Current lightning protection standards use the ground flash density to estimate the upward lightning portion. However, self-initiated upward lightning are not related to the downward cloud-to-ground lightning activity and depends on the situations like winter thunderstorms.

    Second, the mechanisms of lightning damages have been summarized. From arc root thermal effects, electrodynamic forces, effects derived to the current conduction to induced effects form the common primary mechanism of damages. Damages at different parts of the wind turbine have been explained. Since blades are the most exposed part of a wind turbine their damages have been classified and discussed. The worst damages are found when lightning channels punctures the blade and attach to any

conductive component within the blade cavity. The particularities of blades using CFRP have been detailed.

Third, overvoltages in the electric power systems of wind turbines have been discussed. An accurate estimation shall take into account suitable transient models of the components such as the transformer, generator and the power converter as well of the structural parts such as blades, nacelle and tower. Because the lack of attenuation of the electromagnetic fields at the nacelle, magnetic field analysis needs to be performed in order to investigate the induced overvoltages and its mitigation. Grounding has strong incidence on the overvoltage.

Fourth, our current investigations of the induced charge during fair weather and thunderstorms has been introduced. Next generation of wind turbines will have more sensor and control systems within the blades that, without the correct protection design, can be very affected by electrostatic discharge.

To sum up, wind turbines are very particular kind of structures due its rotation and the use of composite materials. In the near future the challenges will be increased because the addition of more control systems in blades and the large offshore installations.

Acknowledgments

References

1. Honjo, N.: Risk and its reduction measure for wind turbine against the winter lightning, in Proc. Asia-Pacific Intl. Conf. on Lightning, 2015, pp. 665-670, 2015.
2. Montanyà, J., Fabró, F., van der Velde, O., March, V., Williams, E. R., Pineda, N., Romero, D., Solà, G., and Freijo, M.: Global Distribution of Winter Lightning: a threat to wind turbines and aircraft, Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2015-302, in review, 2016.
3. Montanyà, J., Soula, S., Diendorfer, G., Solà, G., and D. Romero, D.: Analysis of the altitude of the isotherms and the electrical charge for flashes that struck the Gaisberg tower, in Proc. Intl. Conf. on Atmospheric Electricity, 2007.
4. Williams, E. R., "The tripole structure of thunderstorms," J. Geophys. Res., 94(D11), pp. 13151-13167, 1989.
5. Montanyà, J., van der Velde, O., and Williams, E. R.: Lightning discharges produced by wind turbines, J. Geophys. Res. Atmos., 119, 1455–1462, 2014.
6. Bazelyan, E.M. and Raizer, Y. P.: Spark Discharge. CRC Press Inc., 1998.
7. Warner, T. A., Cummins, K. L., and Orville, R. E.: Upward lightning observations from towers in Rapid City, South Dakota and comparison with National Lightning Detection Network data, 2004-2010, J. of Geophys. Res., vol. 117, D19109, doi:10.1029/2012JD018346, 2012.
8. Montanyà, J., Fabró, F., van der Velde, O., Romero, D., Solà, G., Hermoso, J. R., Soula, S., Williams, E. R., and Pineda, N.:Registration of X-rays at 2500 m altitude in association with lightning flashes and thunderstorms, J. Geophys. Res. Atmos., 119, 1492–1503, 2014.
9. Takahashi, T.: Thunderstorm electrification-A numerical study, J. Atmos. Sci., 41, 2541-2558, 1984.
10. Saunders, C.P.R, Bax-Norman, H., Emersic, C., Avila, E.E., Castellano, N. E.: Laboratory studies of the effect of cloud conditions on graupel/crystal charge transfer in thunderstorm electrification, Q. J. R. Meteorol. Soc., 132, 2653–2674, 2006.
11. Michimoto, K.: A study of radar echoes and their relation to lightning discharges of thunderclouds in the Hokuriku district. II: Observation and analysis of "single-flash" thunderclouds in midwinter, J. Meteorol. Soc. Jpn., 71, 195–204, 1993.
12. Krehbiel, P.R., Riousset, J. A., Pasko, V. P., Thomas, R. J., Rison, W., Stanley, M. A., and Edens, H. E.: Upward electrical discharges from thunderstorms, Nature Geoscience, 1, 233 – 237, 2008.

13. Warner, T. A., Lang, T. J., and Lyons W. A.: Synoptic scale outbreak of self-initiated upward lightning (SIUL) from tall structures during the central U.S. blizzard of 1–2 February 2011, J. Geophys. Res. Atmos., 119, 9530–9548, 2014.
14. MacGorman, D., and Morgenstern C. D.: Some characteristics of cloud to ground lightning in mesoscale convective systems, J. Geophys. Res., 103(D12), 14011–14023, 1998.
15. Rachidi, F., Rubinstein, M., Montanyà, J., Bermudez, J. L., Rodriguez, R., Solà, G., and Korovkin, N.: Review of current issues in lightning protection of new generation wind turbine blades, IEEE Trans. Ind. Electron., 55(6), 2489–2496, 2008.
16. Wang, D., Takagi, N., Watanabe, T., Sakurano, N., and Hashimoto, M.: Observed characteristics of upward leaders that are initiated from a windmill and its lightning protection tower, Geophys. Res. Lett., 35, L0280, doi:10.1029/2007GL032136, 2008.
17. Radičević, R.M., Savic, M. S., Madsen, S. F., and Badea, I.: Impact of wind turbine blade rotation on the lightning strike incidence – A theoretical and experimental study using a reduced-size model, Energy, 45, 644-654, 2012.
18. Wu, T., D. Wang, W. Rison, R. J. Thomas, H. E. Edens, N. Takagi, and P. R. Krehbiel (2017), Corona discharges from a windmill and its lightning protection tower in winter thunderstorms, J. Geophys. Res. Atmos., 122, 4849–4865, doi:10.1002/2016JD025832.
19. Diendorfer et al., 2019) Some Parameters of Negative Upward-Initiated Lightning to the Gaisberg Tower (2000–2007), IEEE Transactions on Electromagnetic Compatibility, vol. 51, no. 3, August 2009.
20. Visacro, S, et al., "Statistical analysis of lightning current parameters: Measurements at Morro do Cachimbo Station," J. Geophys. Res., vol. 109, p. D01105, 2004.
21. March, V., Lightning risk assessment to wind turbines: Methodology and guidelines, in Proc. Of the 33rd ICLP, Portugal, 2016.
22. Sorensen, T., M.H. Brask, P. Grabau, K. Olsen and M.L. Olsen, Lighting damages to power generating wind turbines, in Proc. of the 24th ICLP, England, 1998.
23. Cotton, I., B. McNiff, T. Sorensen, W. Zischank, P. Christiansen, M. Hoppe-Kilpper, S. Ramakers, P. Pettersson and E. Muljadi, Lightning protection for wind turbines, in Proc. of the 25th ICLP, Greece, 2000.
24. Ideno, M. and K. Seki, Study on improvement of performance of wind power generation system and lightning damage, in Proc. Of the 28th ICLP, Japan, 2006
25. Mizuno, E., Overview of wind energy policy and development in Japan, Renewable and Sustainable Energy Reviews, 40, pp. 999-1018, 2014.
26. Montanyà, J., Lightning damages to wind turbines, workshop of the IEEE EMC & SI, Santa Clara, CA, 2015.
27. Candela, A., S.F. Madsen, N. Nissim, J.D. Myers and J. Holboell, Lightning Damage to wind turbine blades from wind farm in U.S., IEEE Trans. On Power Delivery, 99, DOI: 10.1109/TPWRD.2014.2370682, 2014.
28. Minowa, M., M. Minami and M. Yoda, Research into lightning damages and protection systems for wind power plant in japan, in Proc. of the 28th ICLP, Japan, 2006.
29. Romero, D., J. Montanyà and J. Vinck, Test and simulation of lightning current distribution on a wind turbine blade, in Proc. of the 32nd ICLP, China, 2014.
30. Montanyà, J., D. Romero, R. López and G. Tobella, Experimental determination of potential distribution on a CFRP laminate and thermal images of DC and impulse currents: evaluation of connections, in proc. of the Asia Pacific Lightning conference (APL 2015), Nagoya, Japan, 2015.
31. Piantini A. et al, A simple transformer model for analysis of transferred lightning surges from MV to LV lines, In Proc. of the 15th International Conference on Electricity Distribution (15th CIRED), Nice, 1999.
32. Méndez, Y., Tsovilisc T.E., Asimakopoulouc F., Politisc Z., Bartond W. and Martínez M., Simulation approach on rotor blade electrostatic charging and itseffect on the lightning overvoltages in wind parks, Electric Power Systems Research 139, pp. 22–31, 2016.
33. Rison, W, K. Cummins, R. Thomas, P. Krehbiel, D. Rodeheffer, M. Quick, and J. Myers, "Observations of corona discharges from wind turbines," in proc of International Conference on Lightning and Static Electricity, Toulouse, France, 2015.

34. López, J., Montanyà, J, O. van der Velde, F. Fabró, D. Romero, Fair Weather Induced Charges and Currents on Tall Wind Turbines and Experiments with Kites, in Proc. of the 33rd ICLP, Portugal, 2016.