Lightning interaction and damages to wind turbines

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Abstract

1. Introduction

Multi-megawatt wind turbines are a special type of tall structures. Two characteristics stand out from other tall objects such as buildings and telecommunication towers. The first particularity is that a large part of the structure is rotating, and the second, is the extensive use of composite materials in the rotor blades. Due to these two factors, the protection against lightning requests very special attention.

Wind turbines installed all over the world have shown how a particular design of their lightning protection system (LPS) can perform very different in areas with different thunderstorm climatology. Up to now, the most severe damages are reported in those areas affected by winter thunderstorms such as Japan and Europe (e.g. *Honjo, 2015*). These type of storms pose the most favorable conditions for upward lightning initiation from tall structures. That is because the heights of charge regions of winter thunderstorms are significantly low (e.g. *Montanyà et al., 2007*).

On the other hand, most wind turbine blades are built wind composite materials such as glass fibers (GF) and carbon reinforced plastics (CFRP). Blades are typically composed of two shells enclosing a spar. The lighting protection system consists of one or several air terminals connected to a down conductor that brings lightning currents to ground (e.g. *IEC 61400-24, 2010*). However, the insulation provided by the shells is not perfect and it is possible to experience lightning attachments to non-desired locations. Some blades are equipped with electrically conductive carbon fiber reinforced plastics (CFRP), these components shall be bonded to the lightning protection system (*IEC 61400-24, 2010*). CFRP laminates are poor conductive presenting high anisotropy. Moreover, electrical connections to CFRP can be very complex because in most of the cases it is not possible to use bolted connections.

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 blades and protection to CFRP components are highlighted.

2. Lightning interactions with wind turbines

2.1 Summary of lightning interactions

General circulation in the atmosphere determines Earth's climate and thunderstorm distribution producing that thunderstorms and lightning differ from different geographical locations. That is of importance for lightning protection of wind turbines because the same design can be submitted to very different conditions (*Montanyà et al., 2016*). Before the installation of a turbine, engineers do the risk assessment in order to estimate the number of lightning events that a wind turbine will experience in a particular location. Risk assessment can only be done effectively with a complete understanding of the interactions between lightning and the struck object.

Wind turbines are tall structures and in this way can receive downward and initiate upward lightning. Downward lightning to wind turbines (Figure 1a) can be more common in relation to deep convective situations (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. The number of downward lightning events to a particular wind turbine will depend on the exposure of the turbine and the regional ground flash density (N_g).

In the case of upward lightning two situations are distinguished: induced (Figure 1b and 1c) and self-initiated (Figure 1d and 1e). An induced upward lighnting flash is related to the occurrence of a nearby flash (e.g. IC or CG) which do not strike the wind turbine. In such case, a nearby CG (figure 1b) flash or an IC flash (Figure 1c) can provide the electric fields necessary for the inception 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. Under a thunderstorm, due to the intense electric fields produced by cloud charges, wind turbines can produce corona discharges. By means of corona, electric space charge is produced (positive for a typical dipole or tripolar charge structure as discussed in *Williams, 1989*). As indicated by *Montanyà et al. (2014a)* this space charge screens the electric field at the turbine tip 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 turbine (*Bazelyan and Raizer, 1998*). This increase can be produced thanks to the fast neutralization of charge produced in a CG (e.g. *Warner et al., 2012* and *Montanyà et al., 2014b*) or an IC 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).

A more favorable situation for self-initiated upward lightning is present in winter thunderstorms (Figure 1d to 1f). Resulting from the dependence of the electrification processes on temperature (e.g. *Takahashi, 1984 and Saunders et al., 2006*), in winter, cloud charges can be found at lower altitudes. Although the lower height of the cloud charges, winter storms are not prolific generators of downward lightning (e.g. *Michimoto, 1993*). That might 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 (*Krehbiel et al., 2008*). In the case of winter storms in Europe, *Montanyà et al. (2007)* 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. *Warner et al., 2014* and *Montanyà et al., 2014b*).

Another special situation characterized by energetic lightning is produced in relation to the stratiform regions of Mesoscale Convective Systems (MCS) (Figure 1g). MCS are common in winter storm structures (e.g. Mediterranean storms). MCS can present a higher percentage of positive CG lightning flashes and higher peak currents than produced by cellular summer storms (e.g. *MacGorman and Morgenstern, 1998*). It is well known that intense +CG flashes occur in the stratiform regions of MCSs that also excite sprites in the mesosphere (e.g. *Lyons, 1996 and Montanyà et al., 2011*). These intense positive CG flashes can transfer hundreds of Coulombs of charge with continuing currents lasting up to tens of milliseconds (e.g. *Li et al., 2008*). Although downward positive flashes to wind turbines are not common, these can induce the inception of upward flashes. However there is significant variation from one MCS to another.

Since most of the winter lightning strikes to turbines belong to the upward lightning type (*Honjo, 2015*), the effect of rotation on the enhancement of lightning inception has been discussed and investigated (e.g. *Rachidi et al., 2008, Wang et al, 2008, Montanyà et al., 2014a and Radičević et al., 2012*). However, there is no clear evidence that the number of lightning flashes increases significantly with the effect of rotation. In the studies by *Wang et al. (2008)* in Japan, the authors noted slightly larger number of strikes to rotating wind turbines than to a nearby protecting tall tower. Recently *Montanyà et al. (2014a)* showed 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. This activity, although not results in a complete lightning flash, it can stress the dielectric properties of blades and needs to be considered in lightning protection standards.

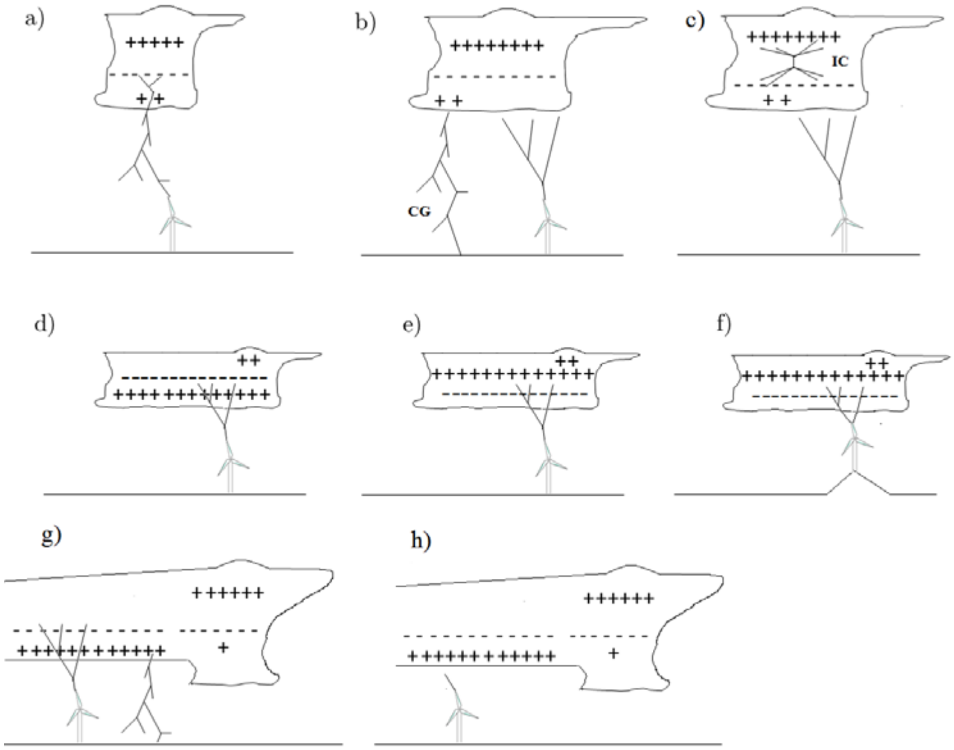

Figure 1 a) Downward lightning stroke to a wind turbine; b) Upward lightning initiated by a nearby CG flash; c) Upward lightning initiated by a IC flash; d) Self-initated wind turbine t in a winter storm (charge distribution as observed winter storms in Japan); e) Self-initated wind turbine t in a winter 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 *Montanyà et al., 2016*.

It has been discussed the different thunderstorm and lightning environment that wind turbines can experience. Since the type of interactions depends on the thunderstorm climatology, it is very important to consider it in order to perform the risk assessment. Currently, lightning protection standards of wind turbines (e.g. *IEC 61400-24, 2010)* use the following method to estimate the total number of lightning events (N_d) to a wind turbine:

$$N_d = N_g 9\pi H^2 C_d 10^{-6} \ \text{[year}^{-1}\text{]} \qquad (1)$$

where N_g is the ground flash density, H is the total height of the wind turbine and C_d is the environmental factor. In the equation, the effect of upward lightning is included within the C_d factor. But this method seems to not be completely realistic because N_g is dominated by deep convection storms which is not representative for winter lightning. A realistic risk assessment should treat separately the estimation of downward and upward lightning. In *Rachidi et al. (2008)* it was discussed the separation between downward (N_{dw}) and upward (N_u) when estimating the total number of events N:

$$N = N_{dw} + N_u \qquad (2)$$

In (2) N_u is calculating by the difference between N and N_{dw}. Where N_{dw} is calculated from equation (1) with a C_d=1 and N with the formula from *Eriksson (1987):*

$$N = N_g\, 24\ {h_{eff}}^{2.05}\, 10^{-6}\ [\text{year}^{-1}] \qquad (3)$$

where h_{eff} is the effective height of the structure. The effective height concept is appropriate once the structure is erected and there is enough historical data. Nevertheless, the dependence of N_g in (3) implies that, for a correct estimation of N, N_g shall be representative of deep convective thunderstorms and winter thunderstorms. Then a precise method for estimation the total number of events would calculate separately each type of contribution:

$$N = N_{dw} + N_{iu} + N_{su} \qquad (4)$$

where N_{iu} is the number of induced upward flashes and N_{su} is the number of self initiated upwawd flashes. The N_{su} depends on N_g but excluding the collection area. Experience (e.g. *Montanyà et al., 2014b and Warner et al., 2012*) show that intense nearby CG provide favorable conditions for upward initiation. Thus, an approach shall calculate the area of nearby lighnting excluding the collection area and taking into account that $I/d_c \propto const$, where d_c is the distance of the flash respect the wind turbine*:*

$$N_{iu} = N_g \pi \left[\int_{I_{min}}^{I_{max}} d_c(I, d > 3H) f(I) dI - 3H\right]^2 10^{-6}\ [\text{year}^{-1}] \qquad (5)$$

For the evaluation of the N_{su}, it does not depend on an N_g in the form in it is commonly calculated. One option is to use the number of days of winter thunderstorms (T_{WL}) which means the number of times in which the turbine can experience the necessary conditions for self-induced upward leader generation:

$$N_{su} = T_{WL}\, f(h_t) P_u \qquad (6)$$

where $f(h_t)$ is a function of the wind turbine height and its exposure (e.g. distance above sea level). The coefficient P_u is the probability that a turbine initiates an upward leader when the conditions are favorable. In order to identify in advance areas that can be affected winter lightning, recently, *Montanyà et al. (2016)* presented global maps of winter lightning (e.g. Figure 3). 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.

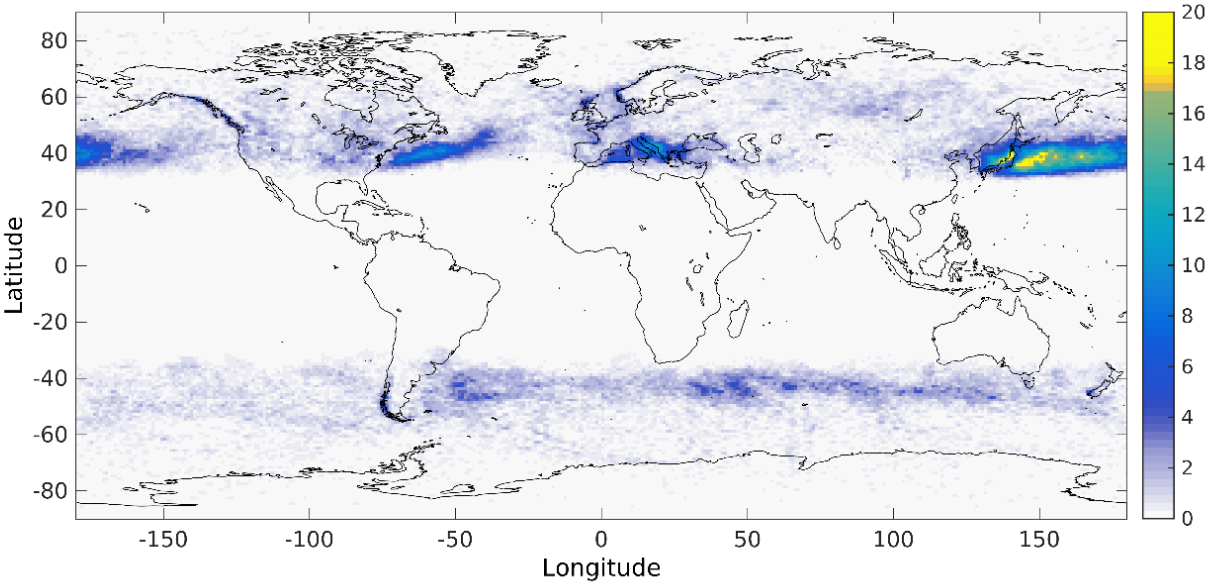

Figure 3. Global map of the average number of winter thunderstorm (TWL) days (adopted from *Montanyà et al., 2016*).

Besides the differences on the number of lightning events that a particular thunderstorm climatology can pose to a wind turbine, lightning currents can be different too. Lightning protection of structures (e.g. *IEC 62305*) are commonly based on downward lightning. A downward negative lightning flash is characterized by one or several return strokes and, in some occasions, continuing currents can appear. In the case of positive downward flashes, most of them present only one stroke followed by continuing currents. Experience in tall structures in Europe showed that they receive 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 (*Diendorfer et al., 2019*), 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 (*Viscaro et al. 2004*) 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 currents 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, (*Honjo, 2015*) 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.

3. Lightning damages to wind turbines

3.1 Statistics of damages

Early comprehensive statistics of lightning damages to wind turbines for the period 1990-1998 (*Sorensen et al., 1998; Cotton et al., 2000* and *CIGRE WG C4.409, 2014*) in Europe showed that control systems, electric systems and sensors were the most affected parts (Figure 4a to c). Some of those turbines had rated powers lower than 450 kW, which would correspond to blade lengths ~20 m or less. Failures related to blades were located at the third position. The analysis separating low power (<450 kW) and high power turbines (>450 kW) brought rotor blade failures to the first (Germany) and second (Denmark) position of the typical damages. Of course, for all kinds of wind turbines blade damages represented the highest repair costs.

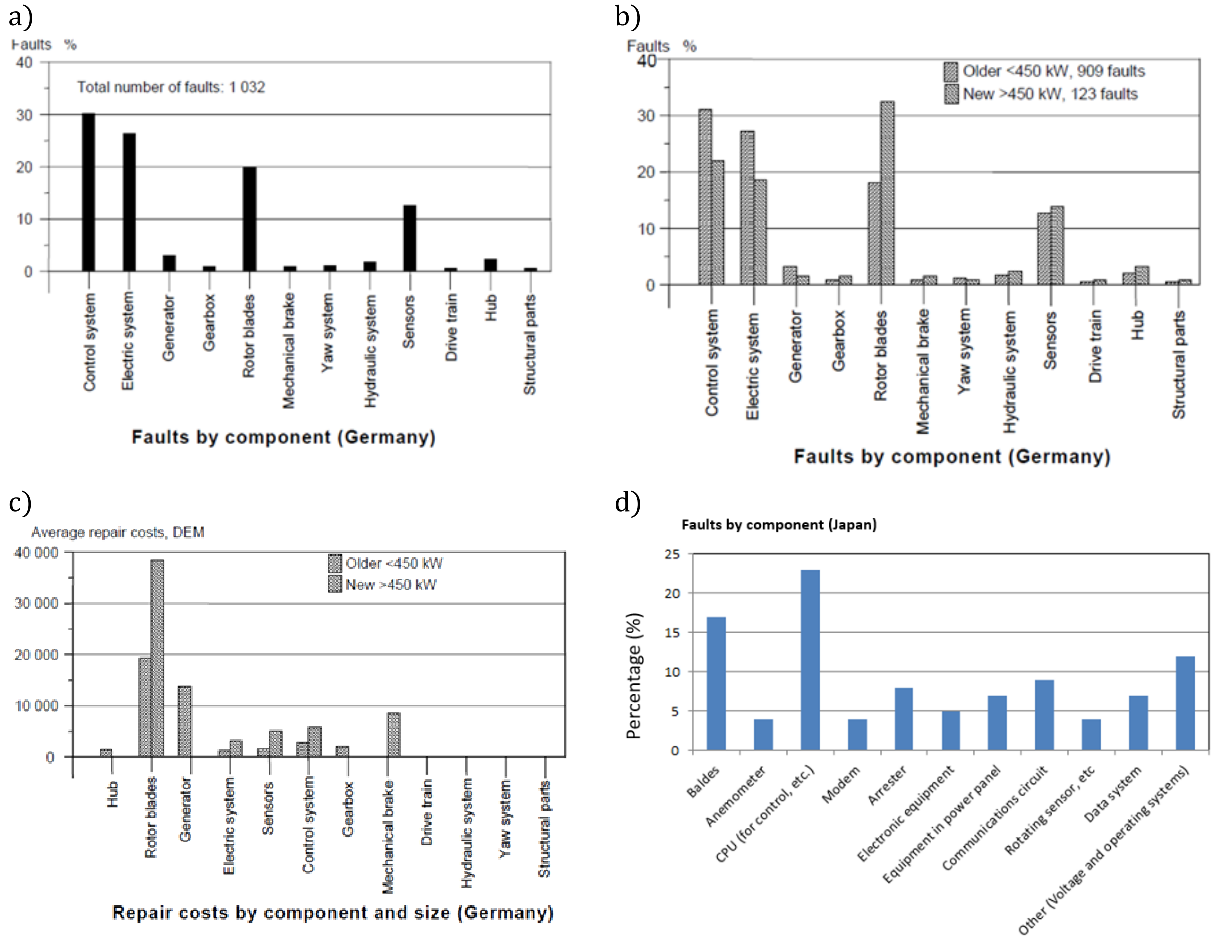

Figure 4. Faults for the period 1991-98 (see, *IEC TR-61400-24, 2002* and references therein): a) Faults caused by lightning; b) Faults distinguishing low and high power wind turbines. c) Average repair costs of lightning related faults. Experience in Japan: d) Faults caused by lightning in Japan (*Ideno, 2006*).

Recent statistics (e.g *Ideno, 2006*) present similar behavior (Figure 4d). In Figure 4d, the number of damages to electronics of control systems competes with damages to rotor blades. However, the number of outage days and the 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 (*Mizuno, 2014*). 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 serious than in summer.

3.2.1 Mechanisms of lightning damages

Before the description of the different lightning damages that a wind turbine can experience the damage mechanisms 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 5a). 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 5b).
- Current conduction: there are several effects due to the conduction of lightning currents (Figure 5c). 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 due to the current through conductive components. These overvoltages are typically due to voltage drops (resistive and inductive) along conductive parts and couplings (magnetic and electric) between conductive parts.
- Indirect effects due to nearby lightning due to the electromagnetic fields and/or incoming currents from lines (Figure 5d).

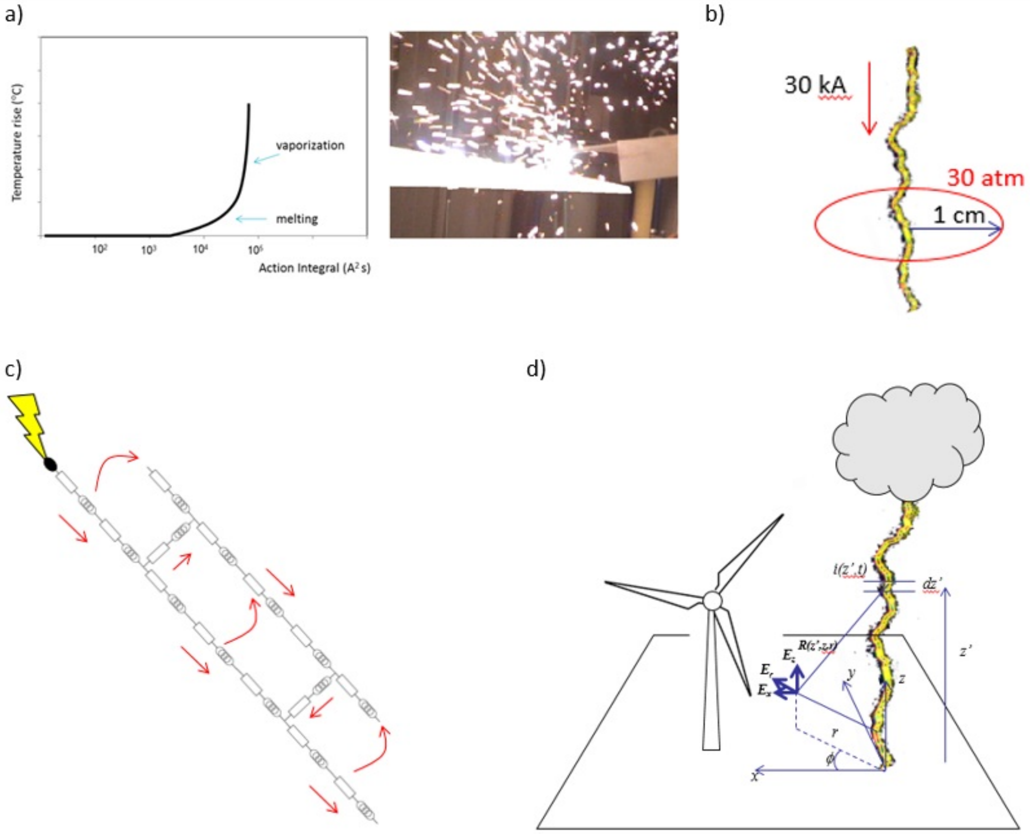

Figure 5. Lightning damage mechanisms. a) Arc root thermal; b) overpressure; c) current conduction; d) induced effects. (Adapted from *Montanyà, 2015).*

3.2.2 Summary of damages to wind turbines

Figure 6 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 is the rotor blades. Blades are equipped with an air termination system that usually consists one or several discrete receptors. It is desired that lightning will attach to these air terminals and do not to another uncontrolled locations. In the case of attachment to the intended receptors, the most common damages are melting and vaporization of the receptors. Receptors needs to be replaced during the blade lifetime, so the degradation of the receptor should still allow the replacement. Experience showed that not all the lightning attachments occur to these receptors, in some cases lightning produce shell punctures and attachments occur to another uncontrolled parts such as 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. Damage statistics has shown that most of the damages occur in the last meters of the blade (e.g. *Candela et al., 2015 and Montanyà, 2015*) . When lightning channels penetrate the blade cavity, the most severe damages can occur. 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 of the shells.

Nevertheless, even with an efficient air termination system, severe damages to blades can occur. Once lightning currents are present in the down conductor system, connection components of the LPS can be stressed but this is not a very common failure mode. Blades equipped with CFRP components such in spars, those must be bonded to the LPS. Special care must be paid to bonding connections to CFRP where those connections are commonly restricted to surface contacts. Due to the lower conductivity of CFRP electrodes suffer intense current densities and high potential differences can appear locally producing delamination. Due to the different paths that lightning currents can find inside a blade, high potential differences can exist between conductive parts. 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 and produce serious damages. If those sparks affects CFRP components those can present delamination. Conduction of lightning currents inside the blades can also induce overvoltages to other electrical systems such as signalization, sensors or actuators.

At the nacelle, direct impacts are not very common. Meteorological instruments and warning lights are commonly protected against direct attachments. Most nacelles are just made with glass fiber where manufacturers install meshed LPS. There are not many reports of direct lightning damages to nacelles. Another component that it is rarely struck by direct lightning 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 thought the main shaft and its bearings. Bearing damages are still in consideration in wind turbine standards. Pitting of bearings have been found in helicopters but there are no many evidences or reports in wind turbines. Inside the nacelle and rotor hub lightning currents can produce intense magnetic fields that can induce overvoltages to electrical wiring. Overvoltage 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.

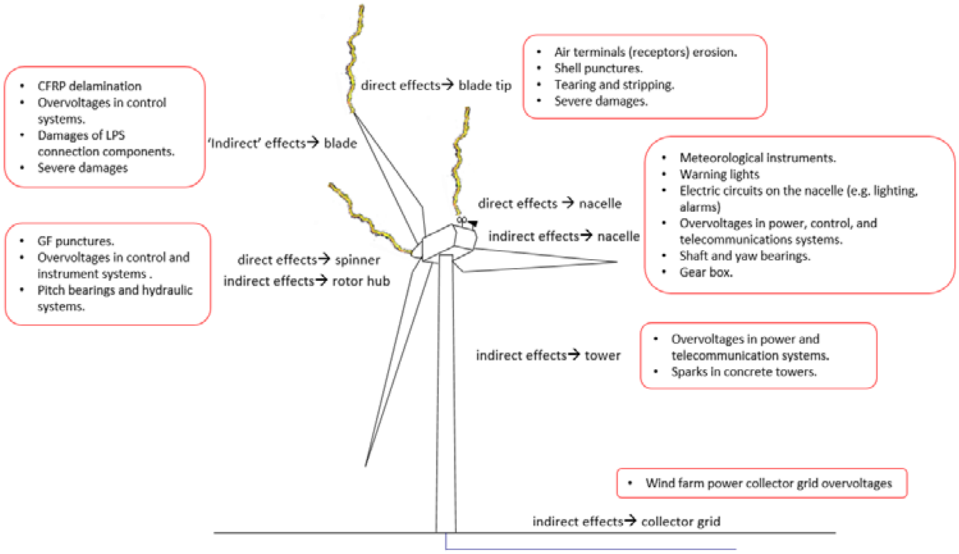

Figure 6. Distribution of lightning damages in a wind turbine (adapted from *Montanyà, 2015).*

3.2.3 Classification and examples of lightning damages to wind turbine blades

The working group of *CIGRE C4.409* 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 7a and 7c), burnout and melting of the down conductor (Figure 7b), etc.

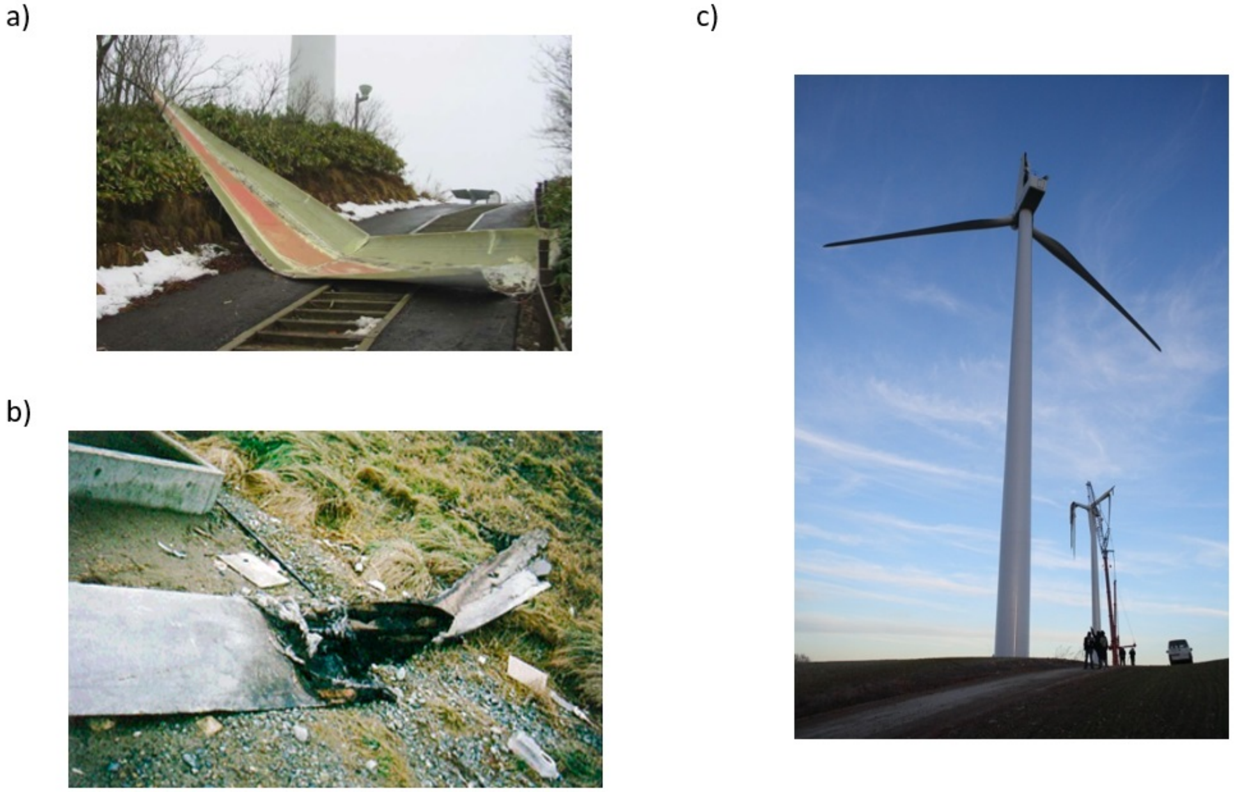

Figure 7 a) Blade breakdown (from *CIGRE WG C4.409, 2014*); b) Blade burnout and wire melting (from *CIGRE WG C4.409, 2014*); c) Blade collapse and destruction (from *Montanyà et al., 2014a*).

Serious damages require immediate repair. These damages include surface cracking (Figure 8a), tearing (Figure 8b) and receptor loss (Figure 8c).

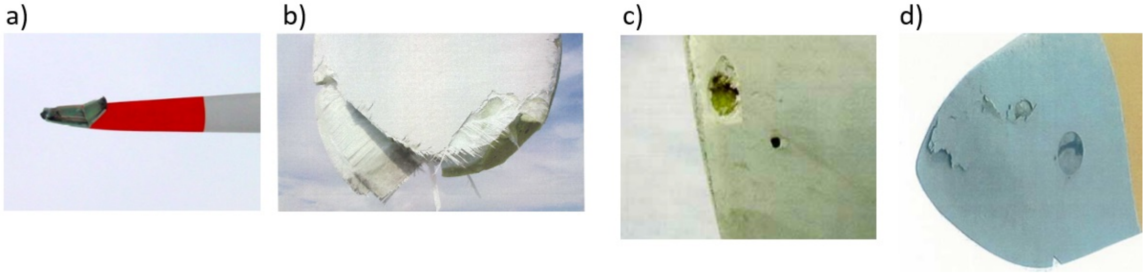

Figure 8 a) Cracking along bond weld; b) Surface tearing; c) Receptor loss; d) surface stripping. All images are adopted from *CIGRE WG C4.409, 2014* and references therein.

Damages classified as normal are those that require repair as soon as possible such as stripping of the blade surface (Figure 8d). Damages that do not imply immediate fix are grouped as minor. Some of these damages are receptor vaporization (Figure 9a), surface scorching (Figure 9b), punctures (Figure 9c), erosion (Figure 9d and e) and other minor damages.

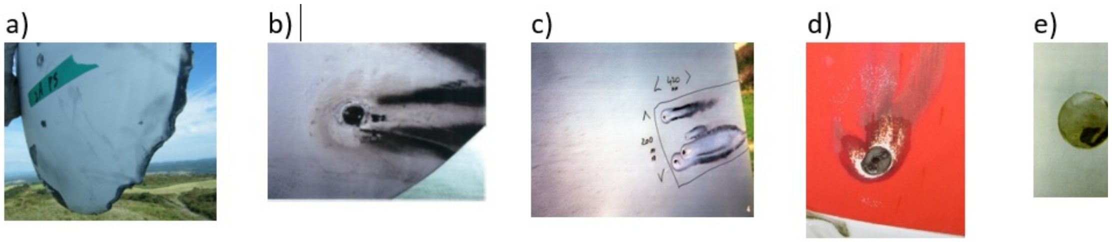

Figure 9 a) receptor vaporization (adopted from *CIGRE WG C4.409, 2014*); b) surface scorching (adopted from *CIGRE WG C4.409, 2014*); c) Shell punctures (*Adopted from Minowa et al., 2006*); d) and e) Receptor and surface (adopted from *CIGRE WG C4.409, 2014*).

3.2.4 The case of CFRP components

Some wind turbine blades use CFRP components because their good mechanical strength properties with a reduced weight. CFRP can be found as part of spars and other structural elements. Unidirectional type of CFRP are 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 axis. This anisotropy produces that currents do not distribute easily along all directions (Figure 10). Then, even large cross-sections can be available in currents can be confined in small sections.

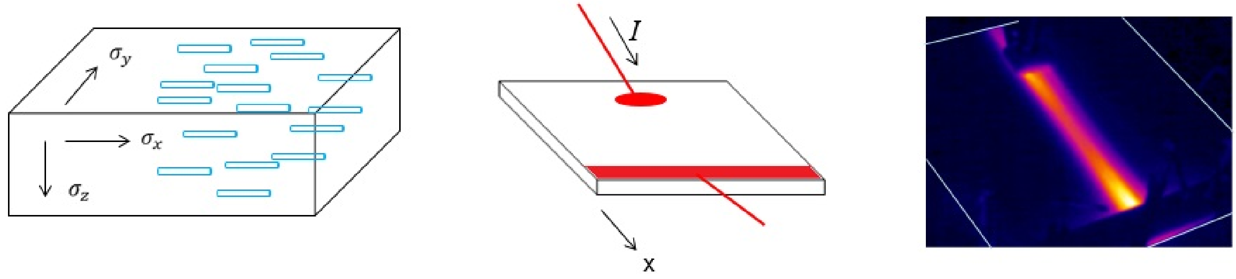

Figure 10. a) Sketch of a unidirectional CFRP; b) Illustration of a test of a CFRP coupon; c) Thermal image of the test described in b. (Adopted from *Romero et al., 2014*).

In order to distribute lightning currents efficiently in CRFP components connections shall be designed considering the particularities of these components. Connections shall have the 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 11a). Intense current densities can produce high potential differences at the contact and result in arcs. This situation is highly dangerous because delamination can occur weakening seriously the area. In addition, Connections to CFRP can be very difficult since in most of the cases those cannot be bolted being limited to surface contacts. Montanyà et al., (2015) studied the potential distribution in the sides of a CFRP coupon and its potential differences (Figure 11b).

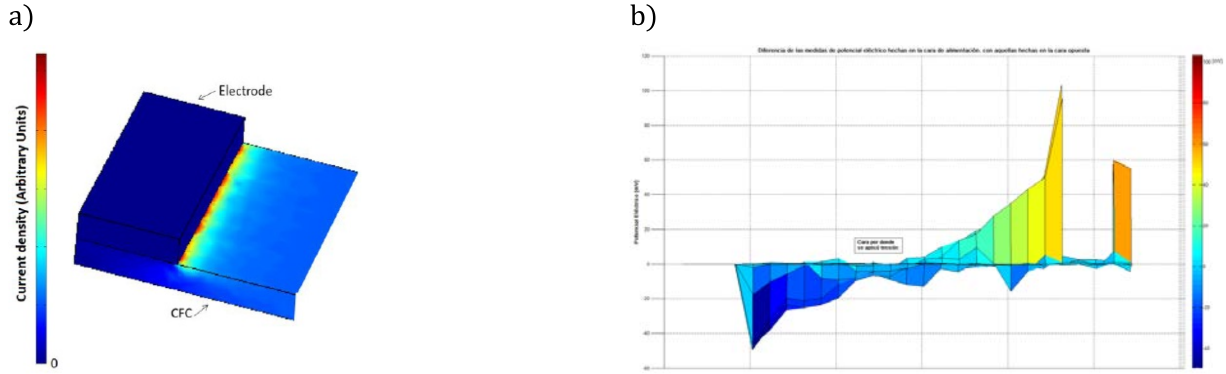

Figure 11. a) Current density in a simulated electrical connection to a CFRP coupon (adopted from *Romero et al., 2014*); b) Distribution of the potential difference between two faces of the coupon in Figure 10 (adopted from Montanyà et al., 2015).

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 12). In such cases, dangerous sparks shall be avoided from the down conductor system to CFRP. As in the case of connections, sparks to CFRP can result in a very serious damage.

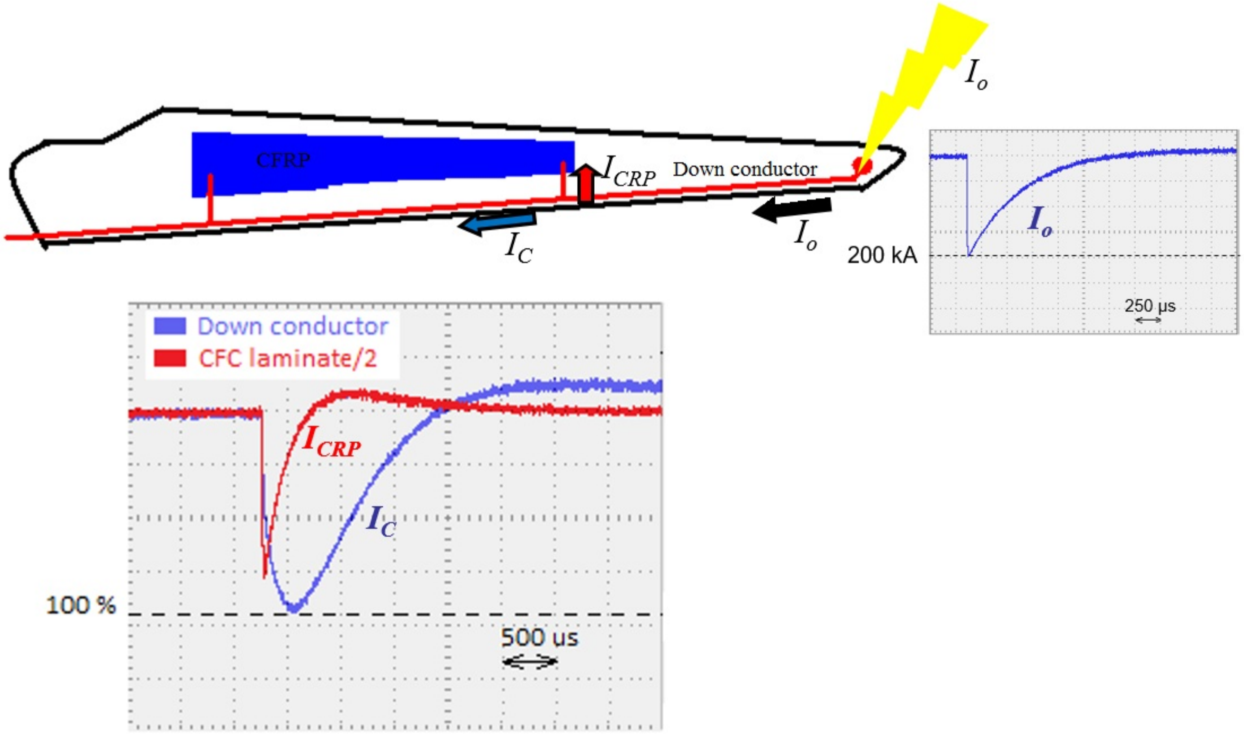

Figure 12. Example of test results of a wind turbine blade. Current I_o was injected at the tip. Current distribution to down conductor I_{CRP} and to CFRP spar I_{CRP} are plotted in the lower graph. (Adopted from *Romero et al., 2014*).

Romero et al., 2014 presented experimental and simulation results of current distributions in a CFRP blade (Figure 12). 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 time) 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 inconvenience that high peak currents are present in the CFRP. These peak currents can produce high voltage drops at the connections.

4. Conclusions

First, the thunderstorm climatology and the characteristics of the wind turbine and its location determines 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 presented. The method separates downward and upward flashes dintinguing induced and self-initiated.

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 lighnting channels punctures the blade and attach to any conductive component within the blade cavity. The particularities of blades using CFRP have been detailed.

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 (e.g. flaps) and the large offshore installations.

Acknowledgments

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