Lightening Driven Wind Turbines Blade Damages

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Abstract— **Lightning-induced damages to wind turbine blades are widely recognized as severe and can result in unplanned plant shutdowns. Therefore, it is crucial to thoroughly investigate the different causes of blade damage and categorize them based on their severity and other relevant factors. By conducting a comprehensive study on the classification of damage characteristics caused by wind turbine blades, taking into account various causes and protective measures, this research aims to provide valuable insights for individuals involved in wind turbine design, construction, and operation. Specifically focusing on damages caused by lightning strikes, this paper also proposes several potential countermeasures to safeguard the blades.**

Keywords— **wind turbine, lightening damage, blades, receptors, down conductors.**

1. INTRODUCTION

Due to the rise in population and economic development, the global demand for energy, particularly fossil fuels, has been steadily increasing. However, as fossil fuels are finite resources, numerous countries are now seeking alternative energy sources such as solar, geothermal, tidal, and wind power. Among these renewable options, wind energy has emerged as a highly promising and cost-effective technology. This is primarily due to the fact that wind turbines, which generate electricity, utilize well-established and tested technology, ensuring a secure and sustainable energy supply. Consequently, many nations are increasingly relying on wind power as it offers a cleaner and more appealing source of energy.

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According to market statistics, it is projected that the total installed wind capacity will reach approximately 593GW by 2018 [1][2][3]. In order to achieve this capacity, an estimated 300,000 wind turbines will be operational by that time. Despite the numerous economic and ecological benefits they offer, wind turbines are susceptible to various types of damage. These damages can be caused by manufacturing defects such as cracks along adhesive joints and de-lamination, as well as handling damage, in-service damage, accelerated fatigue damage due to cyclic loads, lightning damage, and damage caused by strong winds and ice throw.

Lightning damage is widely regarded as the most severe form of damage inflicted upon wind turbines, often resulting in unexpected periods of inactivity and subsequently leading to the loss of numerous megawatts of power generation [1]-[8].

Wind turbines, with their towering structures reaching heights of over 100m, are predominantly situated in remote areas. Consequently, they are highly susceptible to direct lightning strikes and even instigate upward flashes. Not only does the height of the turbine make it more vulnerable to lightning, but the rotation of its blades also serves as a catalyst, increasing the likelihood of strikes. In unfortunate instances, lightning strikes on wind turbine blades can result in explosions, scattering debris in various directions, posing a significant threat to human safety.

The examination of the impact of lightning on wind turbines has become exceedingly critical. In recent times, it has garnered significant significance due to the turbines becoming increasingly difficult to access for repairs and maintenance. Moreover, the downtime of a turbine incurs substantial expenses.

The wind turbine is susceptible to lightning damage, particularly in its generator, gearbox, blades, and control unit. Out of these components, the blades are the most vulnerable and sustain the most severe damage. They also have the highest frequency of strike attachment, accounting for approximately 75% of total failure data, and the longest downtime, averaging around 10 days per lightning incident. Statistical data reveals that almost all direct strikes to the turbine target the rotor blades [3][4][6]. Field observations and statistics confirm that wind turbines encounter a significant number of lightning strikes throughout their lifespan, with the majority of these strikes affecting the turbine blades.

Wind turbine blades are typically in constant motion for the majority of their operational time. Mega-watt wind turbines can rotate at speeds of up to 20 turns per minute. At these rapid rotating speeds, the tips of the blades can reach dangerously high velocities of approximately 10 meters per second. The rapid rotation of the blades at such high velocities can potentially trigger lightning and pose significant safety concerns in worst-case scenarios. Additionally, the turbine blades can generate a shock wave due to the interaction with air or moisture within the blades. The extremely high temperatures associated with this phenomenon can cause the internal moisture to transform into steam, leading to an expansion of pressure and ultimately resulting in blade failure. The damage to the blades necessitates costly repairs and leads to a loss in electric power production.

Areas of vulnerability for damage in wind turbine blades include the tip region, the trailing edge, the leading edge, and the blade surface adjacent to the shell over the spar caps. Lightning damage is predominantly found in the tip region, accounting for approximately 60% of all damages. Spar caps are also susceptible, with around 20% of damages occurring in this area. The remaining 15-20% of damages are distributed between the trailing and leading edges [1] [15]-[17].

Based on field observations, it has been determined that the majority of lightning strikes occur within the last 0.5 meters of the blade. The damages in the tip region are primarily caused by direct lightning strikes hitting the edges. However, there is limited evidence of lightning incidents occurring at a distance of 15-20 meters from the tip region of the blade.

2. CLASSIFICATION OF BLADE DAMAGES

Blade damage caused by lightning can be categorized based on its severity. The severity levels for blade damage are classified as "catastrophic," "serious," "normal," and "minor," depending on the physical characteristics of the damage [4][6]. Lightning can cause various types of damage to blades, including delamination, debonding, shell detachment, and tip detachment. Statistical data reveals that delamination is the most frequently occurring type of damage, followed by debonding of shells. Shell and tip detachment of blades are rare occurrences, accounting for approximately 2.8% of the cases [1]. Furthermore, the types of damage experienced by the blades can be further subdivided into different sub-categories, as presented in Table 1.

TABLE 1: TYPES OF DAMAGES, SUBCATEGORIES AND THEIR SEVERITY.

Sl. No.	**Types of Damage**	**Sub categories**	**Level of severity**
1	Tip Detachment	(a) Blade Rupturing (b) Blade Burn-out (c) Wire Melting	Fatal Damage
2	Debonding & Shell Detachment	(a) Surface cracking (b) Surface Tearing	Serious Damage
3	Debonding	(a) Surface stripping (b) Receptor Loss	Normal Damage
4	Delamination	(a) Receptor Vaporization (b) Surface Scorching and Blotching	Minor Damage

Tip Detachment: This type of damage is considered extremely serious as it will severely damage the structural laminate of turbine in such a way that it will not be able support the mechanical load and breaks. Tip detachment is very rarely seen happening in turbines. Blade rupturing, blade burn-outs and wire melting eventually cause shell detachment and subsequently lead to tip detachment where several meters of blade tip get detached from the rest of the blade.

Shell detachment is not a standalone occurrence; rather, it relies on the initial debonding of the blades. This debonded area, caused by the continuous rotation of the blades and the powerful winds during thunderstorms, generates mechanical forces that further contribute to the process of shell debonding, ultimately leading to shell detachment. In the most severe instances, surface cracking and tearing can escalate into a catastrophic event like shell detachment.

Field observations have revealed that the occurrence of blade delamination often results in localized debonding of shells. This debonding phenomenon is characterized by a partial separation between the upper and lower shells of the blade. The heat generated from lightning strikes causes the moisture within the blade to transform into high-pressure steam, ultimately leading to the gradual separation of the shells within the blade.

Surface Delamination: The occurrence of delamination is the prevailing form of damage in blades, accounting for approximately 70% of all reported cases. Delamination is identified by punctures and burns on the laminate, specifically in the vicinity where lightning strikes. The temperature of the lightning arc induces localized air pressure and rapid expansion of the arc within the layers of laminate. Typically, delamination manifests at the blade's tip, where the laminate is thinner. While delamination is generally regarded as a minor form of damage when it solely impacts the blade's outer layers, it becomes a severe concern if it progresses to affect the spar caps.

The sub-categories of damage which come under "catastrophic" damage are

- (i) Blade Rupturing: Blade rupture typically occurs in turbines that were built in the past when there were no protective components like receptors or down conductors. In severe instances, spar separation may be observed.
- (ii) Blade Burn-out: Blade burn-out occurs as a result of lightning discharge infiltrating the blade surfaces, potentially causing the ignition of the composite material, such as Glass Fiber Reinforced Plastic (GFRP), and leaving scorch marks due to burn-outs.

Damages which can be put under "serious" category includes

- (i) Surface Cracking/ Gelcoat Cracking: Over time, wind turbine blades experience degradation caused by fatigue induced by static and cyclic loads, resulting in the formation of cracks in the blade materials. While cracks in the blades may not pose an immediate threat, they can rapidly develop and ultimately cause the turbine to fail if not addressed in a timely manner.
- (ii) Surface Tearing/ Adhesive Joint failure: Blades, whether equipped with or without receptors, can experience surface tearing. However, blades without receptors are more prone to surface tearing. The adhesive substance used to join the two blade plates is often affected by lightning discharge. This adhesive material is typically mechanically weak and can become heated by the lightning current, ultimately causing tearing on the blade surface. Although surface tearing may initially appear as a minor damage, it can potentially lead to a catastrophic event over time.

Damages classified under "normal" category includes

- (i) Surface stripping: The occurrence rate of surface stripping is higher in blades equipped with receptors. The discharge may penetrate through the surface when the lightning current passes through the receptor, depending on the path of leaders and the azimuth angle of the blade. Experiments conducted to investigate this phenomenon have shown that surface stripping is not influenced by the type or location of the receptor used in the blade.
- (ii) Receptor Loss: There are two scenarios in which receptor loss can occur. Firstly, it can happen when the metal surrounding the receptor melts due to the rotation of blades or strong winds. Secondly, receptors can fly off due to overheating caused by direct lightning strikes or the intrusion of discharge into the voids of the blades. The high field strength inside these voids can lead to an increase in air pressure, ultimately causing the blade to rupture.

Wind turbine blade damages that fall under the category of "normal" can be easily repaired and restored to their normal operating condition within a short period of time, provided that prompt attention is given.

Blade damages under "minor" category include:

- (i) Surface Scorching and Blotching: The material surrounding receptors bears scorching marks as a result of the intense heat produced by the high energy of lightning current. This leads to the burning of the superficial surface material, leaving behind visible marks. In the case of multiple strokes occurring over a prolonged period, the discharge path on the blade's surface may exhibit blotching and burn spot marks. Fortunately, these damages are relatively simple to manage and do not require immediate attention.

(ii) Receptor Vaporization: The receptor tips can sometimes be melted and indentation marks can be left on the surface of blades due to the significant energy released during direct lightning strikes.

3. COUNTER-MEASURES FOR LIGHTENING PROTECTION OF BLADES OF WIND TURBINE

Large wind turbine blades with a rotor diameter over 50 m have been increasingly equipped with lightning protection in recent years. Nevertheless, wind turbine owners have reported that even with this protection, the blades may still suffer significant damage from lightning strikes [9], [10], resulting in substantial repair costs.

The majority of lightning strikes on wind turbines are typically directed towards the rotor blades and the nacelle [3] [6], [7]. The impact of the lightning current on the structural materials of the blades is of utmost importance as it directly affects the integrity of the blades. Hence, it is crucial to install a lightning protection system on the rotor blades. The international standard for lightning protection of wind turbines, IEC 61400-24 [2], which was published in 2010, provides a compilation of various methods to assess the risk of lightning strikes and to design and validate the lightning protection system for wind turbines.

The lightning protection system (LPS) for wind turbine blades poses a significant challenge in terms of design. This is primarily due to the rotation of the blades and the presence of both insulating and conductive materials [8][11].

(i) Receptors and Down-conductor Assembly: Wind turbine blades are produced using a variety of composites, such as carbon reinforced plastics and glass fiber reinforced plastic, as well as metals. The use of different materials in the construction of the turbine makes it challenging to protect. The surface of the turbine blade is composed of a non-conductive composite that needs to be shielded from lightning strikes. One effective method to minimize strikes on the blade surface is by incorporating a receptor at the tip of the blade. The lightning protection system consists of three main components: receptors, down-conductors (installed internally along the cavity of the turbine blade), and a grounding grid. Receptors are metal rods that attract direct lightning strikes and carry the excess electricity surges. The lightning receptor then transmits the electricity down the blade and into wires within the rotor. Cables within the rotor transport the electricity either through or around the nacelle housing. Once the electricity has passed the nacelle housing, the cables continue to transmit it down the inside of the tower. The tower itself serves as a conduit for carrying the electricity to the ground. When the electricity reaches the ground, it is directed into the surrounding earth through large grounding rods.

(ii) Multi-Composite material for design of blades: It is imperative that there are no manufacturing defects such as voids or cracks, as well as deformities in the blade material. The quality of the materials used must be of a high standard in order to ensure sufficient protection against lightning. Wind turbines commonly utilize composite materials in the construction of their blades and nacelles. Among these components, the blades are particularly crucial as they are both composite-based and the most expensive part of the turbine. Considering the different types of load cycles that the blade materials experience, the main laminates endure cyclic tension loads while the opposite side is subjected to compression loads. The trailing and leading edges of the blades, which bear bending moments, are exposed to tension-compression loads. The presence of various cyclic loadings at different locations on the blades suggests that it may be advantageous to employ different materials for different parts of the blade (multi-composites). Therefore, the stiffness-to-weight ratio holds significant importance from a materials standpoint.

Furthermore, since the turbine is designed to operate successfully for 20-25 years, the behavior of the materials under various fatigue-induced cycle loads and at material interfaces (such as bondlines and sandwich/composite interfaces) plays a crucial role.

(iii) Use of Hybrid composites: Carbon fibers are widely regarded as a highly promising substitute for traditional glass fibers. While CFRP (carbon fiber reinforced plastics) offer greater stiffness and lower density, resulting in stiffer, thinner, and lighter blades, they are less resistant to damage due to their lower compressive and fatigue strength. One approach to enhancing material strength is to utilize thicker blades, but this would increase the overall weight and cost of the blades. Another option for reinforcing blade structures is to employ materials with superior insulating properties, mechanical strength, and weight. Hybrid composites, which combine glass fibers with carbon fiber reinforced plastics, are one such material. This combination enhances the impact properties and tensile strain to failure of carbon fibers.

(iv) Placement of lightening rod on nacelle: Placing the lightning rod on a nacelle can prevent blade damage. According to experimental data, the length of the lightning rod should be sufficiently long to protect the blade, even if it is shorter than the blade itself. The experimental results also show that the lightning rod can capture some of the lightning discharges, even if the insulated blade is higher than the lightning rod on the nacelle. In cases where the blade is contaminated due to pollution, there is a higher chance of attracting lightning strikes compared to the lightning rod on the nacelle. This method effectively redirects the path of lightning strikes towards the blades.

4. CONCLUSIONS

This study aims to analyze the comprehensive categorization of damage characteristics inflicted on wind turbine blades by lightning strikes. By examining potential causes and proposing corresponding protective measures, this research paper thoroughly investigates all known types of damages that have been observed in wind turbines worldwide as a result of lightning strikes. The suggested measures for each specific type of blade damage can assist design engineers in developing improved materials and construction features that can effectively withstand the detrimental effects of lightning strikes.

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