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A Review of Lightning Protection Methods for Wind Turbine Blades

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Abstract*-In order to increase the generated power and for better wind conditions, wind turbines are getting taller, the swept area and the blade lengths have been increased, and shifted to offshore locations. All these actions increase the exposure of windplant to lightning. The blades are the most damaged in which case reparing or replacement cost is extremely large. This paper reviews lightning protection and earthing scinenareos such as the receptor, metallic cap, metallic conductor on the blade edges, metallic mesh, two ring electrode, backside electrode, combined method, enhanced method, conductive surface layer on wind turbine blade method and Knitted Soldered Copper Meshes method. Results from various methods are presented and compared with experimental data and field surveys. Most of these methods have been proven to be very effective, however, the trend showed that modern wind turbines are predominantly protected by the single tip receptor method due to weight and cost related issues.In the last few decades, lightning attachment to blades, bypassing the protection system, has been increasingly reported, Indicating that the single tip receptor might not give adequate protection to the safety of longer blades. It will be risky to assume that a single receptor at the blade tip can protect a significantly long blade. It is therefore advantageous to determine the critical lenght of the blade above which the single tip receptor is no longer effective in protecting the blade from lightning.*
Index.FEM, receptor.

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I. INTRODUCTION

For increased generated power and for better wind conditions, wind turbines are getting taller, the swept area and the blade length are increased, and they are also moving offshore bringing them closer to lightning. The blades are at the highest risk of lightning attachment with the tip more exposed than other parts [1].

wind turbine power output is directly related to the area swept by the blades. There is also a relationship between generated power and blade length. The larger the blade's diameter, the more power it can extract from the wind, also, higher power capacity requires higher height but with subsequent nearness to lightning.

Lightning protection systems (LPS) are usually installed on modern wind turbines [2, 3], but laboratory experiments [4]and field observations [5] have shown incidences of damages due to lightning and that it is also possible for lightning attachment on the blade surface and inboard the blade instead of the protection devices, with the risk of substantial damages in the composite structure [6-9]. Damages to the blade are quite severe, replacement cost is high compared to other components [7].

The protection devices, though effective [6], also failed in so many instances [10, 11]. The continuous failure of wind turbines due to lightning despite various advancements has brought it to the front burner in research and a re-evaluation of the lightning problem with the wind turbine.

As detailed in [12], Lightning problems with wind turbine arise due to:

- The nonconductive nature of blade material
- Rotation of the blade
- Increase in size on account of higher power requirement on the order of megawatts.
- Recently, multiple discharge on the turbine associated with nearby cloud to ground lightning [13] and also strikes attaching inboard on the blade due to dart leader [14] are also mentioned as causes of continued blade failures. Malcolm et.al [15], presented a failure rate estimation of wind turbine electrical systems due to lightning strikes.

Proper positioning of the protection devices ensures that upward leader is incepted from it alone. When lightning attaches to the blade surface instead of the air-terminal, the blade and even the entire wind turbine can be destroyed resulting in downtimes, loss of wind turbine, and expensive cost of repair. Lightning attaching to the blade surface instead of the air-terminal is the major cause of damage because when lightning attaches to the air-terminal, it will be conducted to the ground. Therefore, the efficient location of possible leader attachment points, optimization of the location of air termination systems and performance of protection devices is key to improved lightning protection for modern wind turbines.

Some progress has been made with wind turbine lightning protection [8, 16-20] on finding protection measures and their locations [19], and has revealed that the lightning parameters found in probability distributions of standards are no longer appropriate for large wind turbines [1], and that lightning protection proficiency can depend on protection methods, their location, numbers and sizes [21], and concluded that this field requires a detailed investigation. Though wind turbines are protected from lightning using various protection methods, however, as the generated power and the blade lengths are increased, more incidences of damages are recorded thus requiring a review of effective protection for modern longer blades as an attempt at finding more adequate protection. This paper reviews lightning protection methods for wind turbine blades. These methods include: Receptor, Metallic Cap, Metallic conductor on the blade edges, Metallic Mesh and other methods. Model design is done with Comsol Multiphysics software. Conclusion and recommendations are made.

II. WIND TURBINE LPS

In the mid-1990s, lightning protection starts to receive attention in the wind turbine industry when wind turbines with heights of around 50 m started to appear. At that time, lightning strikes each year caused damage to about 4–5 per cent of wind turbines operational in Denmark [22]. With larger wind turbines, it is a different situation, for instance, 2 MW rated power wind turbines exceed 100 m in height, and due to their height, they will most probably all be hit by lightning many times in their 20-year lifetime. Therefore, lightning has become an operational condition for large wind turbines and must be equipped with efficient lightning protection, mostly when situated offshore due to difficulty in access, and maintenance cost are very high. In the mid-1990s, a lightning protection system was developed for GFRP blades using tip air brakes. It comprises of a lightning receptor and is connected with a down-conductor.

(a) Functions of a Wind Turbine LPS.

A lightning protection system LPS is a comprehensive system used to eliminate or lessen physical damage from lightning flashes to a structure such as a wind turbine, and also to protect against injury to life owing to touch and step voltages. It comprises both external and internal LPS.

An efficient wind turbine lightning protection system must carry out the following functions.

1 Allow leader incepting from and attaching to the protection device.
2 Ease the flow to ground of the lightning current from the protection device through the ground wire.
3 Reducing, in and around the wind turbine, the levels of voltages and voltage gradients.

(b) Components of LPS

An efficient lightning protection system typically have the following components:

1 An air-termination system for forming upward and attracting downward propagating lightning leaders.
2 A down conductor for taking the lightning current to ground.
3 A transient suppressor to eliminate the effects of induced voltages.
4 Equipotential bonding to eliminate potential danger to equipment and human life.
5 An earthing system to minimize the local potential gradients.

(c) Lightning Air-Termination Systems

The part of a lightning protection system LPS which intercept lightning flashes and uses metallic elements is called the air-termination system. The intercepted lightning flashes is sent to ground through a down conductor system and an earth termination system. The lightning air-termination system operates on the principle of faraday rod but with complexities when used on wind turbines. Therefore, efficient LPS design begins with proper positioning of the air-terminal system.

(d) Air-Termination System Positioning Methods

The effectiveness of a lightning protection system is most important, and it depends on the position that it is placed on the object that is to be protected. Existing design methods for air-termination placements are (a) Empirical or Classical Design methods, (b) Electro Geometric methods (EGM)

These methods are briefly explained below.

(1) Empirical or Classical Design methods; this method assumes that the protection device (wire or mast) can intercept all the lightning strokes arriving over the subject area if the protection device maintains a certain geometrical relation to the protected object. These methods include; the fixed angle method and the empirical curve method.

(2) Electro geometric methods (EGM's); these methods recognize that the attractive effect of the protection device i.e. wires, or mast depends on the amplitude of the lightning stroke current. In other words, the methods relate the striking distance to the prospective peak stroke current.

(e) The Rolling Sphere Method

Horvath [23], proposed positioning of lightning conductors on structures using fictitious sphere based on the idea of protected spaces boarded by circular arcs introduced by Schwaiger[24], in the early 1960s. Rolling sphere originates from the studies conducted by Lee [25, 26], in the United States. Rodrigues et al. [27], used the rolling sphere method to estimate the lightning vulnerability points on wind power plants.

The Rolling Sphere method is the most common (EGM) in Standards documents, and to apply it on a structure, an imaginary sphere, typically 45 m in radius, is rolled over the structure. All surface contact points are considered to require protection, whereas the unaffected volumes are assumed to be protected. Despite the widespread use of the rolling sphere method, its assumption that the radius is a function of the prospective return stroke peak current only and is independent of the geometry of the structure has led to serious errors in some situations. Rolling sphere method has been used on wind turbines as presented in Figure 1, but according to IEC 61400-24 standard, the rolling sphere method must not be used for the rotor blades.

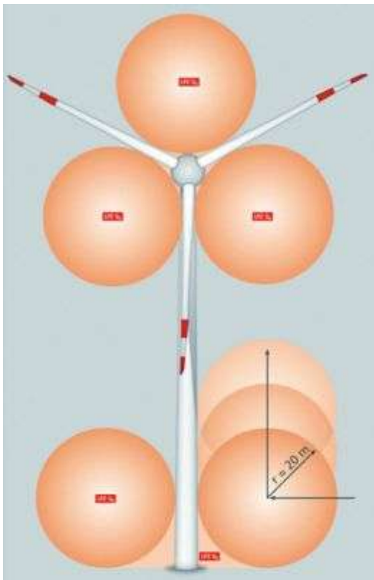

Fig. 1: Rolling sphere method (courtesy Dehn.co.uk)

The point on a structure where lightning will attach as well as the positioning of air-terminal has been a subject of research. Existing methods for air-terminal placement has been very effective for wind turbines except for the rotating blades, also modern wind turbine with higher heights are found to be more vulnerable. The air-termination systems are placed on the surface of the blade at points where connecting leaders might originate and result in lightning flash attachments or punctures if no air terminations are present.

If air-terminal are not well positioned on the blade, lightning can attach on the blade surface instead of the air-terminal with a consequence of damage. The air-termination systems could be part of the blade structure itself or components added to the blade, and even combinations of both. There are a few air-termination positioning methods as mentioned above, and for a particular design, the lightning protection system designer may select.

The processes of downward initiated lightning which begins from the cloud and attaches in the vicinity of the grounded structure can be explained by the Electro Geometric Model (EGM) and to link them to the peak current, the charge, striking distances, etc. but for upward initiated lightning which begins from the grounded structure and propagate upward towards the cloud, the grounded structure determines the attachment point and cannot be explained or described by the EGM, the rolling sphere and others.

Over time, research on various EGM models progressed. The result of the research on lightning protection for high voltage transmission lines was responsible for the emergence of the Electro Geometric Models (EGM). The Monte Carlo Method was developed in 1960 by J. G. Anderson [28], it is a computer program for evaluation of transmission line lightning performance. Young [29], developed the initial version of the (EGM) in 1963, and then, Whitehead model. Also of note is the Simulation of lightning performance using Monte Carlo by Sargent [30], who researched on lightning strokes to high structures. The application of the EGM was extended to substation facilities by Mousa [31], in 1976. There were certain apparent inconsistencies in the EGM that have a tendency to discredit it such as investigation by Eriksson [32], in 1978 and then, work by Anderson and Eriksson reported in 1980. However Mousa [33], proved that, explanations do exist for the apparent inconsistencies, and can be eliminated by the revised electro geometric model. Mousa and Srivastava [33, 34], developed the revised EGM.

(f)Lightning Protection Zones (LPZ)

Some further progress has been made on lightning protection of wind turbines, according to results obtained from the FEA wind turbine model conducted by [35], it was reiterated that the blades are at higher risk of lightning attachment, also, S.F. Madsen et.al [5, 36], presented a paper in which blades where divided into different zones and argue for a pattern of differentiating the lightning protection system and concluded that the tip is more exposed than other part of the blade, but [14], suggests that in lightning attaching to wind turbine blade, there is a possible sequence of events and according to them, due to the stepped leader interception, the first strike attaches to the tip of the blade, then, due to interception of dart leaders, the successive strike attaches to receptors inboard blade. This kind of lightning attachment process according to them, is due to the diverse properties of stepped and dart leaders, blade rotation as well as the blade angle as at when the stepped leader was intercepted. This support the argument that there is a blade length limit before lightning attachment to the middle part is not affected by the presence of the blade tip [5]. Multiple discharge in the turbine associated with nearby cloud to ground lightning has also been reported [13].

The zone where the lightning electromagnetic environment is defined is referred to as the lightning protection zone. S.F. Madsen et.al [5], conducted modeling and field surveys on three different sites. They extended their work in [36], and presented the revised Zoning Concept by evaluating the zones of protection afforded by a protection device even though such has not been extended to upward initiated lightning and suggest that it could help the lightning engineers focus attention on the portion of the blades with highest lightning exposure. The zoning concept in [5],divides the blade into four different lightning protection zones.Figure 2,

Zone $0A_1$ is the outermost 1m tip section exposed to the full threat i.e., direct lightning attachment with a maximum peak current - 200kA, 10/350us

Zone $0A_2$ is the section of the blade from 1m to 5 m inboard the tip, exposed to direct lightning attachment with current levels of only 100kA, 10/350us

Zone $0A_3$ is the section of the blade from 5 m to 20 m inboard the tip, exposed to direct lightning attachment with current levels of only 50kA, 10/350us

Zone $0A_4$ is the section of the blade from 20 m inboard the tip up to the root end of the blade, exposed to direct lightning attachment with current levels of only 10kA, 10/350us

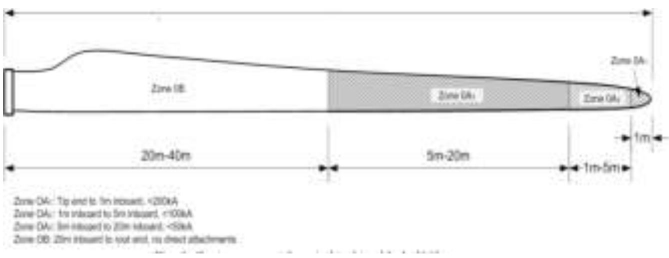

Fig. 2: Zoning concept for wind turbine blade [36]

Accordingly, they suggested an equation relating distance from the blade tip with the probability of attachment for blade length of 40-80 m

$P_{blade} = 0.4 . \exp(-0.4. d)$ (1)

Where P_{blade} is the lightning attachment probability [%], and d is the distance [m] from the blade tip.
However, the zoning concept cannot show where to place air termination system or receptors, it only helps to assess the likely strike amplitudes to different areas on the blade.

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III. WIND TURBINE BLADE LIGHTNING PROTECTION METHODS

Benjamin Franklin first used a metal rod as a lightning receptor and it is still widely in use due to its effectiveness, though attempt has been made to improve its performance but proven to have no significant effect. Radioactive lightning rods were also considered, though they were also effective in attracting lightning strokes but were abandoned due to restrictions in the use of radioactive materials. Early Streamer Emission (ESE) air-terminals were recently explored. As compared to a simple Franklin Rod, the ESE rod were expected to reduce the time of streamer development, but field experiments show that the Franklin Rod can breakdown faster and therefore more effective. Hence, the principle of the franklin rod is still a general guide in modern lightning protection.

Firstly, a brief review of power systems lightning protection is presented.

As Franklin Rod is used in power substation, shielding wire is also used in power transmission lines and they both have similar design principle which aimed to arrest the lightning strokes before they reach the object that is protected. In evaluating the lightning protection for power transmission and distribution system, information about Isokeraunic level, Ground flash density (GFD) and the relationship between the stroke current and the strike distance is very important.

The isokeraunic level is the average number of days per year on which thunder will be heard during a 24-hour period.

Ground flash density (GFD) is the average number of strokes per unit area per year at any location of interest

A number of methods such as Cone of Protection, Faraday Cage, Rolling Sphere and the collection volume methods have been proposed, some of which are in common use. These protection methods have been effective for earth bond structures, however, tall structures such as wind turbines, lightning protection is more complex.

In this section, the various protection methods for wind turbines are reviewed.

3.1. Receptor method

Sometimes, all lightning air-terminal due to their function are generally referred to as receptors, however, the disk type receptor is more often referred to as the receptor method. The receptor method is a disk-type with a metal disk of sizes in mm diameter, it is covered with a flat metal braid. Depending on the protection design, a single receptor or multiple receptors can be applied on the blade. The receptor is usually connected to the ground via down conductor of various cross-sectional area, embedded in the blade. There are two types of receptor method; Single tip receptor method and multiple receptor method.

3,1.1. Single Tip Receptor Method

A single receptor applied on the tip of the blade is shown in Figure 3.

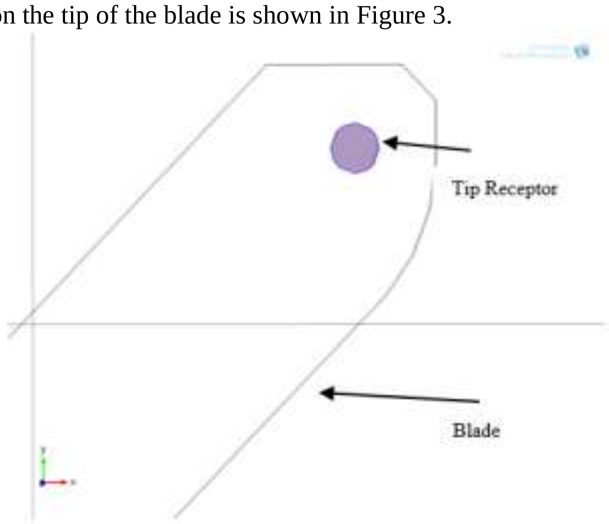

Fig. 3 A single receptor applied on the tip of the blade [12]

3.1.2. Multiple Receptor on the Blade

Multiple receptor on blade implies a protection system with more than one receptor on the blade. Two receptors on the blade is shown in Figure 4(a). It consists of the blade tip receptor and middle blade receptor, which can also be placed on any other part of the blade. Three receptors on the blade is shown in Figure 4(b). It consists of the blade tip receptor, middle blade receptor and the blade bottom receptor, it can also be arranged according to the choice of the design engineer. It should be noted that apart from the receptor arrangement shown, some other type of arrangements do exist.

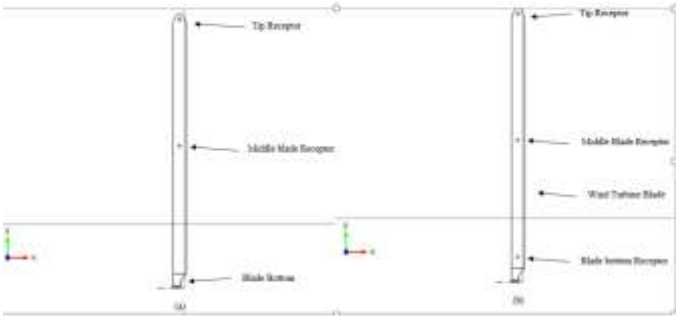

Fig. 4 Multiple Receptor on the Blade. (a) Two receptors on the blade. (b) Three receptors on the blade

The size of the disk type receptor plays a very important role in its efficiency. It was proposed in [37] that 10 mm receptor diameter performed better than other sizes. Also, the position the receptor is placed on the blade affects its effective performance. Analysis in [12], show that locating the receptor 1.5 m away from the blade tip provides higher protection efficiency. Wind turbines are getting taller, moving offshore and coastal areas in search of better wind condition but with a consequence of contact with saltwater. polluted blade surface affects the performance of the receptor. It was found that pollution dampens the performance of the receptor by 93%, resulting in lower lightning protection performance [38].

3.1.3. Metallic Cap Method

In this system, part of the blade tip is completely covered with copper foil and connected to the ground via down conductor. Figure 5 show the metallic cap method.

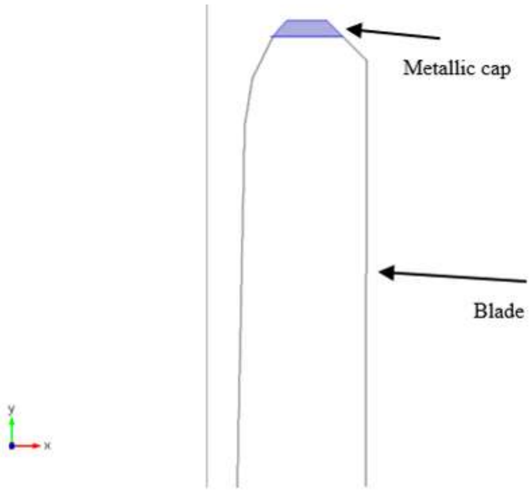

Fig. 5 Metallic Cap Method [37]

3.1.4. Enhanced Method

In the performance enhancement method [39], the performance of the metallic cap is improved by adding a receptor at the middle of the bladeand connected to ground via down conductor. The enhanced method is shown in Figure 6.

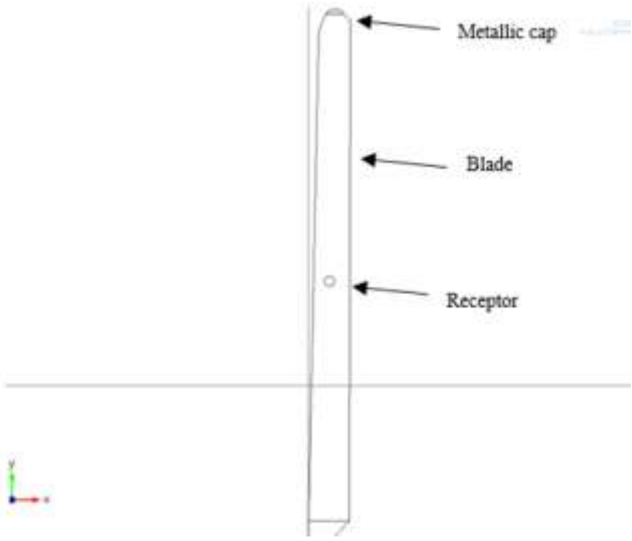

Fig. 6 Enhanced Method [39]

3.1.5. Metallic Conductor on the Blade Edges Method

Metallic conductors on the blade surface serving as an air-termination system is another method of protecting wind turbine blade from lightning. In the metallic conductor on the blade edges method, metallic conductor connected to the blade root is placed on the blade surface along the trailing and the leading edges and then connected to ground. The metallic conductor on the blade edges method is shown in Figure 7. Conductor used in this system must have sufficient cross section to be able to withstand a direct lightning attachment and conduct the full lightning current. In addition, certain dimensions are needed in order to achieve reliable fixing to the blade surface. The minimum cross section for aluminum is 50 mm^2 and achieving reliable fixing of such conductors may be problematic.

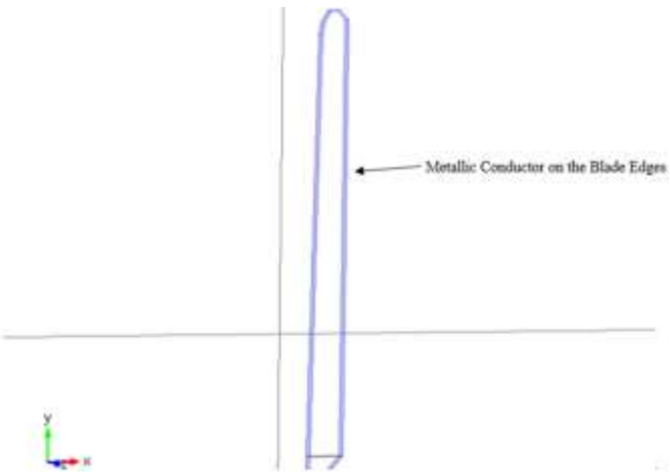

Fig. 7 Metallic Conductor on the Blade Edges.

3.1.6. Metallic Mesh

In this system, a metallic mesh is glued on the blade surface from its top to the root using a thin film of silicone adhesive. The methods mentioned above, and the mesh method are shown all in one in Figure 8 below. Mesh method improved with the metallic conductor on the blade edges proposed in [40] is shown in Figure 9.

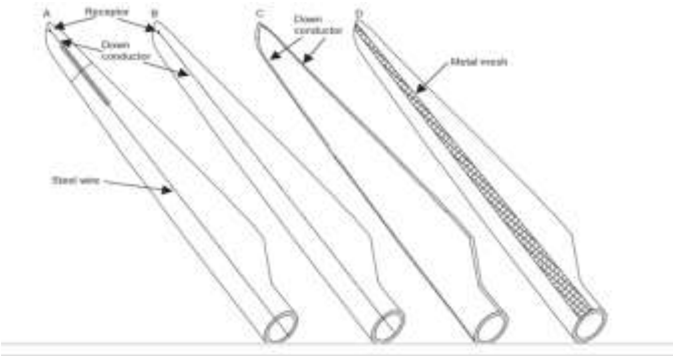

Fig. 8 Lightning protection methods on the blade. (A and B, Receptor Method), (C, Metallic Conductor on the Blade Edges), (D, Metallic Mesh). IEC 61400-24

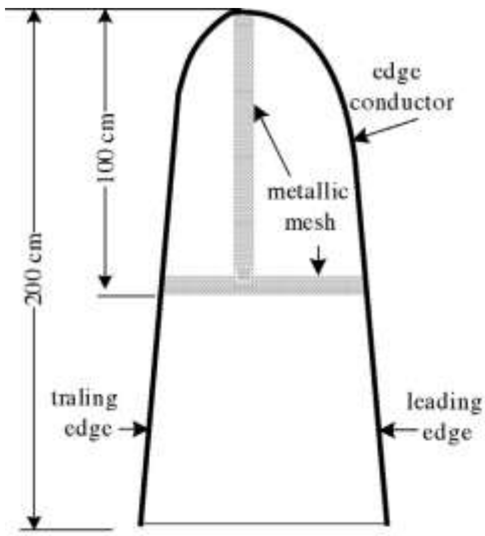

Fig. 9 Mesh method improved with the metallic conductor on the blade edges proposed in [40]

3.1.7. Knitted Soldered Copper Meshes

Knitted soldered meshes and nanostructured carbon particles for lightning protection of composite wind turbine blades was presented in [41]. The experience in using knitted soldered copper meshes in aircraft engineering is employed as lightning conductors for wind turbines. Knitted soldered meshes are shown in Figure 10.

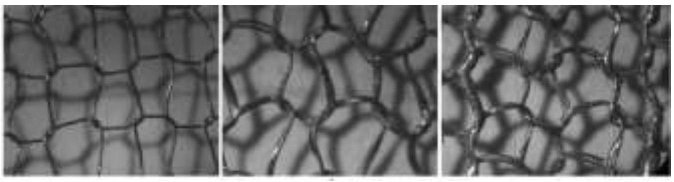

Fig. 10 Knitted soldered mesh of copper wire 0.12 in diameter with one (a), two (b), and three (c)wires in a bundle [41]

3.1.8. Two Ring-Shaped Electrodes

Two ring-shaped electrodesused for lightning protection of wind turbines was presented in [42]. The system has two ring-shaped electrodes of several meters diameter, one vertically attached to the nose cone and the other laterally placed at the top of the wind tower lying just below the nacelle. The pair of rings is arranged with a narrow gap of no more than 1 m in order to avoid mechanical friction during rotation of the blades and the nacelle's circling. When lightning strikes a blade, the current reaches the upper ring from a receptor through a conductive wire. Then, the electric field between the two rings becomes high and finally sparks over and the lightning current flows downwards. The current propagates along the lower ring and the grounding wire, which is arranged outside of the wind tower rather than inside and is safely led to a grounding electrode placed far enough away from the tower's grounding system. Two ring shaped electrode method is shown Figure 11.

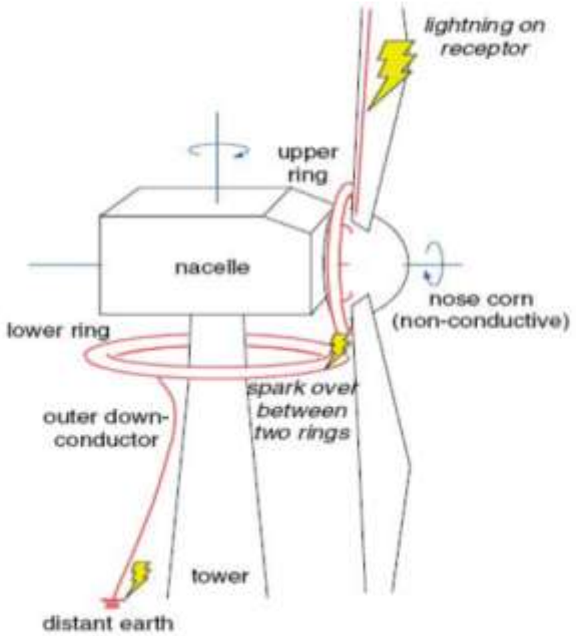

Fig. 11 Two ring-shaped electrodes[42]

3.1.9. Combined Method

Wind turbines protection against lightning strike using a combined method is presented in [2]. It is similar to the two ring-shaped electrodes above in that it also consists of two ring-shaped electrodes and in addition, it has a choke on the shaft.

3.1.10. Backside Electrode

A study of lightning protection for wind turbine blade by using creeping discharge characteristics was presented in [3]. It suggests that it is possible to lead the lightning discharge to the receptor smoothly on the blade by using the backside electrode. Image of creeping discharge leading to receptor with backside electrode is shown in Figure 12.

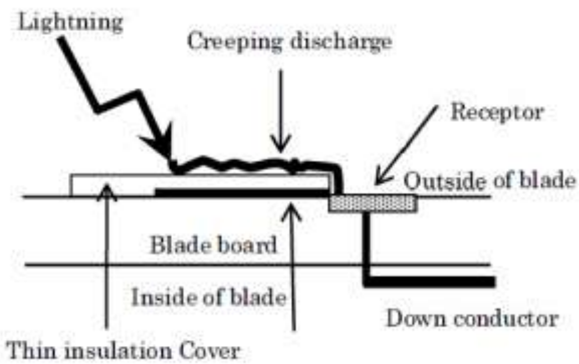

Fig. 12Image of creeping discharge leading to receptor with backside electrode [3]

The front view and cross-sectional view of the Back-side electrode is shown in figure 13 below.

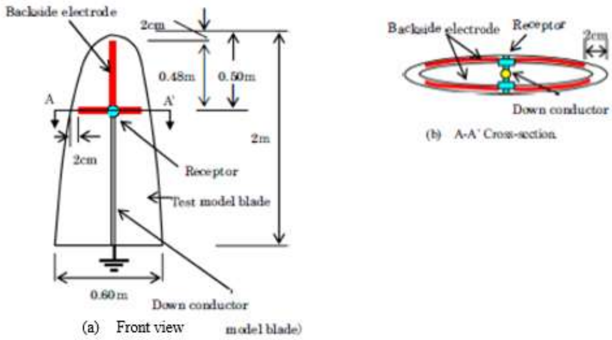

Fig. 13 Backside electrode used on the blade [3]

3.1.11. Conductive Surface Layer on Wind Turbine Blade

The impact of conductive surface layers as improvement of the lightning protection system was presented in [43]. Electric and dielectric attributes of glass-fiber material equipped with either a conductive coating or conductive metal mesh was analyzed**.**

Progress made in wind turbine lightning protection with protection methods are discussed in the next section.

IV. PROGRESS MADE SO FAR WITH WIND TURBINE LIGHTNING PROTECTION METHODS

Various lightning protection methods has been shown in the last section. In this section, some progress made with the lightning protection methods are discussed.

Wind turbine lightning protection methods were experimentally evaluated in [40]. The methods are; receptor, metallic mesh, metallic conductor on the blade edges and the metallic cap on the blade tip. The lightning attachment manner to the wind turbine blade was studied under positive and negative impulse voltages and for polluted and unpolluted blade surfaces. As the blades were rotating, the experiments were conducted considering five positions with different angels. The protection evaluation was done using 2 m blade tip section that is a part of 19.1 m actual blade length of 600 kW wind turbine. The results are as follow

(1) The blade air-termination system has better performance with the negative pulses than positive pulses.
(2) In case of unpolluted surface, the air-termination system successfully captures surges more than in case of polluted surfaces
.(3) The blade punctures occurred only when the down conductor is embedded in the blade surface. Therefore, in order to decrease such damage, it is important to use insulated down conductor or increase the thickness of the blade skin to avoid streamer to path inside the blade. Also, the damage was prevented when the down conductor was presented on the blade surface.
(4) The blade trailing edge attracts discharges more times than the blade leading edge.
(5) The blade positions significantly affect the attachment manner as well as the performance of the blade lightning protection. Therefore, it is important to use air-termination systems suitable for all blade positions.
(6) Although the metallic conductor system is found to be the best one, it needs to be improved.

The effects of various types of receptors, the polarities of the applied voltages, and pollution on the blade surface were presented in [6]. Sparkover characteristics were studied experimentally under various conditions, using the 3-m tip part of an actual wind turbine blade. The main results obtained are as follows.
(1) If a blade is made only of dielectric material, discharges to the blade occur due to the effects of a grounded part nearby and to pollution of the blade surface, which may cause damage to the blade. However, no tendency for carbonization of the blade surface to attract discharges was found.
(2) Receptors are an effective lightning protection method for wind turbine blades, especially if the receptor becomes positive and discharges easily develop from it. Even in that case, not a direct discharge to the receptor, but a discharge to the receptor via a surface discharge, may occur, depending on conditions such as whether the blade surface is polluted. To prevent these phenomena, it is effective to set a conductor at the tip of the blade or at the edges of the blade. Because their interception effects are affected by the direction of arrival of lightning strokes, further studies of the arrangement of receptors are needed.
(3) When receptors are installed, there is a possibility that discharges may start from a grounded wire inside the blade and that a puncture discharge may occur. Therefore, sufficient care should be taken regarding the arrangement and structure of the grounded wire.

Experimental studies on lightning protection design for wind turbine blades was presented in [44]. In order to investigate the lightning attachment manner to wind turbine blades, long-gap discharge experiments were performed using one of the largest impulse generators in the world with a capacity of 12 MV. Blade-samples of 3 m long were cut from 12 m long actual wind turbine blades and studied under different setup. The following results were obtained.

1. Regarding non-conductive blade, creeping discharge occurred more frequently in the polluted condition, and sometimes penetrative destruction was also observed.
2. The effectiveness of the receptor lightning protection method was not found to be adequate. The vertically arranged blade-sample was damaged at the tip, and in the case of horizontally arranged blade-samples, discharge penetrated the edge of the middle part of the blade-samples. Obliquely arranged blade-sample was not damaged, but since the discharge progressed on the surface of the blade-sample to the receptor, it has high probability to strike the edge of the blade and cause damage.
3. The blade-sample covered with conducting-cap at the top of the blade showed relatively high protection efficiency. If the improvement such as coating material and planar dimension of coating area is achieved, this approach will be expected to work much better.

Experimental study for wind turbine blades lightning protection was presented in [45], and thefollowing results were obtained.

1) The electrical discharge might invade an insulated surface of a blade instead of receptors.
2) The receptor on the blade tip is easy to receive a direct electrical discharge.
3) The discharge of a positive polarity easily attached to an insulated surface of a blade, on the other hand the discharge of a negative polarity attached to the receptors.

Investigation of the effects of receptors on the lightning strike protection of wind turbine blades was presented in [46]. To investigate the effects of receptors with different shapes and sizes on the LSP, five different receptor configurations were applied to the blade of a wind turbine. Results show that the disk shape receptor presents more favorable interception efficiency than the tip shape receptor does. In addition, increasing the size of the disk receptor and using dual disk receptors may also increase the interception efficiency. However, the additional weight could lead to an increase of cost and a possible compromise of mechanical performance.

Lightning protection of wind turbine blades was presented in [4], and the summary of result is shown below

(2) Results of long discharge experiments Regarding non-conductive blades, creeping discharges occurred more frequently under the polluted condition, and sometimes penetrative discharges into the cavity of a blade occurred. Lightning protection method using receptors was not perfect. Vertically arranged blade-samples were damaged at the tip, and in the case of horizontally arranged blade-samples, discharge penetrated the edge of the middle part of blade-samples. Blade-samples covered with conducting-cap at the top of a blade showed high protection efficiency. It is necessary to develop better protection measures for wind turbine blades. As an example, protection performance of various blade materials, such as carbon reinforced plastics, should be examined.

On the interception of dart lightning leaders from wind turbine blades was presented in [14], it suggests a possible sequence of events in the lightning attachment to wind turbine blade: the first strike attaches to the blade tip due to the stepped leader interception, then, the subsequent strike attaches to inboard blade receptors due to interception of dart leaders. The reason for this kind of lightning attachment process is caused by the different properties of stepped and dart leaders and the rotation of the blade due to the time interval between first and subsequent strokes. The lightning

attachment to inboard blade receptors is found to also depend on the angle of the blade when interception of the stepped leader takes place, on the time interval between first and subsequent strokes, and the prospective peak current of the subsequent strokes. Consequently, it is shown that the interception of dart leaders can be a mechanism for lightning damages of inboard areas (towards the blade root) of wind turbine blades.

The results show a progression in the lightning protection of wind turbine, however, due to higher generated power and better wind conditions, wind turbines are getting taller and the blade length are increased bringing them closer to lightning. Modern wind turbines are predominantly protected by the single tip receptor method due to weight related matters and more also, conductors mounted on the blade surface may compromise the aerodynamics of the blade or generate undesirable noise. Again, strikes attaching inboard of the blade are highly reported. Indicating that the single tip receptor might not give adequate protection to inboard of longer blades. It will be very risky to assume that a single receptor at the blade tip can protect an infinite blade length. It is therefore necessary to investigate the distance from the blade tip at which the single tip receptor is no longer effective.

V. CONCLUSION

This paper reviewed various lightning protection methods. The methods have all proven to be very effective, however, due to weight related matters and more also, conductors mounted on the blade surface may compromise the aerodynamics of the blade or generate undesirable noise, constituting another major problem. Consequently, the trend showed that modern wind turbines are predominantly protected by the single tip receptor method. However, strikes attaching inboard of the blade are yet highly reported. Indicating that the single tip receptor might not give adequate protection to inboard of longer blades. It will be very risky to assume that a single receptor at the blade tip can protect an infinite blade length. It is very important to know how long a blade can become before the effect of the single tip receptor is no longer felt at the bottom of the blade. Detailed research is required on this

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