Receptor Sizes and Its Effect on Lightning Protection of Modern Wind Turbines

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Abstract

Wind turbine can be destroyed when not adequately protected by the receptor. According to recent research, the size of the receptor plays a very important role in its efficiency. The effect of receptor size has not been well considered in literature and standards. This paper investigates six receptor sizes (10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 35 mm receptor diameters), encompassing adopted sizes in literature. As the blade is rotated, the interception efficiency of various receptor sizes is evaluated on a modern wind turbine. The vertical tri-pole cloud charge model developed with finite element analysis is used to study the maximum electric field strength required for the initiation of upward leader from the blade surfaces. The interception efficiency of each receptor size is evaluated by comparing the maximum electric field strength. The results of the point of initiation of upward leader match well with those obtained by experimental measurements from lightning discharge attachments.

Keywords: Simulation, Lightning protection, Receptor size, Wind turbine.

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1 Introduction

Lightning is a worldwide problem, Germany alone reported 393 events of lightning damage to wind turbines between 1992 and 1995 [1]. When lightning attach to the blade surface instead of the air-terminal, the blade and sometimes, the entire wind turbine can be destroyed resulting in downtimes, loss of wind turbine, and expensive cost of repair. Modern wind turbines with increasing height have become more vulnerable to increased number of lightning strikes. When lightning strikes a wind turbine, the resultant damage could be by direct strike or by producing electric and magnetic fields that can induce voltages in local wiring.

Damages vary in magnitude, more severe with unprotected blades and can be eliminated or reduced by efficient protection with air termination. Lightning protection systems (LPS) are usually installed on modern wind turbines [2–4]. It encompasses; a network of air terminals, bonding conductors, and ground electrodes, designed to provide a low impedance path to ground for potential lightning strikes [5]. There are a number of lightning protection methods used on wind turbines, these includes; Receptors, Metallic Cap, Metallic Conductor on the Blade Tip, Mesh, Ring Electrode [2] and the Backside Electrode [3] methods. However, modern wind turbines are predominantly protected with the receptor method. More also, multiple receptors on the blade has been a focus of research but the single-receptor method has remained the preferred choice. Therefore, only the single-receptor method is considered in this paper.

The receptor though effective [6], also failed in so many instances as mentioned in [7, 8]. The efficiency of the receptor is dependent on its interception proficiency which is its ability to intercept a lightning stroke. This strongly dependent on the size of the receptors [9]. The effect of receptor size has not been well considered in literature and standards. An attempt was made by Wang et al. [10], however, only the shape (tip shape receptor, also referred to as metallic cap and disk shape receptor) were considered and not the various sizes.

Since there are no standard governing receptor sizes, choices are made randomly by researchers. for instance; Abd-Elhady et al. [11], used 20 mm in diameter; Wang et al. [10], used 0.2 m and 0.3 m radius; Naka et al. [12], used 25 mm in diameter; in IEC61400-24, 15 mm in diameter was applied; Peesapati and Cotton [13], used 10 mm in diameter; Minowa et al. [3], used 20 mm in diameter; Shindo et al. [6], used 35 mm in diameter; Yokoyama et al. [14], used 25 mm in diameter and Danoon et al. [15], used 30 mm in diameter.

This is not healthy for an efficient lightning protection because the results are affected as the size of the receptor has been found to significantly affect its efficiency. It is therefore necessary to harmonize on the most efficient receptor size for an efficient lightning protection of wind turbines.

In this paper, the extended vertical tri-pole thundercloud model in our previous paper [16] is used to evaluate the maximum electric field strength required for the initiation of upward leader from a modern wind turbine: Vestas V100. The numerical model is developed with COMSOL Multiphysics software. The receptor size is evaluated and optimized by comparing the electric field strength as the receptor size is changed and the blade is rotated. Six receptor sizes (10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 35 mm receptor diameters), encompassing adopted sizes in literature are investigated. The point of upward leader inception is predicted by the magnitude of the electric field strength. The paper is organized as follows: Section 2 deals with design model, while Section 3 contains results and discussions, Section 4 concludes the paper.

2 Design Model

Software modelling of lightning attachment to wind turbines has recently gained attention, with many research works focused on downward propagating lightning. Nevertheless, a few work, done on upward propagating lightning (Particularly due to electric fields from winter clouds developed at lower altitudes) has shown that apart from the fact that tall wind turbine can increase the number of lightning strike, due to rotation, turbines are triggering their own lightning [17–19], indicating that large portion of the lightning that attach to a wind turbine are upward initiated. This type of lightning are majorly influenced by the slowly increasing electric field with a rise rate lower than 1 KV/m/s [20], and the formation is dominated by the electric field distribution and the wind turbine geometry. The stepped leader position influence is removed. Therefore, the analysis in this paper only involves upward lightning strike.

The thundercloud structure used in this paper is detailed in our previous paper [16], it consist of a vertical tri-pole. In the simulation, the three charges of +40C, −40C and 3C are placed at height of 12, 7 and 2 k m from the ground respectively and modelled as spheres of radii 900 m for the 40C charges and 150 m for the charge of 3C [13, 21]. The size of the spheres is such that during meshing, the accuracy of the electric field in the area of interest within the model is ensured.

As was shown in [16], the vertical tri-pole model is used to create an ambient field representing uniform electric field due to cloud charge distribution at 200 m above ground. A uniform electric field produced by a plane electrode located 200 m above the ground is then applied on the wind turbine model. The electric field at ground from the vertical tri-pole thundercloud charge coincides with that in [21] with maximum ambient field of just over 5kV/m. This is used in this paper and an upward-directed electric field is defined as positive [21]. In the simulation, the information from the cloud model is combined with the wind turbine model. The magnitude of the applied electric field is 1MV/m.

A vista wind turbine model V100 is used. It is a horizontal axis wind turbine with three blades, and has the following properties; 2 MW rated power, 100 m rotor diameter, swept area of 7.854 m² and a 49 m long blade. Details of the wind turbine model, the receptor and their parameters are shown in [16]. The model is shown in Figure 1.

Blade in the vertical position used in the investigation referred here as blade A is shown in Figure 2.

Figure 1 Full scale wind turbine model showing blades (blue), electrode and receptor.

Six receptor sizes (10 mm, 15 mm, 20 mm, 25 mm, 30 mm and 35 mm receptor diameters) (Figure 3), are applied on the wind turbine model to investigate the effect of receptor size on initiation of upward leader. In each case, the blade is rotated through -60 , -30 , 0 , 30 and 60 degrees from the vertical position. The receptor is placed 1.5 m from the blade tip as recommended in [16]. In this paper, the blade in the vertical position in Figure 1 is referred to as blade A. values obtained from the blade tip, leading edge, trailing edge and the receptor tip for blade A only are provided in this paper.

Figure 2 Blade in the vertical position used in the investigation. It is referred here as blade A.

Figure 3 Different receptor sizes: (a) No receptor (b) 10 mm; (c) 15 mm; (d) 20 mm; (e) 25 mm; (f) 30 mm and (g) 35 mm diameters.

The major interest in this paper is to investigate the interception efficiency of various receptor sizes. The computational domain in COMSOL Multiphysics software is shown in Figure 1. The peak current I_{peak} applied is 30 kA [22], selected because it represents the general situation of lightning strikes.

3 Results and Discussion

This section presents the results obtained from different receptor sizes and discussions. The electric field strength on the rotated blade (A) surface is shown. The locations with higher electric field strength are considered to have higher possibility of inception of upward leader. Obtained results are compared and plotted for the blade tip, leading edge, trailing edge and the receptor tip. The most efficient receptor size is the one with highest electric field on the receptor and minimum at the tip, leading and trailing edges.

In evaluating the effect of receptor sizes on the electric field strength, the simulation is conducted on the wind turbine, first without receptor and then as the blade is rotated, the receptor size is changed. The simulated model is shown in Figure 4.

Figure 4 Simulated model showing electric field strength and leader inception.

Figure 5 Activities around the receptor preceding leader initiation [16].

In other to protect the wind turbine, the receptors are activated and field enhancement is seen as shown above. Detailed activities around the receptor is shown in Figure 5, these include; the upward positive polarity for streamer activities; positive polarity on the blade surface; the negative polarity going to ground through ground wire; and the produced corona charge (qc) which lowers the electric field on the tip impeding the occurrence of a streamer.

Blade A is rotated from -60 to $+60$ degrees from the vertical position and the maximum electric field distribution is shown which appears higher at the tip than other parts of the blade, this supports experimental results in [23], indicating more vulnerability of the blade tip. In this paper, the locations with higher electric field strength are considered to have higher likelihood of inception of upward leader.

Figure 6 shows the simulation for different receptor sizes used in the comparison of the maximum electric field strength distribution: (a) 10 mm; (b) 15 mm; (c) 20 mm; (d) 25 mm; (e) 30 mm and (f) 35 mm diameters respectively.

Table 1 Maximum electric field strength distribution (kV/m)

Angle from Vertical	Blade Tip	Leading Edge	Trailing Edge	Receptor
Receptor 10 mm Diameter				
−60	20.12	36.25	0.43	60.78
−30	43.96	42.64	21.93	121.0
0	58.29	26.93	45.70	193.0
30	45.03	2.04	51.43	135.0
60	21.27	−14.83	37.41	61.35
Receptor 15 mm Diameter				
−60	20.45	36.58	−0.69	43.79
−30	47.09	42.87	25.37	79.96
0	57.54	28.03	52.57	89.22
30	44.10	4.02	57.29	59.87
60	20.51	−13.09	41.06	14.76
Receptor 20 mm Diameter				
−60	20.95	36.66	−0.15	40.49
−30	44.87	40.81	25.36	74.01
0	57.49	27.58	52.17	82.63
30	44.93	2.16	57.83	56.58
60	19.88	−14.05	39.65	13.60
Receptor 25 mm Diameter				
−60	18.22	38.36	0.18	32.83
−30	41.18	42.18	20.91	82.58
0	55.01	28.06	44.47	98.13
30	46.35	1.04	53.38	79.29
60	20.37	−15.01	36.93	33.74
Receptor 30 mm Diameter				
−60	18.33	38.81	−0.06	31.23
−30	43.33	45.64	20.90	70.08
0	55.96	28.83	43.62	93.47
30	46.87	2.10	53.07	83.28
60	20.72	−14.55	37.73	31.62
Receptor 35 mm Diameter				
−60	19.77	39.74	−0.66	29.24
−30	41.75	43.88	21.82	68.24
0	56.05	29.31	46.48	88.84
30	48.88	1.27	56.42	68.55
60	21.12	−14.36	38.30	30.84

Figure 6 Receptor sizes and their various maximum electric field strength distribution: (a) 10 mm; (b) 15 mm; (c) 20 mm; (d) 25 mm; (e) 30 mm and (f) 35 mm diameters respectively.

The results are shown in Table 1 and plotted in Figures 7–12.

1. Receptor 10 mm diameter

Figure 7 Maximum electric field strength distributions due to 10 mm diameter receptor as blade A is rotated.

A receptor 10 mm in diameter is used on the model, the simulation result is shown in the plot above (Figure 7). The electric field distribution on the blade is shown. As expected, it is highest at the receptor and as such, leader will incept from it first followed by other part of the blade in the sequence as depicted by the plot.

2. Receptor 15 mm diameter

Figure 8 Maximum electric field strength distributions due to 15 mm diameter receptor as blade A is rotated.

The receptor size is changed to 15 mm and the process is repeated, obtained result is plotted in Figure 8. It is observed that the change in receptor size has significantly affected the result as shown by the plot.

3. Receptor 20 mm diameter

Figure 9 Maximum electric field strength distributions due to 20 mm diameter receptor as blade A is rotated.

As shown in Figure 9 above, the effect of receptor size is seen. In this instance, the size is increased to 20 mm. Here, there is a possibility of leader

incepting from the trailing edge before the receptor at between 40 and 60 degrees.

4. Receptor 25 mm diameter

Figure 10 Maximum electric field strength distributions due to 25 mm diameter receptor as blade A is rotated.

The receptor size is increased to 25 mm and the effect is shown in Figure 10 above.

5. Receptor 30 mm diameter

Figure 11 Maximum electric field strength distributions due to 30 mm diameter receptor as blade A is rotated.

Similarly, the receptor size is increased to 30 mm diameter and the effect is shown in Figure 11.

6. Receptor 35 mm diameter

Figure 12 Maximum electric field strength distributions due to 35 mm diameter receptor as blade A is rotated.

Finally, the receptor size is increased to 35 mm in diameter. The result is shown above in Figure 12 in this case, it is also observed that it is possible for leader to incept from other part of the blade before the receptor.

The comparison for various receptor sizes is shown in; (Figure 13) for blade tip, (Figure 14) for leading edge, and (Figure 15) for trailing edge.

7. Comparison

Figure 13 Comparison for various receptor sizes at the blade tip.

Figure 14 Comparison for various receptor sizes at the leading edge.

Figure 15 Comparison for various receptor sizes at the trailing edge.

Figure 16 shows the comparison of maximum electric field strength on the receptor for various receptor sizes.

It is desirable, for efficient lightning protection that the electric field distribution at the blade tip, leading edge, trailing edge and the entire wind turbine surface be kept to a minimum due to the presence of the receptor,

Figure 16 Comparison for various receptor sizes at the receptor tip.

whereas, most significantly, it should be maximum on the receptor so that leader will incept from the receptor first before any other part of the wind turbine. The receptor size with the highest maximum electric field on the receptor is 10 mm diameter as shown above in Figure 16.

As discussed in [16], the negative polarity going to ground through ground wire as shown in Figure 5 is usually confined to the ground wire and not on the surface of the blade, therefore, only the positive parts of various plots are relevant.

Experimental validation of the extended vertical tri-pole model used in this study as compared with results from Elhady et al. [11] is shown in [16]. Obtained results of maximum electric field strength agrees with experimental data on points of leader attachment and upward leader initiation points. It also corroborated that the blade positions significantly affect the lightning attachment manner as well as the performance of the blade lightning protection systems. The maximum electric field strength locations on the trailing edge are higher than that of the leading edge which agrees with experimental result that the blade trailing edge attracts discharges more times than the blade leading edge.

It is found that 10 mm receptor diameter presents the highest electric field strength on the receptor than other receptor sizes. Also, relatively, the electric field distribution at the blade tip, leading edge, trailing edge for 10 mm receptor diameter is lower than that of other sizes. This indicates that 10 mm receptor

diameter will allow leader to be initiated from the receptor before any other part of the blade or wind turbine and as a result prevent damage. This receptor size will therefore provide higher protection efficiency than other receptor sizes and is therefore recommended. 10 mm is the smallest amongst the sizes considered and would be thought least in withstanding high current, however, it has been shown in literature that this size is adequate for an average peak stroke current and if need be, this can be improved by increasing the diameter of the down conductors. With proper scaling, findings in this paper can be extended to other wind turbine sizes.

4 Conclusion

This paper investigates the effect of receptor size on wind turbine lightning protection systems. The extended vertical tri-pole model has been used to create a uniform electric field using Comsol Multiphysics. This has been applied to a Vestas V100 wind turbine to study the variations in maximum electric field strength required for the initiation of upward leader. The receptor size is studied by comparing the electric field strength. The applied model was initially validated by experimental data.

Results show that receptor size 10 mm diameter provides higher protection efficiency than other sizes and is therefore recommended for efficient lightning protection of modern wind turbines. Further work will include polluted blade condition as in the case of offshore wind turbines.

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