Performance Enhancement of Lightning Protection Systems for Offshore Wind Turbine Blades

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***Abstract*— When offshore wind turbines are polluted with salt, their surface characteristics change. Pollution affects the performance of the protection systems which can result in damages when hit by lightning. In this paper, two lightning protection systems (metallic cap and receptor methods), commonly in use, are applied on a full scale polluted offshore wind turbine to compare their performance. The lightning attachment to the offshore wind turbine blade is studied by analyzing the variations in maximum electric field strength required for the initiation of upward leader due to a vertical tri-pole cloud charge distribution. The computation is done for a polluted Vestas V100, 2 MW wind turbine. A new protection system (enhanced method) with higher lightning protection efficiency is developed. The performance of the metallic cap was enhanced by adding a receptor at the middle of the blade. This is having a significant impact on the electric field distribution of the blade. The new method was compared with the metallic cap method and the tip receptor method. The proposed method can markedly improve the lightning protection performance for offshore wind turbines. The results of the point of initiation of upward leader coincides with experimental data from lightning discharge attachments.**

***Keywords*— FEM, lightning protection, Metallic cap, Pollution, performance enhancement, Receptor, wind turbine blade.**

I. Introduction

Windmills have become an attractive source of energy because it is renewable and non-pollutant. Relative to other energy sources, it is fast growing globally. For better wind condition and higher power generation, they are getting taller. At the same time the swept area and the blade length are getting larger. The offshore wind energy production is now in the increase resulting in more exposure to lightning. Wind turbine damages from lightning are quite serious due to repair time and replacement cost. It is very expensive to repair the blades once they are damaged [1]. This is even more problematic for offshore wind turbines because when they get in contact with salt water, they can be polluted with salt deposit. Non-conducting blade surface, when polluted, can become conducting resulting in lightning current channels through it, thereby increasing the lightning risk.

Lightning protection systems (LPS) such as Receptors, Metallic Cap, Metallic Conductor on the Blade Tip, Mesh, Ring Electrode [2] and the Backside Electrode [3] are usually fitted on modern wind turbines [2, 3], but laboratory experiments [4] and field observations [5] have revealed that it is also possible for lightning attaching on the surface of the blade instead of the protection systems and enormous damage still occurs [6, 7]. Again, the position of the blade during rotation greatly affects the performance of the blade lightning protection systems and also the lightning attachment manner, it is therefore important to use lightning protection systems suitable for all blade positions [12]. The type, shape, size, number and spacing of lightning protection system [8] can influence the maximum electric field strength required for the initiation of upward leader from wind turbine.

Apart from lightning current channels through the blade, pollution has been found to greatly dampen the interception efficiency of the lightning protection systems resulting in lower lightning protection performance for offshore wind turbines. Therefore, the performance of offshore wind turbine lightning protection system needs to be enhanced for higher efficiency.

Evaluation of lightning protection system has been carried out with useful findings in [4, 6, 7, 9-15]. Wang et al. [16], investigated receptor effects. Kumar et al. [17], quantified salt deposits on wind turbine blade surface. Godson et al. [18], recommended optimum receptor location and investigated receptor sizes [19]. However, few protection methods were considered and sometimes, the blades were unpolluted.

The effect of Pollution on wind turbines has been evaluated experimentally [9, 20], however, a small blade tip section were considered and not full blade length, but the electric field present between a small blade sample is different than when the entire blade is present. In order to assess the normal distribution of the points of discharge attachment on the blade surface, a large sized wind turbine hit by natural lightning strike is experimentally required while it is rotating, this can only be done in the natural lightning laboratory such as in Florida [14].

It is important to use full scale wind turbine blade in order to emulate real situation of lightning hit blades.

In other words, high failure rate of existing protection systems for offshore wind turbines is largely due to the size of test sample which does not represent real lightning situation. To come up with solutions to evaluate offshore lightning protection systems, a full-scale offshore wind turbine is designed in this paper and is applied to study the performance of offshore wind turbine lightning protection systems.

In this paper, two lightning protection systems (The Receptor method and The Metallic Cap method) commonly in use are applied on a full scale polluted offshore wind turbine and compared for efficiency in lightning protection. The blades are polluted and rotated. Finally, an enhanced system, a new method (not implemented yet in literature) comprising a metallic cap at the tip of the blade and a receptor at the middle of the blade is designed and compared with the two methods. This is found to influence the electric field distribution immensely and has increased the lightning protection efficiency of offshore wind turbines. In order to provide evidence of the efficiency of the proposed protection system, the concept of evaluation methodology that has been reported in our earlier publications [18, 19] is applied. It is an extension of our previous work after rigorous test with the receptor on every part of the blade protected by the metallic cap, in which we consequently found that the addition of a receptor at the middle of a metallic cap protected blade affected the electric field distribution immensely.

II. SIMULATION MODEL

The lightning attachment manner to the offshore wind turbine blade is studied by the variations in maximum electric field strength required for the initiation of upward leader due to the vertical tri-pole cloud charge distribution. The simulation model used in the analysis is shown in Figure 1, it consists of the cloud, wind turbine and the lightning protection system.

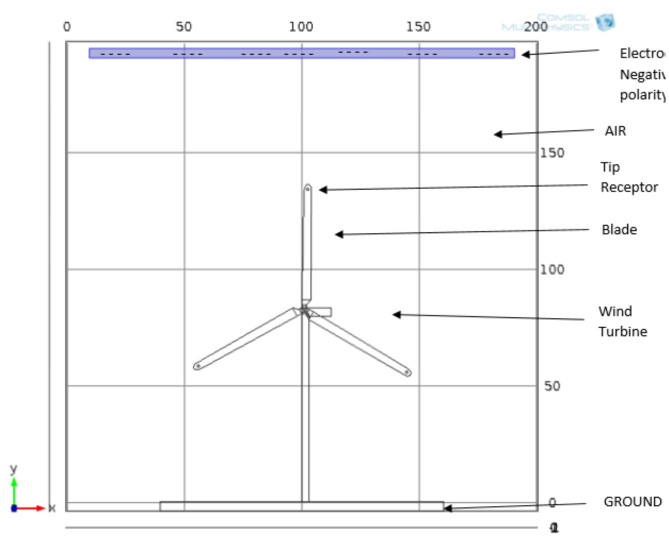


Figure 1. Simulation model

The vertical tri-pole model consists of an upper positive charge center, lower negative charge center and positive charge pocket at the bottom representing the idealized gross charge structure of a thundercloud 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 200m above the ground is then applied on the wind turbine model. The magnitude of the applied electric field is 1MV/m (200 X 5KV/m = 1000000V/m) [18].

The wind turbine model used in this paper is a vesta's wind turbine V100 with 2 MW rated power, 100 m rotor diameter, swept area of 7.854m^2 and a 49 m long blade. V100-2MW is a horizontal axis wind turbine with three blades. The blade made of fibred glass is used in the simulation. Details of the simulated model was already explained in our previously published papers [18, 19].

A. *Lightning Protection Systems on the Blade*

Two configurations of blade protection system commonly used with offshore wind turbine are considered with various specification.

(1) Receptor: A disk type receptor made of copper (conductivity: 6.0×10^{-7}S/m), 10 mm in diameter, inserted at 1.5 m away from the blade tip [18] and connected to ground as shown in Figure 2

(2) Metallic cap: In this system, 150 mm tip part of the blade is completely covered with copper foil and connected to ground as seen in Figure 2.

The protection systems are connected to the down conductor inside the blade shell.

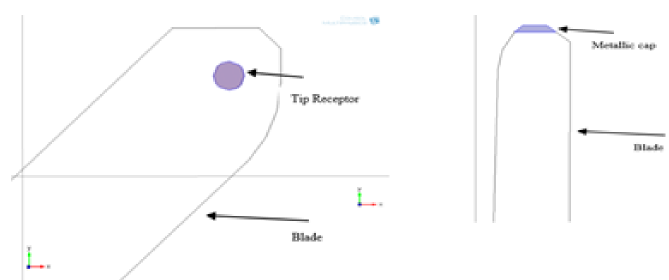


Figure 2. Tip receptor ant the metallic cap design

B. *Evaluation Conditions*

Figure 3 (a). Shows the model for rotation mode of the blade. As the blade rotates, it is tested in different five positions to investigate the performance of offshore wind turbine lightning protection systems on initiation of upward leader. The positions of the blade are chosen to determine the complete successes and failures of each protection systems. These positions are shown in Figure 3, they are: (b) vertical, (c) 45^0 (Trailing edge facing the cloud) (TEFC), (d) 45^0 (Leading edge facing the cloud) (LEFC), (e) horizontal (Trailing edge facing the cloud) (TEFC), and (f) horizontal (Leading edge facing the cloud) (LEFC).

The blade in the vertical position in Figure 3 (a) is referred to in this paper as blade A and only the results for blade A are provided. A full-scale model is employed in this analysis against the usual small tip section because it is more appropriate for the evaluation of the normal distribution of the discharge attachment points or locations along the blade surface

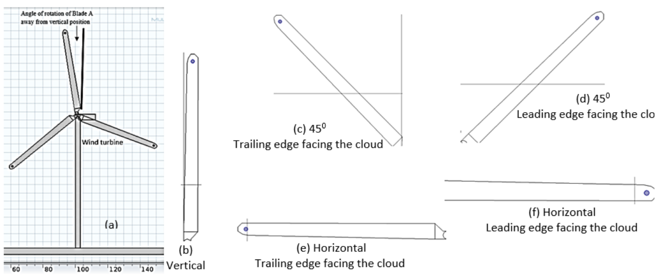


Figure 3. (a) Model for rotation mode, (b, c, d, e and f) Arrangement of blade sample

The focus is on evaluating the efficiency of the protection systems by obtaining the maximum electric field strength required for the initiation of upward leader due to thunder cloud charge. The peak current I_{peak} applied is 30 kA, this value is chosen because it represents the general situation of lightning strikes [21].

C. Evaluation Procedure

The maximum electric field strengths on the wind turbine surface due to a vertical tri-pole cloud charge distribution are obtained with COMSOL Multiphysics to develop a numerical model that simulate the electric field produced by the cloud charge [18]. The predicted point of upward leader initiation on the blade surface is taken to be the points with the highest magnitude of electric field strength necessary for the initiation of upward leader. This is also the predicted or probable lightning strike attachment point. By comparing the corresponding maximum magnitudes of electric field strength on the lightning protection systems as well as on the blade surfaces, the interception efficiency of the protection system is evaluated. In this paper, it is considered that the protection systems with better interception efficiency is the one with highest electric field on the protection system and minimum on the entire wind turbine surface. The electric field strength on the lightning protection system and on the blade surface is compared for all blade positions. The results for this system are summarized in Tables1, 2 and 3. The obtained results are of great importance in lightning protection of offshore wind turbines.

The simulation for polluted blades condition is done with values of the conductivity of the blades at 0.9 S/m and relative permittivity 80. These values corresponds to that of salt-water [9].

Electrostatic equations are used to calculate the electric field due to thunder cloud charge and the governing equations are solved with FEA software COMSOL Multiphysics and the computational domain is shown in Figure 1. The experimental setup and concept of evaluation used in published articles [4, 9, 20, 22] are utilized for analysis in the present work. A full-scale actual wind turbine and blade length are used.

III. EVALUATING OFFSHORE WIND TURBINE BLADE LIGHTNING PROTECTION SYSTEMS

The evaluation of the maximum electric field strength on the surface of the blade and the protection system using three lightning protection methods are presented in this section. The blades are polluted and rotated. Only the results for blade A (blade at its top vertical position) are provided. The locations with higher electric field strength are considered to have higher possibility of inception of upward leader. Two lightning protection systems (metallic cap and receptor methods) commonly in use are applied on a full scale polluted offshore wind turbine and compared initially. Finally, an enhanced system, a new method comprising a metallic cap at the tip of the blade and a receptor at the middle of the blade is designed and compared with the two methods. Each protection system is discussed in turn in the following subsections. Results are plotted and compared for values obtained from the blade surface and the lightning protection system. The most efficient method is the one with highest electric field on the lightning protection system and minimum on the blade surface. For a better understanding of the reader, the initial comparison plot between the receptor method and the metallic cap method are not shown separately but are shown with the three methods combined.

A. Receptor Method

The simulation is conducted with the receptor method considering the arrangements shown in Figure 3. Initially, the model is simulated for unpolluted blade (shown in Figure 4), and then the blade is polluted.

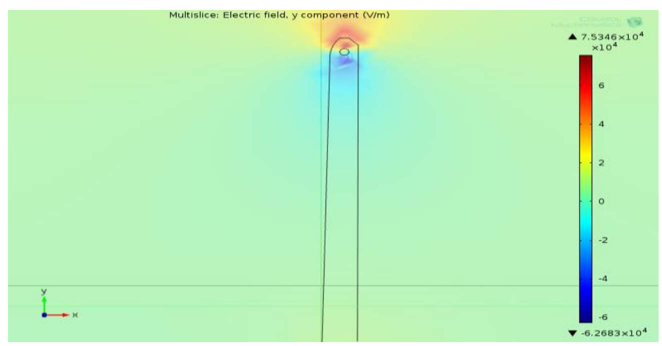


Figure 4. Unpolluted blade with receptor method

Details of the activities such as field enhancement around the protection methods for unprotected, unpolluted and polluted wind turbine blade were already given in [18].

The simulation for the polluted blade arrangement for the receptor method is shown below in Figure 5.

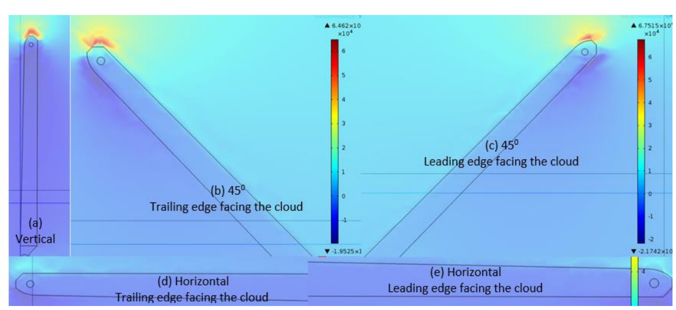


Figure 5. Polluted blade arrangement for the receptor method

It shows the maximum electric field distribution as blade A is rotated through; (a) vertical, (b) 45^0 (Trailing edge facing the cloud), (c) 45^0 (Leading edge facing the cloud), (d) horizontal (Trailing edge facing the cloud), and (e) horizontal (Leading edge facing the cloud).

Generally, the electric field strength around the tip region is higher than that at the inboard region. This is supportive of laboratory experiments and field survey demonstrating that the tip is more exposed than other parts [23] and that upward lightning leader is more likely to originate from the tip of the lightning protection system. The locations with higher electric field strength are considered to have higher possibility of inception of upward leader.

The results for the maximum electric field distribution on the receptor as well as on the blade surface for various arrangements are tabulated in Table 1 and the comparison with other methods are plotted.

B. Metallic Cap Method

The simulation is also conducted with the metallic cap method considering the arrangements shown in Figure 3. The simulation includes unpolluted blade (shown in Figure 6), and polluted blade (Figure 7).

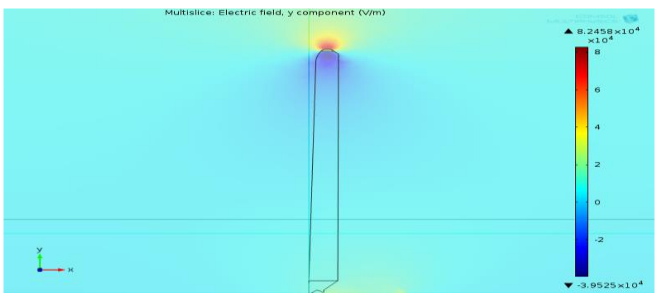


Figure 6. Unpolluted bade with metallic cap method

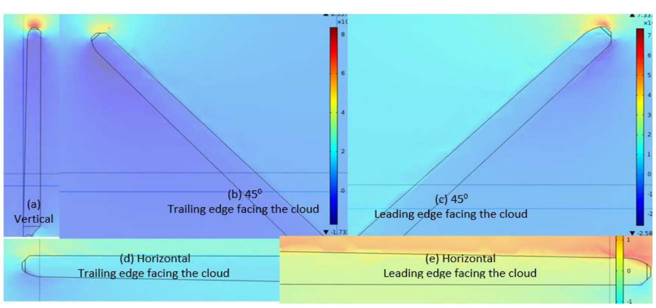


Figure 7. Polluted blade arrangement for the metallic cap method

The results for the maximum electric field distribution on the tip of the metallic cap as well as on the blade surface for various arrangements are tabulated in Table 2 and the comparison with other methods is also plotted.

C. Performance Enhancement method for Offshore Wind Turbine Blade Lightning Protection Systems

Research has shown that pollution has been found to dampen the performance of the protection devices. Existing protection systems, even though they perform well in unpolluted wind turbines, the same protection system performs poorly when applied on a polluted wind turbine. The metallic cap method performs better than other method in some arrangements but failed in some others [20].

In the performance enhancement method, the performance of the metallic cap was improved by adding a receptor at the middle of the blade. The model is shown in Figure 8

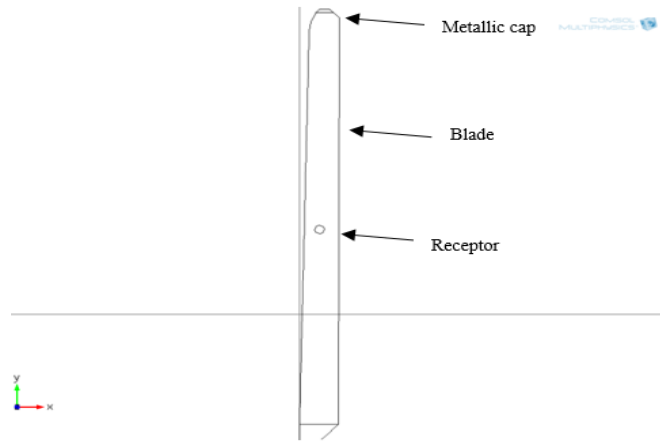


Figure 8. Enhanced method

The enhanced method is applied on the polluted wind turbine, evaluated and compared considering the arrangements shown in Figure 3. The simulation is shown in Figure 9.

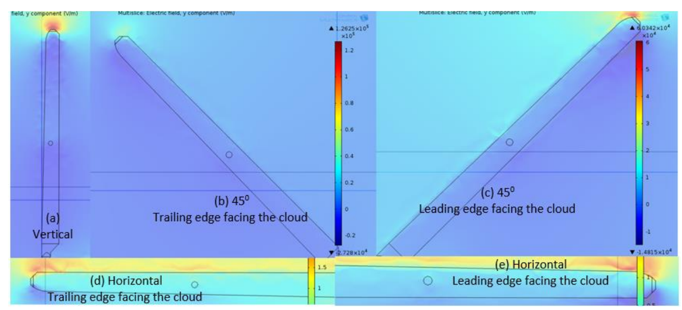


Figure 9. Polluted blade arrangement for enhanced method

The results for the maximum electric field distribution for the new method as well as on the blade surface for various arrangements are tabulated in Table 3 and the comparison with other methods are shown.

Table 1, 2 and 3 provide details of the maximum electric field strength on various protection systems and on the blade surfaces for various arrangements.

Table 1. Maximum electric field strength KV/m with the Receptor method

Blade position	Maximum electric field strength	
	Receptor tip	Blade surface
Vertical	7.12	0.43
45^0 (TEFC)	5.66	0.64
Horizontal (TEFC)	0.54	2.13
45^0 (LEFC)	3.97	0.46
Horizontal (LEFC)	1.66	1.16

Table 2. Maximum electric field strength KV/m with the Metallic cap method

Blade position	Maximum electric field strength	
	Metallic Cap tip	Blade surface
Vertical	54.39	0.26
45^0 (TEFC)	30.87	0.34
Horizontal (TEFC)	0.37	1.74
45^0 (LEFC)	17.47	1.44
Horizontal (LEFC)	2.43	1.31

Table 3. Maximum electric field strength KV/m with the Enhanced Method

Blade position	Maximum electric field strength	
	Metallic Cap tip	Blade surface
Vertical	53.68	0.25
45^0 (TEFC)	31.87	0.33
Horizontal (TEFC)	0.55	1.63
45^0 (LEFC)	26.10	0.45
Horizontal (LEFC)	2.43	0.75

The results for maximum electric field strength distributions for various configurations obtained from the protection systems and the blade surfaces as blade A is rotated are plotted in Figure 10 to Figure 14. As was said earlier, the most efficient method is the one with highest electric field on the lightning protection system and minimum on the blade surface.

(a) Vertical

The plot for the maximum electric field strength distribution on the three protection systems and the blade surface while the blade is in the vertical position is shown in Figure 10.

The maximum electric field strength on the various protection system is shown in Figure 10(a). The metallic cap method is higher followed by the enhanced method and lowest for the receptor method. Since the metallic cap method has the highest value on the cap, it is more proficient at this position than other methods.

The distribution on the blade surface is shown in Figure 10(b) above. With blade A in the vertical position, the maximum electric field strength for the receptor method is higher followed by the metallic cap method and lowest for the enhanced method. Since the enhanced method has the lowest value on the blade surface, it is more proficient at this position than other methods.

(b) 45^0 (TEFC)

The plot for the maximum electric field strength distribution on the protection system on the three protection systems and the blade surface while the blade is in the 45^0 (TEFC) from the vertical position is shown in Figure 11below

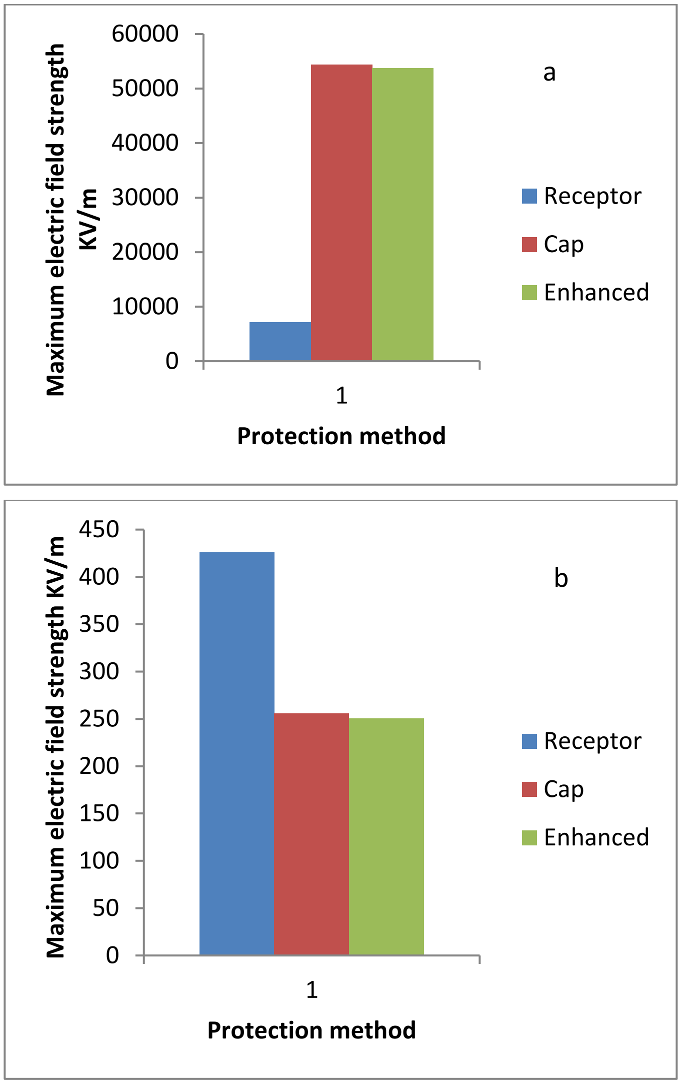


Figure 10 Maximum electric field strength distributions on the protection system and blade surface for vertical position

The maximum electric field strength on the various protection system is shown in Figure 11(c). The maximum electric field strength for the enhanced method is higher followed by the metallic cap method and lowest for the receptor method. Since the enhanced method has the highest value on the cap, it is more proficient at this position than other methods

The distribution on the blade surface is shown in Figure 11(d) above. With blade A 45^0 (TEFC) from the vertical position, the maximum electric field strength for the receptor method is higher followed by the metallic cap method and lowest for the enhanced method. Since the enhanced method has the lowest value on the blade surface, it is more proficient at this position than other methods.

(c) Horizontal (TEFC)

The plot for the maximum electric field strength at the tip of the protection system on the three protection systems and the blade surface while the blade is in the horizontal (TEFC) position is shown in Figure 12 below

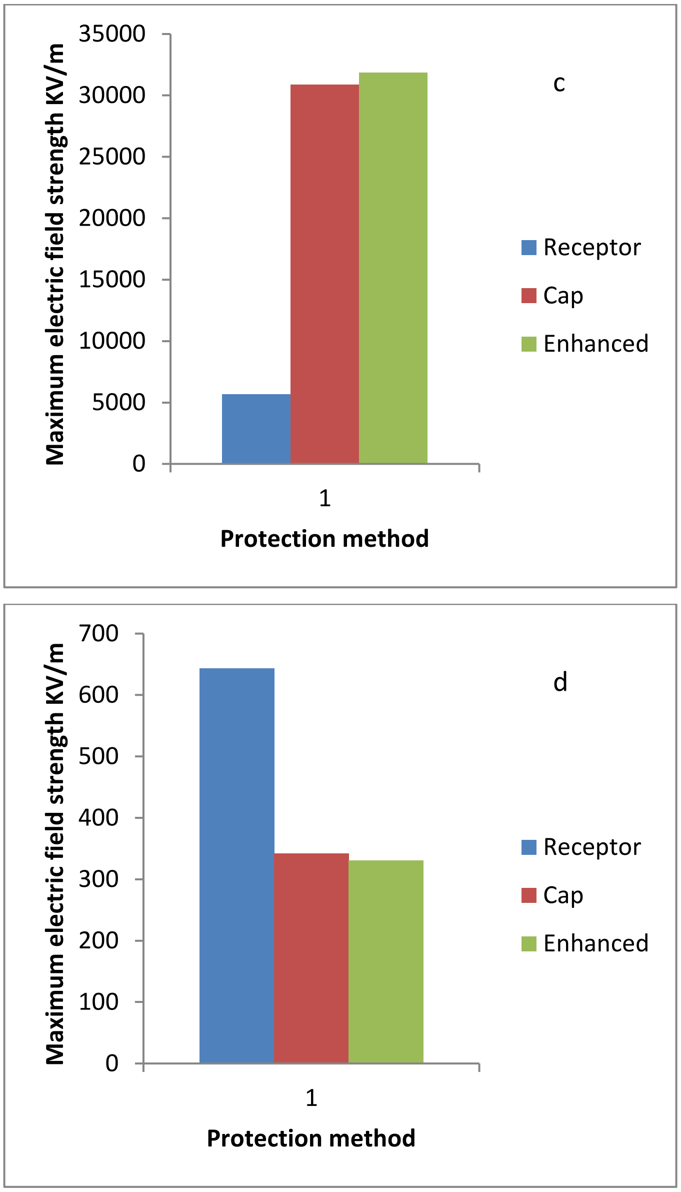


Figure 11. Maximum electric field strength distributions on the protection system and blade surface for 45^0 (TEFC) position

The maximum electric field strength on the various protection system is shown in Figure 12(e). The maximum electric field strength for the enhanced method is higher followed by the receptor method and lowest for the metallic cap method. Since the enhanced method has the highest value on the cap, though with a small margin, it is more proficient at this position than other methods.

The distribution on the blade surface is shown in Figure 12 (f) above. With blade A in the horizontal (TEFC) position, the maximum electric field strength for the receptor method is higher followed by the metallic cap method and lowest for the enhanced method. Since the enhanced method has the lowest value on the blade surface, it is more proficient at this position than other methods.

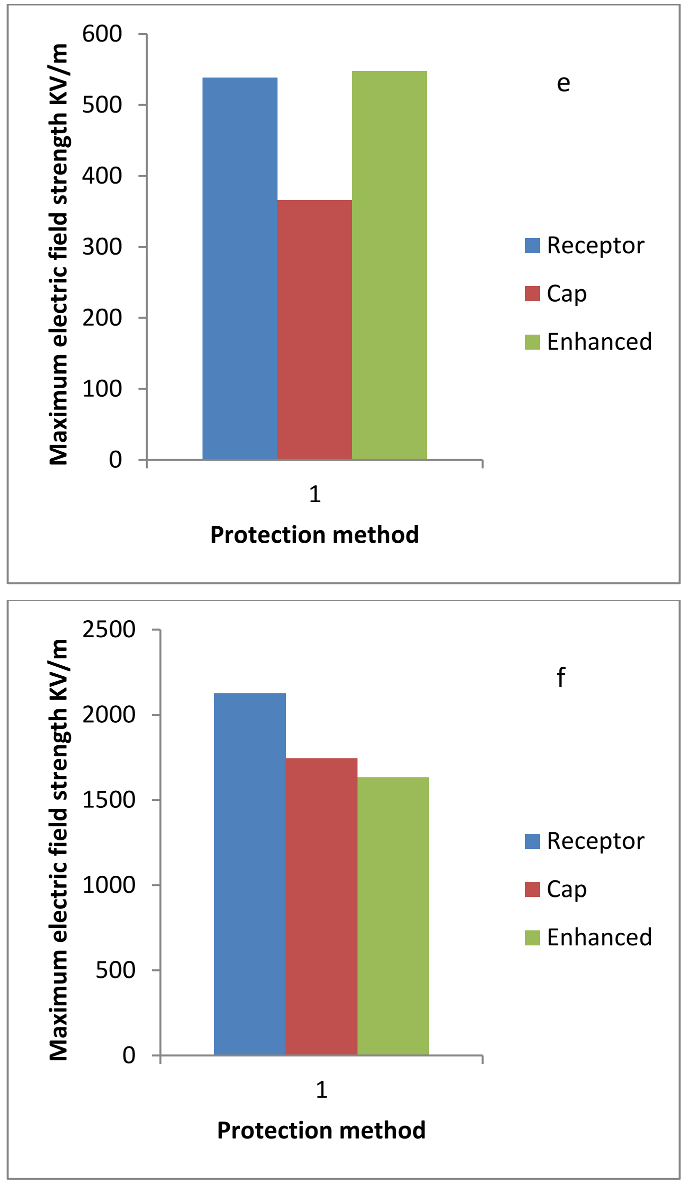


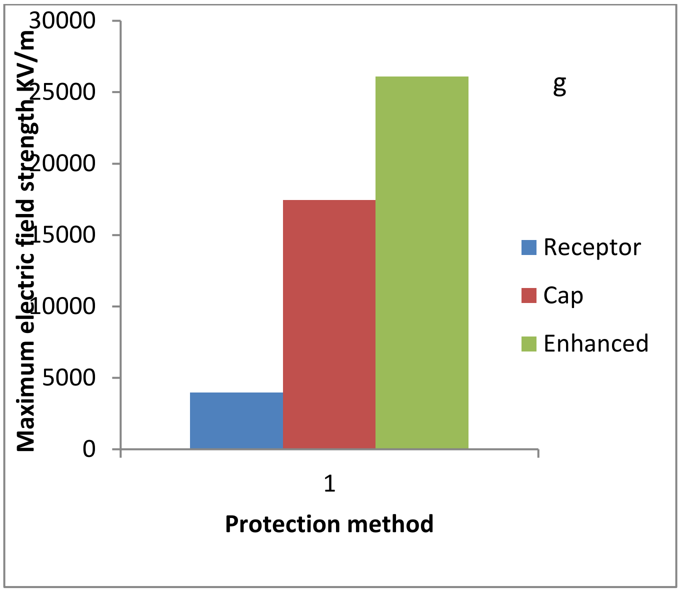
Figure 12. Maximum electric field strength distributions on the protection system and blade surface for horizontal (TEFC) position

(d) 45^0 (LEFC)

The plot for the maximum electric field strength on the protection system for the three protection systems and the blade surface while the blade is 45^0 (LEFC) from vertical position is shown in Figure 13 below

The maximum electric field strength on the various protection system is shown in Figure 13 (g). The maximum electric field strength for the enhanced method is higher followed by the metallic cap method and lowest for the receptor method. Since the enhanced method has the highest value on the cap, it is more proficient at this position than other methods

The distribution on the blade surface is shown in Figure 13(h) above. With blade A 45^0 (LEFC) position, the maximum electric field strength for the metallic cap method is higher followed by the receptor method and lowest for the enhanced method. Since the enhanced method has the lowest value on the blade surface, it is more proficient at this position than other methods.



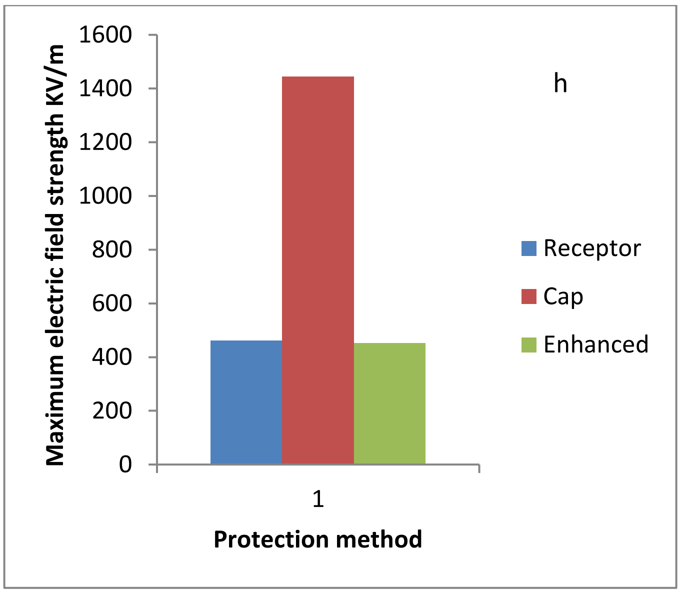


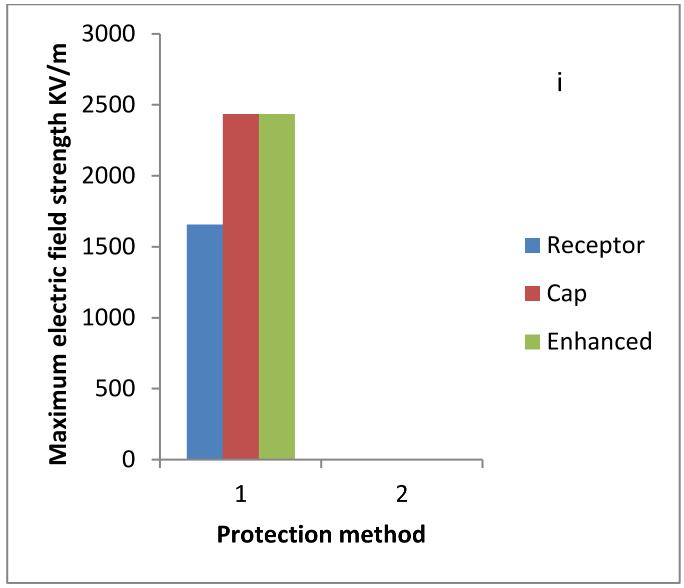
Figure 13. Maximum electric field strength distributions on the protection system and blade surface for 45^0 (LEFC) position

(e) Horizontal (LEFC)

The plot for the maximum electric field strength distribution on the protection system for the three protection systems and the blade surface while the blade is in the horizontal (LEFC) position is shown in Figure 14.

The maximum electric field strength on the various protection system is shown in Figure 14(i). The maximum electric field strength for both the metallic cap method and the enhanced method is the same and higher compared to the receptor method. Since the metallic cap and the enhanced both has the highest value on the cap, they are more proficient at this position than the receptor method.

The distribution on the blade surface is shown in Figure 14(j) above. With blade A in horizontal (LEFC) position, the maximum electric field strength for the metallic cap method is higher followed by the receptor method and lowest for the enhanced method. Since the enhanced method has the lowest value on the blade surface, it is more proficient at this position than other methods.



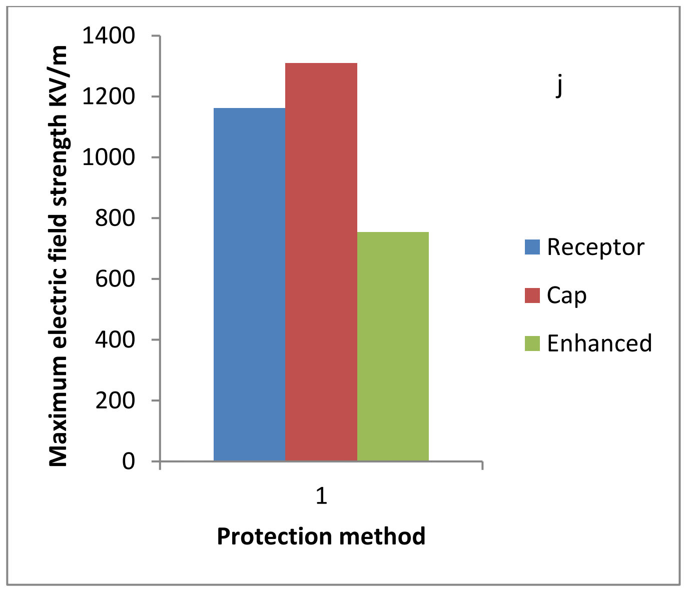


Figure 14. Maximum electric field strength distributions on the protection system and blade surface for horizontal (LEFC) position

Considering efficient lightning protection, the presence of the protection system should ensure that the electric field on the blade surface is kept minimum but maximum on protection system so that leader will incept from the protection system first. On the average, the new protection system (the enhanced method) has the highest maximum electric field on the protection system and lower on the blade surface. The electric field at the metallic cap of a blade protected with the enhanced method is found to be boosted when compared to other methods. Adding a receptor at the middle of a blade protected by the metallic cap method was found to influence the electric field distribution immensely.

The effectiveness of the numerical model used in this work was validated with results from experimental evaluation of air-termination systems for wind turbine blades reported by Abd-Elhady et al. [20] in which the receptor was used to study the lightning attachment manner. The experimental results provide some qualitative insight into the role of the protection systems on points of leader attachment. We recommend that testing of the outcomes of this study should be done for the full length of the blade, rather than a small tip segment of the blade to ensure the reliability of the simulation [24].

Results of maximum electric field strength for both polluted and unpolluted blade conditions agree with experimental data on points of leader attachment and upward leader initiation points. It corroborated the experimental result in [20], that, In case of unpolluted surface, the air-termination system successfully captures surges more than in the case of polluted surfaces. The level of damping on the polluted blade surface also supports the findings by Naka et al. [9], that, regarding non-conductive blade, creeping discharge occurred more frequently in the polluted condition, and sometimes penetrative destruction has also been observed.

The simulation also supports the following experimental results;

1. The number of discharges attached to polluted surface is higher than that of the unpolluted surface.

2. Blade with metallic cap is suitable for discharge coming from the blade top.

3. Protection system using the metallic cap has a higher protective efficiency than using the receptor.

IV. CONCLUSION

Offshore wind turbines, when in contact with salt water, become polluted. Pollution drastically affects the lightning protection systems, resulting in serious damages. Two lightning protection systems (metallic cap and receptor methods) commonly in use have been applied on a full scale polluted offshore wind turbine and compared for efficiency in lightning protection. In the enhanced method, the performance of the metallic cap was improved by adding a receptor at the middle of the blade. This was found to influence the electric field distribution immensely. The new method was compared with the metallic cap method and the tip receptor method and it performed better. It can greatly improve the lightning protection performance for offshore wind turbines.

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