Effect Of Pollution On Offshore Wind Turbine Blade Lightning Protection Systems

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***Abstract*—Wind turbines are getting taller, moving offshore and coastal areas in search of better wind condition but with a consequence of contact with salt water. With pollution from salt deposit, insulation strength of nonconductive (glass fiber) blade surface decreases, raising its conductivity, which could result in the blade going into competition with the receptors for lightning attachment. Streamers can initiate from the surface of the blade instead of the receptors and as an unintended lightning part, the blade is severely damaged when hit by lightning. This is a major problem for lightning protection of large wind turbine constructed near seaside or offshore. It is therefore necessary to investigate how a polluted blade surface affect the performance of the receptors. In this paper, the effect of pollution on the performance of the receptor is evaluated and estimated on a full scale offshore polluted and unpolluted wind turbine using COMSOL Multiphysics software. Simulation results compared with experimental data. It is found that pollution dampens the performance of the receptor by 93%, resulting in lower lightning protection performance. This indicates that offshore wind turbines are at higher risk of failure of its lightning protection systems and are prone to higher probability of damage.**

Keywords—Lightning protection, pollution, wind turbine blade, simulation, modeling, electric field.

1. Introduction

Due to increase in power generating capacity, modern wind turbines are increasing in height. They are mostly installed in isolated location like mountain and offshore (Winds are stable and strong at the ocean owing to the absence of structures blocking the wind) regions with better wind condition, making them more exposed to lightning. As their number and size are increasing, lightning damages has also increased with the blades at the highest risk of lightning attachment [1, 2]. Lightning damages to wind turbine blades are quite serious due to high cost for replacements and long repair time, particularly, blades made from glass fiber reinforced plastic (GFRP) material.

Offshore windfarm data shows that most lightning strikes to wind turbines happen during winter months [3] and that winter lightning occurs frequently [4]. Compared to summer clouds, winter clouds which develop at lower altitudes are more capable of developing higher electric fields at ground. The current duration of winter lightning is usually very long, and it tends to strike tall structures such as wind turbines intensively. Since its energy is remarkably large, winter lightning causes considerable damage.

The risk of lightning striking offshore wind turbine is higher because they are subjected to moisture, contaminations such as dust, sand and salt. When these contaminations accumulate on the surface of the blade, for instance, if it gets polluted with salt deposit, it can cause its insulation strength to decrease and raise the conductivity which can greatly affect the interception efficiency of the receptor. The problem with this is that on lightning strike, streamers can initiate and propagate from the surface of the blade instead of the receptors and as an unintended lightning part, the blade is severely damaged and puncture of the blade can occur. This is a major problem for the wind industry.

Lightning protection of wind turbine has attracted research. Wang et al. [5], investigated the effects of receptors on lightning protection of wind turbine blades. Kumar et al. [6], used a remote laser-induced breakdown spectroscopy (LIBS) technique for the detection and quantification of salt deposits on wind turbine blade surface.

It has been found that pollution affects the performance of the receptor. i.e., if receptor A for instance, is used on an unpolluted blade, and the same receptor is also used on a polluted blade, that same receptor will perform better in an unpolluted blade condition. Therefore, understanding the extent pollution can affect the receptor, will enable the design engineer to improve on the properties of the receptor.

The effect of Pollution on wind turbines has been experimentally evaluated as in [7, 8] however, a small blade tip section was used and not full blade length, more also, the performance of the receptor considering pollution influence has not been considered in literature and are not suggested in the current lightning protection standards. Up to date, the level of pollution influence on receptor performance has not been estimated and simulation studies associated to this topic have rarely been reported. The effect of pollution on offshore wind turbine receptor performance is very important to enable improvement on the protection systems.

In this paper, the effect of pollution on the performance of the receptor is evaluated and estimated on a full scale offshore wind turbine. In order to provide evidence of the reliability of the proposed estimation, the same concept of methodological evaluation and experimental setup published in [7, 8] are utilized. The design and analysis is done for polluted and unpolluted blade conditions as the blade is rotated. Later section shows a comparison between polluted and unpolluted wind turbine blades. Finally, the estimation is proposed to increase the lightning protection efficiency.

2. Pollution

As was stated earlier, winds are stable and strong at the ocean owing to the absence of structures blocking the wind. When wind turbine is located offshore and in contact with salt water, it gets polluted with salt deposit which causes its insulation strength to decrease and raising the conductivity, this could result in the blade going into competition with the receptors for lightning attachment. The problem with this is that Streamers can propagate from the surface of the blade instead of the receptors and as an unintended lightning part, the blade is severely damaged when hit by lightning.

Technically speaking, as compared to unpolluted blade surface, the conductivity as well as the relative permittivity are increased in polluted blade condition as observed from the distributed electric field on the surrounding air and the blade surface. A brief illustration is shown below.

The relative electric permittivity of water decreases as the temperature rises, for example, at 0°C its relative permittivity is 88, at 20°C it is 80.1, at 100°C it is 55.3 and at 200°C it is 34.5. Hasted (1948) experimentally conducted study on the dielectric properties of salt-water solutions, a dielectric decrement with salt concentration was observed. This means that the addition of sodium chloride to water results in a reduction in electrical permittivity.

There is an electric field between sodium and chloride ions when they dissociate in solution. The polarized water molecules, under the effect of the electric field get oriented so that their oxygen atoms (a partial negative charge carrier) face toward the sodium ion then their hydrogens (partial positive charges carrier) face toward the chloride ion. The polar water molecules orientation causes its own electric field that cancels out most of the electric field that would be present if the ions were in a vacuum. The result is that the sodium and chloride ions are well 'shielded' by a 'hydration shell' of polarized water molecules which effectively reduces the applied external field and hence lowering the electric permittivity (dielectric constant) as the ionic concentration increases.

3. Estimating the Effect of Pollution on The Performance of The Receptor

Tall structures such as wind turbines having height more than 100m experience both downward and upward lightning strikes, in fact, more than half of the lightning strikes on a 200m tall structure are upward initiated strikes [9]. The knowledge of both upward and downward lightning strikes are very important for efficient lightning protection. Up till now, research focus has been on downward lightning strikes. Few work done on upward lightning strikes has shown that tall wind turbine can increase the number of lightning strike, and also, due to rotation, turbines are triggering their own lightning [10], demonstrating that large portion of the lightning strikes that attach to a wind turbine are upward initiated. Therefore, the analysis in this paper only involves the interaction between wind turbine and the thunder cloud charge considering upward initiated lightning strikes.

3.1. Evaluation Model

The model used for the evaluation in finite element analysis; COMSOL Multiphysics software, for the cloud, wind turbine and lightning protection systems are discussed below.

3.1.1. Thunder Cloud Model:

As mentioned above, tall wind turbines, in the presence of a thundercloud, are increasingly subjected to upward initiated lightning attachment triggered by the wind turbine itself [10-12]. Report shows that this upward lightning flashes are initiated from the enhancement of the electric field produced by thundercloud charge or close lightning discharges [11, 13] and not by a stepped leader. Therefore, for upward leader formation, the strong influence of the stepped leader position is eliminated and the formation will be dominated by the wind turbine geometry and the electric field distribution. Upward leaders in self-initiated upward lightning are majorly influenced by the slowly increasing electric field component, with a rise rate lower than 1 KV/m/s [14] i.e., during the inception of stable upward leaders, it is considered to be constant because this process has duration of about few hundred microseconds.

As was shown in our previous paper [15], the extended vertical tri-pole thundercloud model, is made from a negative charge and two positive charges, a summary of various models that have been produced are shown in [9, 16], and the cloud model in [9] is implemented in this paper. As shown in Fig. 1, the charge structure has positive at the top, negative in the middle, and a smaller positive at the bottom, and the ground modeled as a perfect conductor. The top two charges form a dipole, said to be positive because the positive charge is above the negative charge, this gives an upward-directed dipole moment.

The three charges of +40C, -40C and 3C are placed at height of 12, 7 and 2 km from the ground respectively and modelled as spheres of radii 900m for the 40C charges and 150m for the charge of 3C [3, 9]. 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.

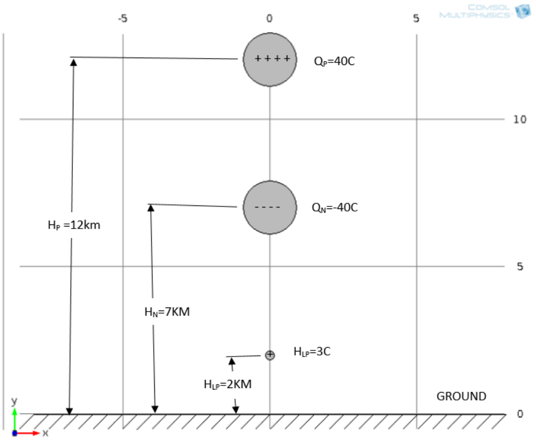

Figure 1. A vertical tri-pole made from two positive charges and a negative charge representing the idealized gross charge structure of a thundercloud. [15]

Where Q_p is the main positive charge, Q_N is the main negative charge, H_{LP} is the lower positive charge and H_P, H_N and H_{LP} are their various distances (in kilometer) from ground.

Shown above in Fig. 1 is the system of three charges and the results of the electric field at ground agrees with the report in [9] with maximum ambient field of about 5kV/m. This values are applied in this paper and an upward-directed electric field is considered as positive [9].

In order to evaluate the maximum electric field strength required for the initiation of upward leaders from wind turbines, the information from the wind turbine model is combined with the cloud model in the simulation.

As mentioned earlier, the vertical tri-pole model is used to create an ambient field which represent uniform electric field due to cloud charge distribution at 200m 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). This is based on the results found from Malan's charged cloud model as mentioned above. The polarity of the electrode is negative, the environment is modelled as air and the wind turbine is sited on the ground. The dimension of the electrode is large enough to prevent flashover from the edges. These details were shown in [15].

3.1.2. Wind Turbine Model

The wind turbine model used in the simulation is the same as the one in our previous paper [15], it is a vesta's wind turbine V100, with the following properties; 100 m rotor diameter, swept area of 7.854m^2 and a 49 m long blade. It is a horizontal axis wind turbine with three blades. The blade is made of fibred glass with a relative permittivity of 4.2. Conductivity:1.0×10^{-14} S/m. Blade thickness: 10cm, chamber length: 0.9m, airfoil chord length 2.75m (varied at blade root and tip). The nacelle and tower are conductive and are set to ground potential. Hub height (height from the lowest part of the tower to the Centre of the hub) is 80 m. The tower is tubular steel type. The nacelle is 10.4 m long and 3.5m wide. The wind turbine is shown below in Fig. 2. Air is modelled as the environment. 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, this corresponds to the value of salt-water [8], the relative permittivity for normal water is higher than this value.

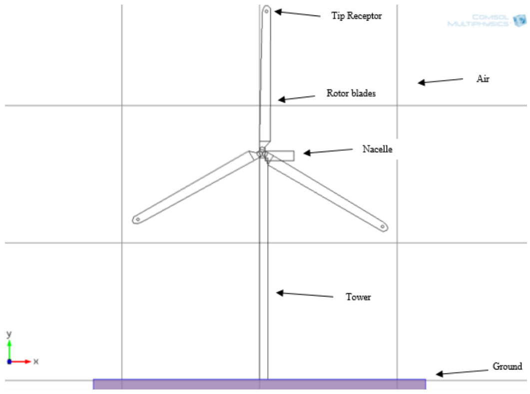

Figure 2. Wind Turbine Model

3.1.3. Receptor on the Blade

The wind turbine blade of a V100 and the tip receptor design is shown below in Fig. 3. The receptor (purple colour in fig. 3 below) is the air terminal of the lightning protection system used on the blade. The receptor is designed and placed 1.5m from the blade tip as recommended in [15], it grounded or earthed so as to take the lightning current to ground. The receptor's design is such that it can be activated or deactivated when the need arises, during analysis. It is 10mm in diameter [17] and made of copper (conductivity: 6.0×10^{-7}S/m).

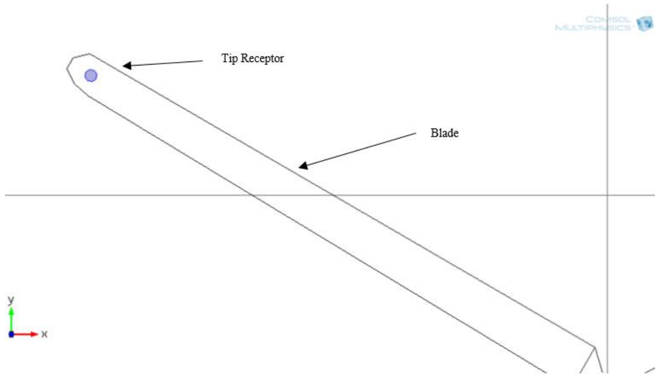

Figure 3. Wind Turbine Blade and the Tip Receptor

3.2. Procedure of Simulation Evaluation

The maximum electric field strengths on the surfaces of the wind turbine due to a vertical tri-pole cloud charge distribution are obtained by using COMSOL Multiphysics to develop a numerical model that accounts for the electric field produced by the cloud charge. The predicted point of initiation of upward leader on the blade surface is taken to be the location with the highest magnitude of electric field strength necessary for the initiation of upward leader. This is also the predicted lightning strike attachment point. By comparing the corresponding maximum magnitudes of electric field strength on receptors as well as on the blade surfaces with different blade conditions, the interception efficiency of the receptor is evaluated. In this paper, it is considered that the receptor with better interception efficiency is the one with highest electric field on the receptor and minimum at the tip, leading, trailing edges and the entire wind turbine surface. The results for this system are summarized in Table 1, also plotted in Fig. 9. The obtained results are of great importance in the design and development of lightning protection systems on wind turbines.

Three blade conditions are applied on the wind turbine to investigate the effect of pollution on the initiation of upward leader from wind turbine. The blade conditions are unprotected, unpolluted and polluted blade conditions respectively. As mentioned earlier, 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, this corresponds to the value of salt-water [8]. In each case, the evaluation is done as the blade is rotated through -60 to + 60 degrees from the vertical position. The blade in the vertical position in Fig. 5 is referred to in this paper as blade A and only the results for blade A are provided in this paper and values are obtained from the receptor tip.

The focus is on estimating the efficiency of the receptor 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 chosen because it represents the general situation of lightning strikes [18].

Electrostatics equations can be 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 Fig. 2. The same concept of evaluation and experimental setup that have been published as in [7, 8, 19, 20] are utilized for this analysis.

4. Results and Discussion

This section contains the evaluation of the maximum electric field strength on the surface of the blade using various blade conditions. The blade is rotated and values are obtained from blade A. The locations with higher electric field strength are considered to have higher possibility of inception of upward leader. Results are plotted and compared for values obtained from the receptor tip. The most efficient receptor position is the one with highest electric field on the receptor and minimum at the blade surface.

To investigate the effect of pollution on offshore wind turbine blade's lightning protection system's performance, the simulation is initially conducted on the wind turbine without the receptor and then the blade surface conductivity is changed starting with unpolluted and then polluted blade condition as the blades are rotated.

For an unprotected blade, as expected, there was no field enhancement around the metallic receptor, instead, a very high electric field was observed across the blade length, indicating that without protection or when the receptors are not grounded, the blade is highly vulnerable to lightning strike and that discharge to the blade can occur even though it is made entirely of nonconductive material.

Field enhancement is seen on a wind turbine when it is protected, i.e. when the receptor is activated as shown below. Fig. 4 shows the detailed activities around the receptor, these include; the upward positive polarity for streamer activities, the negative polarity going to ground through ground wire, positive polarity on the blade surface. Also shown is the produced corona charge (qc) which lowers the electric field on the tip inhibiting the occurrence of a streamer [15].

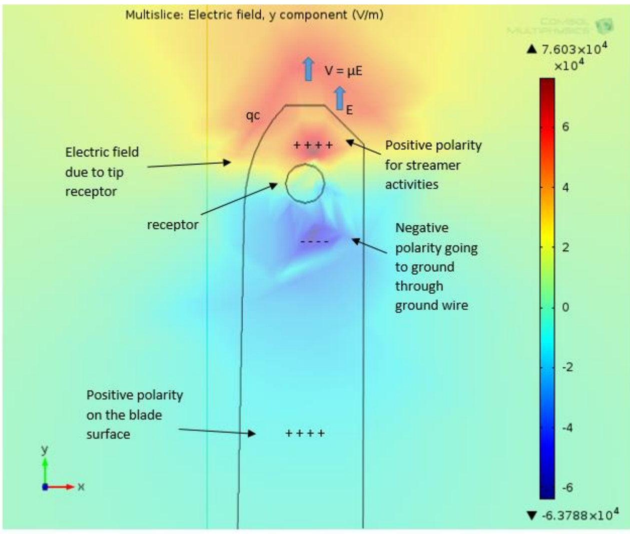

Figure 4. Activities around the receptor preceding leader initiation [15]

If lightning attaches to the receptor, it will be conducted to ground through ground wire without causing damage to the turbine. This is the intent of the lightning protection designer. But, when lightning attaches to the blade surface instead of the receptor, the blade and sometimes the entire wind turbine can be destroyed. The positions with higher electric field strength are considered to have higher possibility of inception of upward leader in this paper.

4.1. Unpolluted Wind Turbine Blade

As was mentioned earlier, the model is first simulated without protection by deactivating the three receptors. The turbine is then protected by activating the receptors. When the receptors are activated, field enhancement is seen around them. It is also possible to have field enhancement on the blade surface instead of the receptor. Note that in this case, the turbine is protected but not polluted. Fig. 5 and Fig. 6 shows the simulation model for unpolluted wind turbine blade condition used in the comparison of the maximum electric field strength distribution.

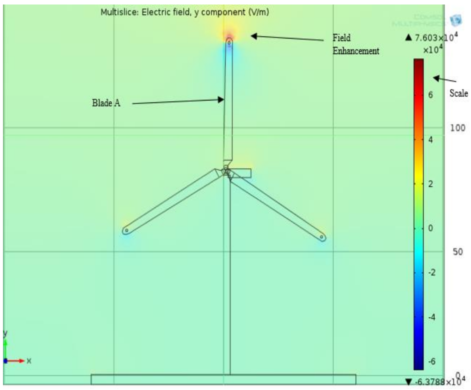

Figure 5. unpolluted wind turbine

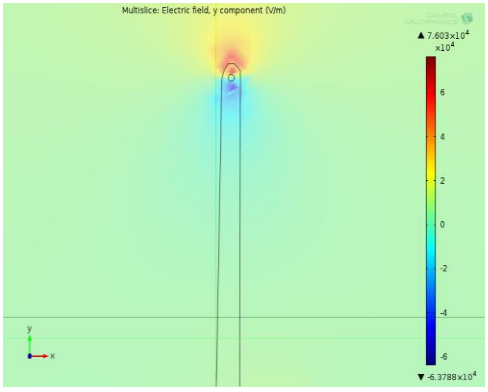

Figure 6. unpolluted wind turbine blade

The protected model was simulated with a single receptor at the tip of each blade. As compared to the unprotected condition, the blade is protected but unpolluted. The tip enhancement around various receptors is shown and the value for the maximum electric field strength for blade A is shown in table 1. This value is 89.71 kV/m, with blade A in the vertical position. Note that the relative permittivity for the blade is 4.2 and Conductivity:1.0×10^{-14} S/m.

When upward lightning does not incept from the receptor, then, any part of the blade with the highest stress corresponding to largest electric field strength will be the likely attachment point. There are reports of multiple discharge in the turbine associated with nearby cloud to ground lightning [21] and also strikes attaching inboard on the blade due to dart leader [22].

4.2. Polluted Wind Turbine Blade

The turbine model is protected and polluted. In this condition, the simulation for polluted turbine blades condition is done with values of the conductivity of the blades at 0.9 S/m and relative permittivity 80, this corresponds to the value of salt-water. Fig. 7 and Fig. 8 shows the simulation model for polluted wind turbine blade condition used in the comparison of the maximum electric field strength distribution.

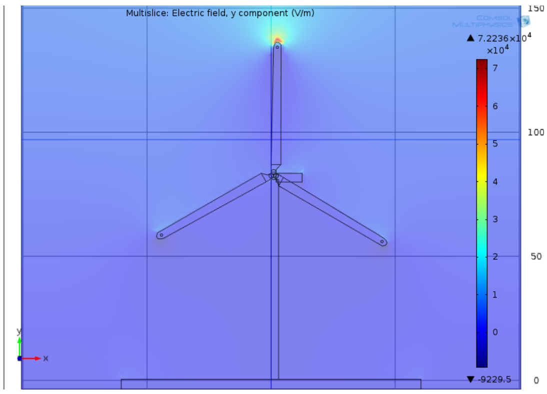

Figure 7. Polluted wind turbine

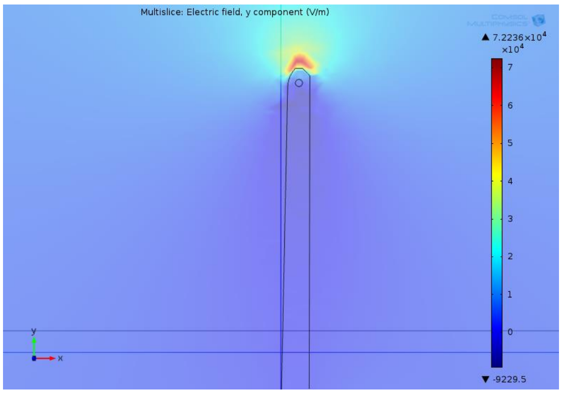

Figure 8. Polluted wind turbine blade

The polluted condition was simulated and the tip enhancement around various receptors is also shown and the value for the maximum electric field strength for blade A is shown in table 1. This value is 5.96 kV/m, with blade A in the vertical position. This is a significant reduction on the field enhancement by the receptors.

Table 1. Maximum electric field strength distribution (kV/m) at the receptor tip on blade A for various blade condition

Maximum electric field strength Kv/m on the Receptor tip		
Angle from vertical	Unpolluted	Polluted
-60	29.28	1.93
-55	36.34	2.41
-50	42.89	2.87
-46	29.16	1.95
-40	56.13	3.73
-35	65.96	4.47
-30	68.67	4.60
-20	80.44	5.45
-15	82.15	5.52
-10	90.46	5.99
0	89.71	5.96
10	85.26	5.71
15	86.04	5.72
20	63.41	4.30
26	76.08	5.10
30	69.39	4.57
35	66.20	4.41
40	56.87	3.76
45	61.44	4.22
50	43.12	2.83
55	35.38	2.29
60	31.29	2.04

The table above shows the effect of pollution on the receptor. The interception efficiency is dampened by pollution. As the blade is rotated from -60 to +60, it is observed that the values of the maximum electric field strength required for the initiation of upward leader is uniformly reduced for the polluted condition when compared with the unpolluted condition. Therefore, leader might incept from the blade surface earlier than the receptor in the polluted blade condition, which might cause severe damage to the wind turbine. The values for blade A at the vertical position which represents the critical position is plotted below in Fig. 9. The percentage damping at this instance is evaluated.

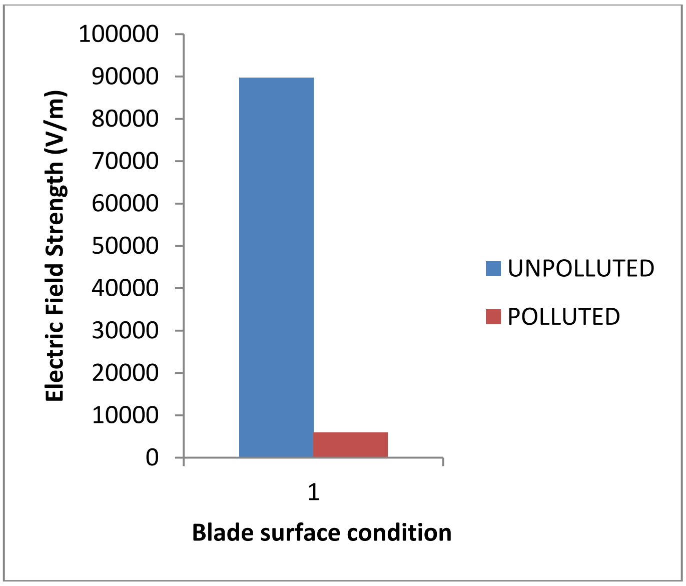

Figure 9. Pollution effect on the receptor

The effect of pollution on the receptor is depicted in the plot above. A damping of

89707.9712V/m - 5961.671163V/m = 83746.300037V/m is estimated.

Therefore, % damping,

$$X = \frac{U - P}{U} X100$$

Where U is unpolluted, P is polluted,

$$X = \frac{83746\ X\ 100}{89708} X100$$

= 93%

is estimated at blade A in the vertical position.

The numerical evaluation is validated by qualitatively comparing the point of inception of upward leader on the blade surfaces with those obtained by experimental observations.

It is generally observed that the electric field strength at the tip region appears to be higher than that at the inboard region. This is corroborative of laboratory experiments and field observations indicating that the tip is more exposed than other parts [1] and that upward leader is more likely to initiate from the tip receptor.

Obtained 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 [7], that, In case of unpolluted surface, the air-termination system successfully captures surges more than in case of polluted surfaces. The level of damping on the polluted blade surface also support the findings by Naka et al. [8], that, regarding non-conductive blade, creeping discharge occurred more frequently in the polluted condition, and sometimes penetrative destruction was also observed.

The maximum electric field strength at the receptor tip as the blade is rotated and at different positions of the blade are shown in table and plots above. It is found that pollution dampens the performance of the receptor by 93% and on average, the general performance of the receptor in a polluted blade condition is found to be less than 10%. If receptor A for instance, is used on an unpolluted blade, and the same receptor is also used on a polluted blade, that same receptor will perform better in an unpolluted blade condition, i.e. under the same condition, upward leader can initiate from a receptor used in an unpolluted blade condition earlier than the polluted blade condition. This indicates that offshore wind turbines are at higher risk of failure of its lightning protection systems and are prone to higher probability of damage.

5. Conclusions

In this paper, the effects of pollution on the efficiency of lightning protection system of wind turbine has been investigated. The vertical tri-pole model has been used to create an ambient field which is used to study the variations in maximum electric field strength required for the initiation of upward leader from wind turbine, this is done with COMSOL Multiphysics software. By comparing the electric field strength as the blade surface condition is changed from unpolluted to polluted and the blade is rotated, the damping effect of pollution on the proficiency of the receptor is estimated. point of initiation of upward leader was compared with experimental data to validate the efficiency of applied numerical model. Results show that pollution dampens the performance of the receptor by 93% and on average, the general performance of the receptor in a polluted blade condition is found to be less than 10%. Indicating that offshore wind turbines are at higher risk of failure of its lightning protection systems and are prone to higher probability of damage.

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