Testing of Wind Turbine Lightning Protection Systems – Comparison of Testing the Full-Scale Blade Length and a Small Section of the Blade Tip

Godson I. Ikhazuangbe[1], Mumtaj Begam[1], Chandima Gomes[2*], Anandan Shanmugam[1], Agbeb Stephen[3], Philip Kpae[3], Edward Jaja[4]

1-Department of Electrical and Electronic Engineering, University of Nottingham Malaysia Campus, 43500, Semenyih, Selangor, Malaysia
2- School of Electrical & Information Engineering, University of the Witwatersrand, Johannesburg, South Africa
3- Department of Electrical and Electronic Engineering, Kenule Beeson Sarowiwa Polytechnic Bori, Rivers State, Nigeria
4- Captain Elechi AMadi Polytechnic Portharcourt, Nigeria

*chandima.gomes@wits.ac.za

Abstract— **To ensure safety against lightning of wind turbines, high-voltage strike attachment tests specified in IEC 61400-24 are adopted to determine points of lightning attachments. These tests are usually conducted with a small blade sample as a representative of the full-scale blade length. However, incidents of lightning damage to wind turbines are still high, which indicates that small blade samples may not be an adequate representation of full-scale blade. In this paper, the extended vertical tri-pole cloud charge distribution model is used to compare the maximum electric field strength around a full-scale blade and that of a small blade section to show how they affect the maximum electric field strength required for the initiation of upward leaders from wind turbines. The results show an average difference of 15.16% between the maximum electric field relevant to the full-scale blade and that of the blade segment. Thus, a tolerance of 16.95 kV/m is recommended in using the blade segment in the laboratory testing. The results of the point of initiation of upward leader coincides with experimental data from lightning discharge attachments.**

Keywords- Full-scale blade, lightning protection, small blade, wind turbine.

I. INTRODUCTION

High voltage testing is given in section 8.1 of IEC 61400-24 to verify the functionality of a protection system. To ensure efficient lightning protection of wind turbines, experimental analysis is usually done in accordance with the test methods and as generated power capacity is increasing, offshore wind turbines are getting taller with longer blades, resulting in increased probability of lightning strike majorly due to upward lightning. Research has shown that the features and physical characteristics of natural lightning are different from those in the laboratory. Furthermore, recent studies reveal that the electric field distribution between a small test sample and the high voltage electrode (as it is currently practiced in the laboratory), is different from the case where the sample is replaced by the entire blade [1-2].

Full scale blade tests are still complex to be conducted under laboratory conditions, since modern wind turbine blades may be as long as 80 m [3]. Thus, indoor experiments and testing are presently conducted with small blade samples such as 3m or 2m cut from a full blade. Then the electrode configurations are set as reduced sized or down-scaled models. Various test procedures and results can be found in literature in this regard [3-6]. Various test methods are available in international standards for developing new blade designs or verifying existing blade design performances with respect to their capabilities. Some progress has been made with wind turbine lightning protection technologies, and testing methods [7-11]. Glushakow [12] discussed the formulation of the 10/350 test waveform and D'Alessandro and Gumley [13] presented a perspective on protection of direct lightning strike. Also, Zhou et al [14], has made a review of wind turbine blade's full-scale structural testing. Yang et al [15] has also made some insight to nondestructive testing for wind turbine composite blade. For obvious reasons, it is impossible to replicate lightning itself in testing: about 6 MV are the highest voltages that can be generated inside laboratories and 10 MV for outdoor equipment [16]. Laboratory size is another limitation as it is difficult to accommodate full blade with length as long as 80 m, and also preventing stray discharges much longer than 10 m or so. Again, there is no available equipment that can produce the high voltages and high currents of natural lightning, simultaneously with the same machine.

To assess the normal distribution of the points of attachment on the blade surface, a large wind turbine hit by natural lightning, while it is rotating, is experimentally required. This can only be done in a triggered lightning site such as that in Florida [17]. The usual practice to ensure efficient lightning protection of wind turbines, is to apply tests specified in IEC 61400-24. Such tests could determine points of lightning attachments on wind turbines. These tests are conducted on a small blade sample as a representative of the full-scale blade length. These results may be different if the full blade length is used for the test. Since there are no standards or detailed experimental / numerical research covering this subject, it is a requirement at present to study the correlation between the results on segment and full blade. Again, incidences of lightning damage to wind turbines are still highly recorded indicating that small blade sample might not be an adequate representation of full-scale blade.

In this paper, the extended vertical tri-pole cloud charge distribution model is used to compare the maximum electric field strength around a full-scale blade and that of a small blade section to show how they affect the maximum electric field strength required for the initiation of upward leaders from wind turbines. The simulation is done with COMSOL Multiphysics software and it is considered that the magnitude of the electric field strength distributed on the wind turbine model determines the point of upward leader inception.

II. WIND TURBINE BLADE DESIGN

The extended vertical tri-pole cloud charge distribution model, details of wind turbine and the lightning protection system used in this paper are detailed in [1]. The capacity of the wind turbine is 600 kW with 19.1 m blade length and the receptor is placed 0.9 m away from the blade tip for both the full-scale model and a small blade section. This same receptor position applied in both cases is for the purpose of fare comparison. A sample of a full-scale blade is shown in Figure 1.

Figure 1. V164-80m long wind turbine blade [16]

Figure 2 is a full-scale blade model and Figure 3 is the 3 m blade tip section model.

In this section, by comparing the electric field strength as the blade is rotating, the effect of a full-scale wind turbine blade and a 3 m blade tip section on the points of upward leader inception is investigated to understand how they behave during the testing. The evaluation is done as the blade rotates through angles of -60, -55, -50, -45, -40, -35, -30, -25, -20, -15, -10, -5, 0, 5, 10, 15, 20, 25, 30 35, 40, 45, 50, 55 and 60 degrees from the vertical position. Values are obtained from the blade tip, leading edge, trailing edge and the receptor tip. The focus is on evaluating the maximum electric field strength required for the initiation of upward leader due to thunder cloud charge. The positions with higher electric field strength are considered to have higher possibility of inception of upward leader.

As was shown in [1] and [2], 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 [17] 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 [17]. 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. The distance between the electrode and the base of the blade is 100 m while the blade is 80 m away from the ground.

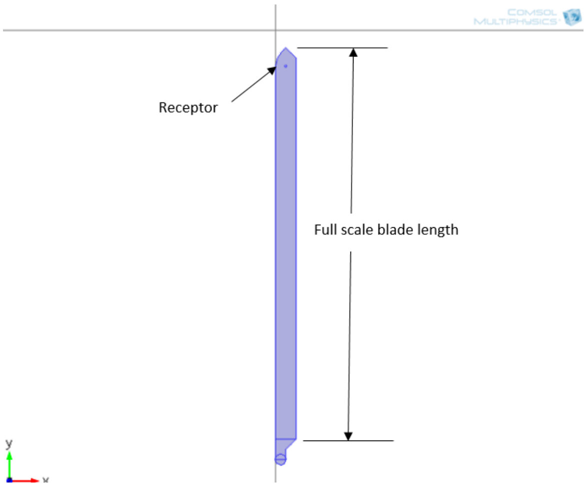

Figure 2. Full scale blade model

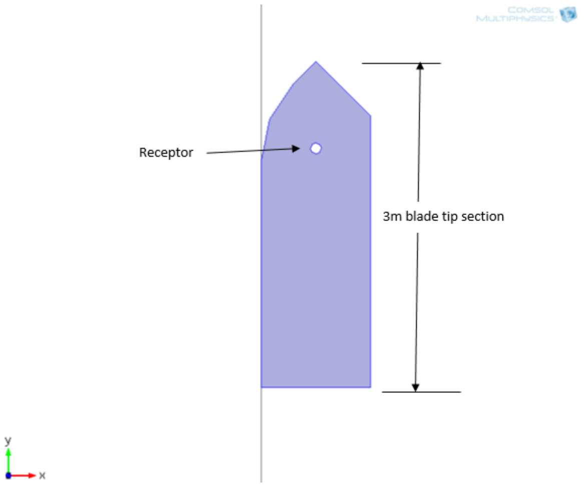

Figure 3. 3 m blade tip section model

III. MAXIMUM ELECTRIC FIELD REQUIRED FOR THE INITIATION OF UPWARD LEADERS FROM WIND TURBINE

A. *Full scale blade*

The model used for the Full-scale blade analysis is shown in Figure 4.

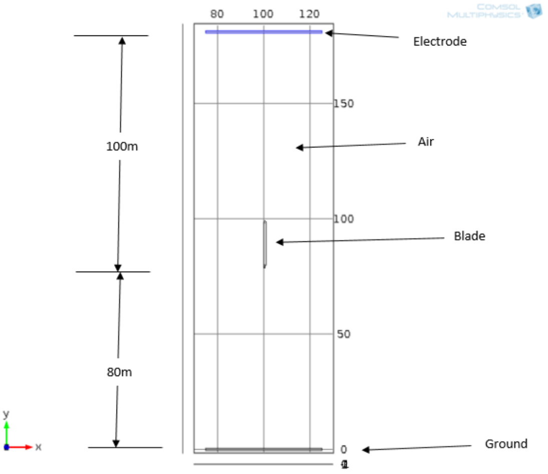

Figure 4. Design of the model

The simulation is first conducted without the receptor and then the receptor is placed at the described location. The electric field distribution for the receptor-free blade is given in Figure 5. Then the blade with receptor is rotated from the vertical position (Figure 6), to both clockwise (where the leading edge starts facing upwards as in Figure 7) and anticlockwise (trailing edge facing upwards as in Figure 8). Details of activities around the receptor preceding leader inception are given in [1].

The results for maximum electric field strength distribution patterns for various positions of the blade, as the blade rotates, are depicted in Table 1. The field plots for vertical and inclined positions are shown. Note that a negative angle implies that the trailing edge is facing upwards.

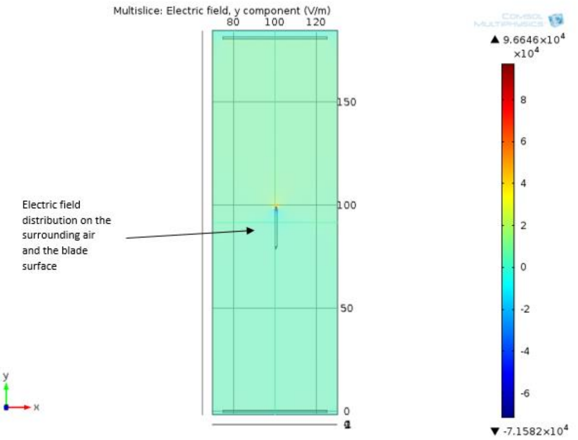

Figure 5. Simulation model

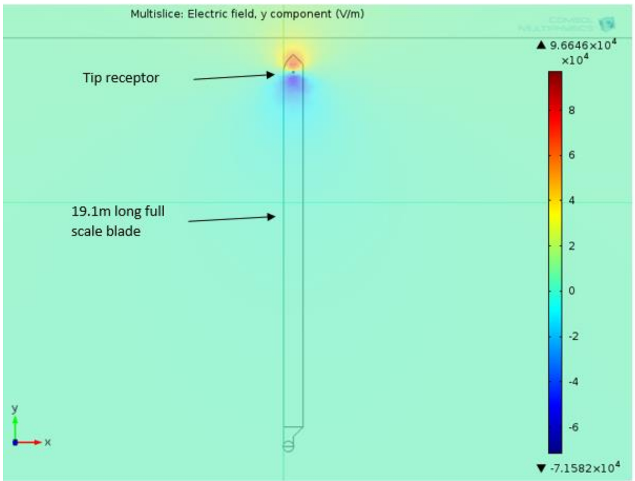

Figure 6. Full scale blade in the vertical position

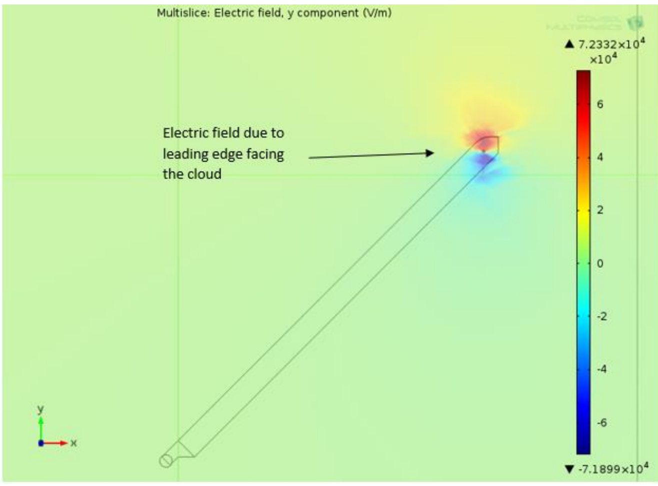

Figure 7. Blade leading edge turning upwards

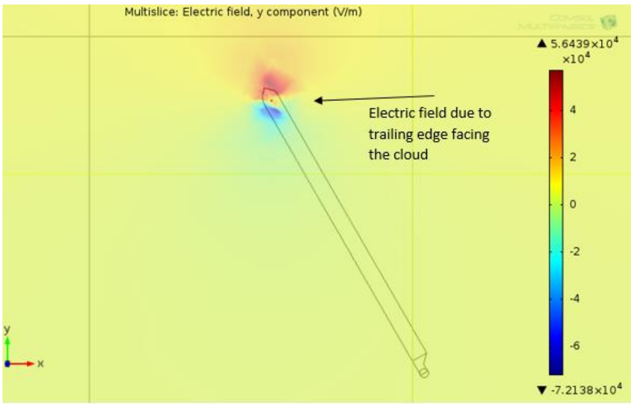

Figure 8. Blade trailing edge turning upwards

B. A 3 m Blade Tip section

In this section, a 3 m blade tip section that is part of 19.1m blade length, presently the size used for laboratory testing is investigated and result are compared with that of the full blade length. As was done earlier for the full scale, the simulation is first conducted without the receptor and then the receptor is placed.

The electric field distribution in this case is shown in Figure 9. The blade is rotated from the vertical position as in the case of the full-scale blade with inclinations on both clockwise and anticlockwise directions (Figures 10, 11 and 12).

For this case too, the results for maximum electric field strength distribution patterns for various positions of the blade, as the blade rotates, are depicted in Table 2. The field plots for vertical and inclined positions are also shown.

Table 1 Maximum electric field strength (kV/m) obtained from full blade length

Angle from Vertical	At blade Tip	At leading Edge	At trailing Edge	At receptor
-60	39.97	93.85	14.69	754.55
-50	51.22	94.03	25.00	1102.33
-45	612.99	98.77	43.94	1272.47
-40	68.19	106.95	45.16	1505.73
-35	84.05	101.26	45.37	1625.78
-30	72.88	97.51	55.43	1674.44
-25	84.05	98.6	56.63	1738.05
-20	78.49	87.59	65.18	1831.50
-15	92.66	87.77	68.45	1846.43
-10	85.02	84.26	67.36	1935.70
-5	84.50	78.42	69.16	2016.46
0	94.85	82.29	80.20	2035.26
5	83.81	67.25	83.60	2035.56
10	81.72	60.71	82.53	2025.91
15	90.29	58.94	92.03	2014.26
20	81.02	48.34	97.29	2004.15
25	75.97	38.75	91.54	2001.08
30	66.77	28.44	95.29	1912.10
36	62.18	20.78	91.34	1732.35
40	57.02	21.09	91.34	1618.83
45	56.63	-5.42	84.90	1357.35
50	51.39	-8.92	86.24	1005.40
60	39.87	-14.22	83.32	692.51

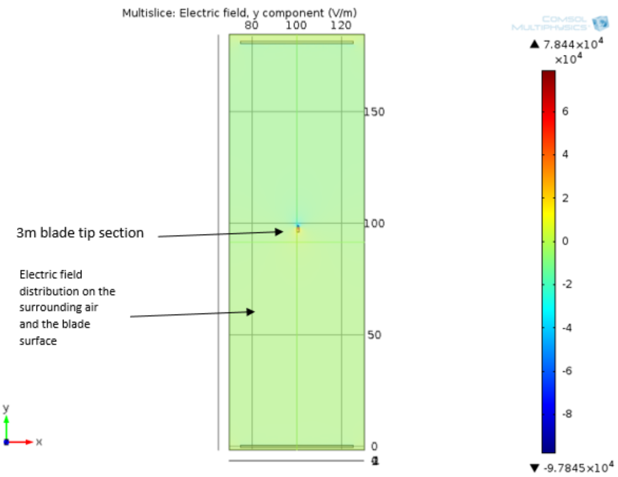

Figure 9. Simulation model

C. *Comparison*

Obtained results for full scale and 3 m blade tip section are plotted and compared as shown in Figures 13 – 16

The plot in Figure 13 shows electric field distribution of both samples at the blade tip. Figure 14 is for the leading edge, Figure 15 is for the trailing edge and Figure 16 is for the tip receptor. In the comparison of the samples, the factors considered are magnitude, smoothness and complexity. These factors would influence the leader inception points.

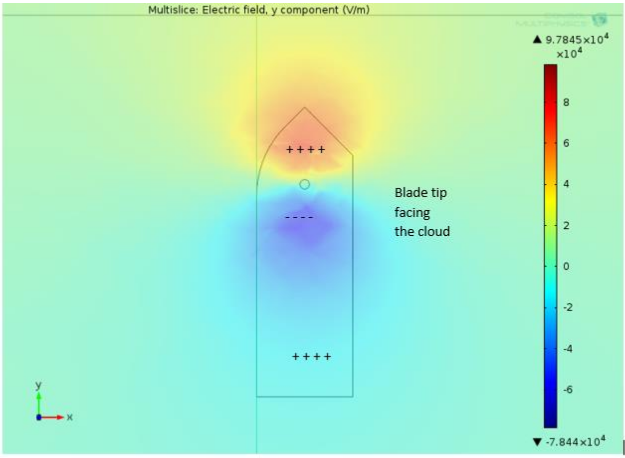

Figure 10. A 3 m blade Tip section in the vertical position

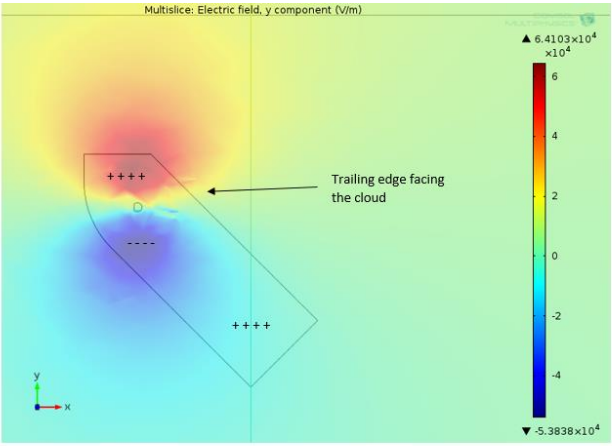

Figure 11. Trailing edge facing the cloud

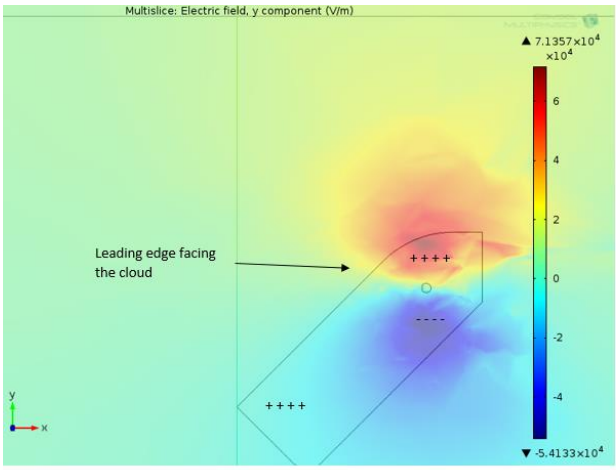

Figure 12. Leading Edge facing the cloud

The electric field distribution at the blade tip for both samples are shown above in Figure 13, it is observed that the full-scale values are lower, and complex compared to the 3m tip section with a smooth plot when the blade is rotated through +50 to -50 from the vertical position.

The electric field distribution at the leading edge for both samples as shown in Figure 14 follows a similar pattern between 50 degrees and -50 degrees. After this range, the small blade sample continues with a smooth curve, however, the full blade sample start to show some complexity.

Table 2 Maximum electric field strength (kV/m) obtained from 3m blade tip section

Angle from vertical	Blade tip	Leading Edge	Trailing Edge	Receptor
-55	61.96	107.54	19.30	711.11
-50	65.68	107.39	27.68	747.52
-45	67.95	106.33	36.81	1408.63
-40	80.36	105.41	46.37	1605.91
-35	83.57	104.66	54.71	1774.53
-30	90.39	101.14	58.37	2017.24
-25	94.61	99.49	66.96	2055.15
-20	97.43	95.88	73.19	2224.68
-15	98.65	93.88	80.69	2250.64
-10	102.82	86.53	85.81	2200.69
-5	106.13	79.87	89.52	2113.12
0	111.80	78.73	90.84	1983.79
5	110.86	68.22	95.41	1880.18
10	105.06	60.48	97.78	1809.83
15	101.06	51.61	100.68	1767.16
20	95.04	42.12	99.62	1694.03
25	86.57	31.59	99.91	1642.68
30	85.92	25.18	101.50	1454.12
35	82.15	15.39	102.98	1385.53
40	71.73	5.64	97.98	1142.71
45	69.51	-2.58	96.21	109.94
50	72.20	-12.45	96.15	10976
55	59.97	-19.84	89.29	819.62
60	57.16	-31.52	88.47	411.10

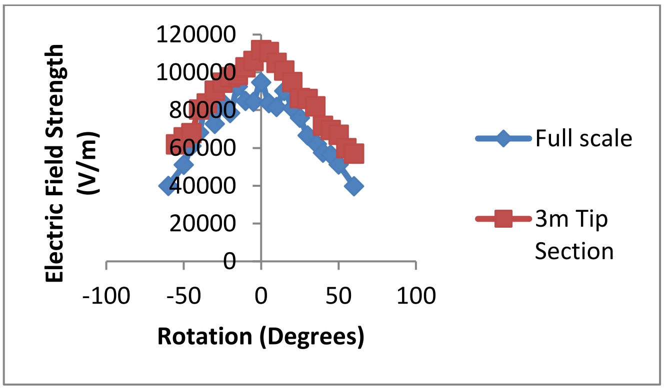

Figure 13. Maximum electric field at the blade tip

The electric field distribution at the trailing edge for both samples as shown in Figure 15 also follows a similar pattern between -50 degrees and 50 degrees. However, the full blade sample start to show some complexity at -25 degrees.

The electric field distribution at the tip of the receptor for both samples as shown in Figure 16 slightly follows a similar pattern between 60 degrees and -60 degrees, both samples showing complexity. However, a significant difference in magnitude and shape is observed prominently as the blade tip is approached.

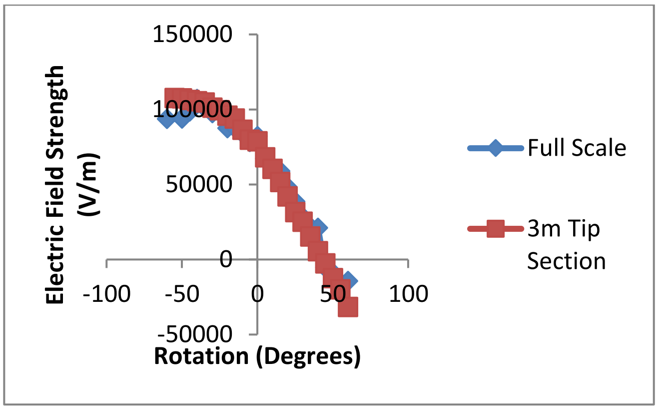

Figure 14. Maximum electric field at the leading edge

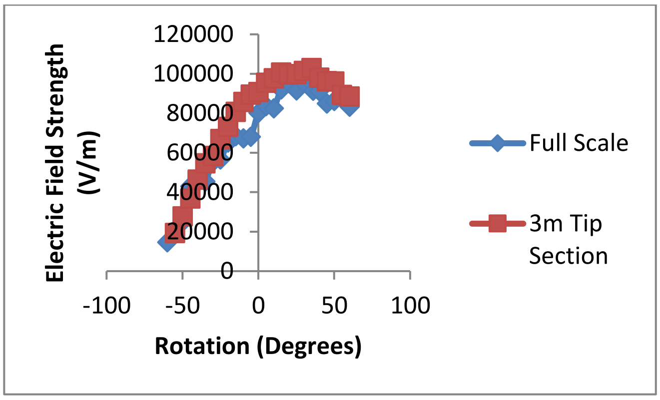

Figure 15. Maximum electric field at the trailing edge

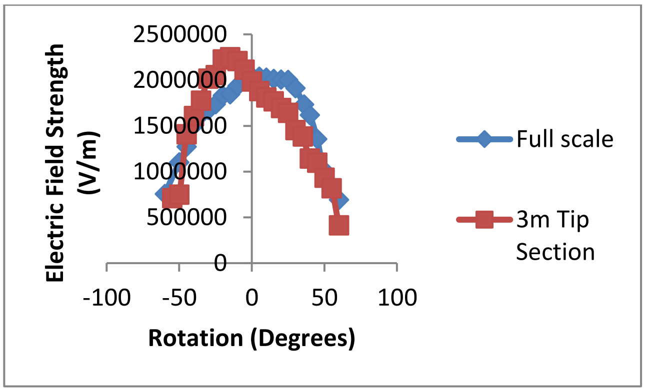

Figure 16. Maximum electric field at the tip of the receptor

Generally, an average difference of 16.95 kV/m representing a percentage difference of 15.16% between the maximum electric field relevant to the full-scale blade and that of the blade segment. For an efficient lightning protection, experiments conducted with the small blade tip section should incorporate this difference. This will ensure an adequate representation of full-scale blade. Otherwise, relying on 3m tip section for instance as a representation of a full-scale blade could be a misrepresentation. Applicability of the outcomes of this paper to special cases of wind turbines, such as offshore units [18] will be investigated in the future.

V. CONCLUSION

The extended vertical tri-pole cloud model has been used to compare the maximum electric field strength around a full-scale blade and that of a 3m blade tip section to show how they affect the maximum electric field strength required for the initiation of upward leaders from wind turbine. The evaluation was done with a 600kw wind turbine with 19.1m blade length. Results show that the maximum electric field strength and its distribution were different for the full-scale blade length and the 3m blade tip section. The full blade length showed more complexity than the 3m blade tip section which has a smoother plot. Relying on experimental results from a 3m blade tip section for the protection of modern wind turbine might be a misrepresentation. The result shows an average difference of 15.16% between the maximum electric field relevant to the full-scale blade and that of the blade segment, so that a tolerance of 16.95 kV/m was recommended for testing under laboratory conditions.

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