

External Lightning Protection System for Wind Turbine Blades – Further Considerations

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Abstract—The installation of a lightning protection system for wind turbine blades has been adapted from other industries (i.e. building, aircraft) where a lightning down conductor is installed internally so as to preserve the aerodynamic performance of the blade. Having the down conductor internally within the blades would indeed preserve their aerodynamic performance. However the blades are, as a consequence, vulnerable to damage and burn resulting from lightning strikes. Owing to that, the authors believe that by having the down conductor on the external surface of the blade, the incidence of blade damage would be reduced. The authors have not found any literature in the public domain that quantifies the effect of having an external down conductor on the aerodynamic property. Hence, this aspect is being undertaken. Previous studies conducted by the authors were on two different arrangements. In one arrangement, a single 1 mm thick conductor was placed at 1m from the leading edge on the upper and lower parts of the blade. In the other arrangement, multiple conductors were placed at 1m intervals. The results from previous studies indicated that external down conductors affect the aerodynamic performance significantly but the first conductor (as encountered by the wind flow) appear to have the maximum influence. Hence, this paper addresses the question whether a single external down conductor could be deployed in an optimal position for least effect on the aerodynamic performance. The results show that the degradation on aerodynamic property is least at the trailing edge or the leading edge of the blade and these indicate that the installation of external down conductors may be viable in that region.

Keywords—Aerodynamic performance, computational fluid dynamics, down conductor, k- ϵ turbulence model, wind turbine blades

I. INTRODUCTION

THERE are three essential elements in a lightning protection system (LPS) for wind turbine generators. These are lightning receptors (also called air termination points), lightning down conductors and grounding in the soil of each wind turbine. In general, the method of installation is adapted from practices in other industries (e.g. buildings and aircraft) [1, 2] where the main difference is the bonding network arrangement which depends on the geometry of the structure itself. Nonetheless, the development of lightning protection systems for wind turbines has increased in importance in the last 20 years and which culminated in the production of a revised International Standard in 2010 [1]. The International Standard provides guidelines on how to integrate the different parts of a lightning protection system on a wind turbine to obtain the highest reliability.

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The lightning receptors and down conductors associated with wind turbine blades may be installed, as suggested by the standard, on the internal or external side of the blade's surfaces [1]. Despite the choice available, manufacturers have opted to install the down-conductors on the internal side of a blade surface in order to preserve the aerodynamic properties of the blades' surfaces [1, 3]. Typically, the system that is often implemented by the wind turbine blades manufacturers is the placement of the lightning receptors on the surface of wind turbine blades but the lightning down conductor is placed internally in the blades [1, 3], as depicted in Fig. 1. However, by having an internal down conductor, other problems occur (e.g. blade disintegration, burn) due to the impact of lightning strikes [1].

Therefore, in the attempt to reduce the likelihood of this particular event happening, a group of researchers from the University of Strathclyde, Scotland [4-7] has questioned whether the installation of the down conductor on the external surface of the blade is preferable.

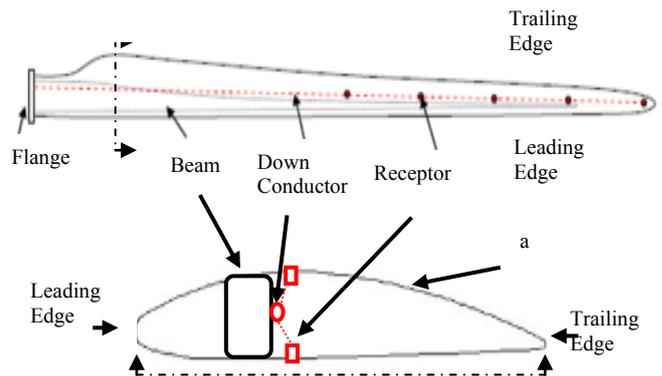


Fig. 1 Typical Lightning Receptors and Internal Down Conductor System Installation – 2D view (i.e. a, a') from blade's root, adapted from [1, 3]

An external lightning protection system on the blade's surface is likely to compromise the aerodynamic properties of the blade but the system would be more effective in providing lightning attachment points. The installation of such a system on the external surface of the blade is likely to affect the smooth (i.e. streamline) wind flow due to the protrusion of the down-conductor above the surface of the blade. A disturbed (i.e. turbulent) wind flow would also compromise the overall performance of the turbine blade itself (i.e. aerodynamic properties) [1].

Previous experimental and numerical findings by other researchers addressed surface roughness due to ice accretion and dust accumulation on aerofoil surfaces; particularly on the leading edge where the roughness was just below 1 mm [8, 9]. On the other hand, the Standards [1] has recommended that the typical cross section for down conductor is 50 mm² when considering a lightning protection system. Generally,

this is achieved practically (i.e. down conductor for building) by having a rectangular cross-section and where the thickness is greater than or equal to 1 mm. Consequently, previous findings are not completely helpful in assessing the effect of the higher protrusions in various positions on the aerofoil surfaces. Hence, this information gap is being addressed by the authors and this paper discussed the progress of the investigation on aerodynamic studies when considering external lightning protection systems (LPS) for aerofoils.

Modelling of fluid (i.e. wind) flow field around wind turbine blades in 3 dimensions is a challenging task. Furthermore, the available turbulence models have yet to demonstrate acceptable level of stability that correctly predicts the results for turbulent flow [10]. Therefore, the wind flow in this study is considered to be turbulent (due to high Reynolds Number – order of 10^6), incompressible (i.e. constant flow density) and only for two dimensional (2D) geometries of the aerofoil. The incompressible flow refers to the flow density as being constant throughout the space around the aerofoil and where the large pressure changes and high wind speed (exceeds Mach number 0.3) are insignificant and thus can be ignored. Furthermore, although the simulation is based on 2D geometry, the results produced are still valid due to the similar airflow characteristic (determined by dimensionless Reynolds number) with three dimensional (3D) geometries [11-16]. In other words, the investigation based on a 2D model is still valid as long as the Reynolds number remained similar to that of the 3D geometry.

In the following sections, this paper will provide a concise background on wind flow around an aerofoil. The paper then discusses the numerical modelling methodology (i.e. turbulence modelling). Previous studies conducted by the authors were discussed to provide an overview for the work undertaken prior to this paper. Using similar numerical modelling methodology, simulations on protrusions (i.e. down conductors) at different locations on aerofoil surfaces were investigated followed by analyses and discussions of the results. Finally, conclusions were drawn and future work proposed.

II. CONCISE BACKGROUND ON AERODYNAMIC

The fundamental description concerning the aerodynamic properties of an aerofoil is concisely presented in this section so as to provide an overview of the subject under investigation. This includes the introduction of aerofoil's terminology and the concept of wind flow behaviour around aerofoil surfaces. Further information on the above-mentioned sub-topics is widely available in textbooks [11, 12, 14-16].

A. Aerofoil Geometry and its Terminology

A cross section of aerofoil geometry is drawn in two dimensions (2D) and its terms are labelled as illustrated in Fig. 2. There are 2 components associated with an aerofoil in terms of aerodynamic properties, which are lift (L) coefficient and drag (D) coefficient. Lift is the component that is perpendicular to the oncoming flow direction whilst drag is the component that is in parallel with the oncoming flow. Both are created from the wall shear stresses at each aerofoil profile points (at lower and upper surfaces) where the forces

are called lift and drag forces. The performance of an aerofoil profile is determined by ratio between generated lift and drag when an aerofoil moves through the air and it is called lift to drag (L/D) ratio. The L/D ratio is one of the important parameters in an aerofoil design such as glider, aircraft and wind turbine blade [11, 12, 15, 16].

B. Wind Flow Around an Aerofoil Surface – Brief Concept

In general, the air flow around an aerofoil surface of wind turbine blades is similar to an aircraft wing. As airflow meets the leading edge of the aerofoil, as illustrated in Fig. 2, it separates. Part of it goes over (i.e. upper surface) and the rest goes under (i.e. lower surface) the aerofoil respectively.

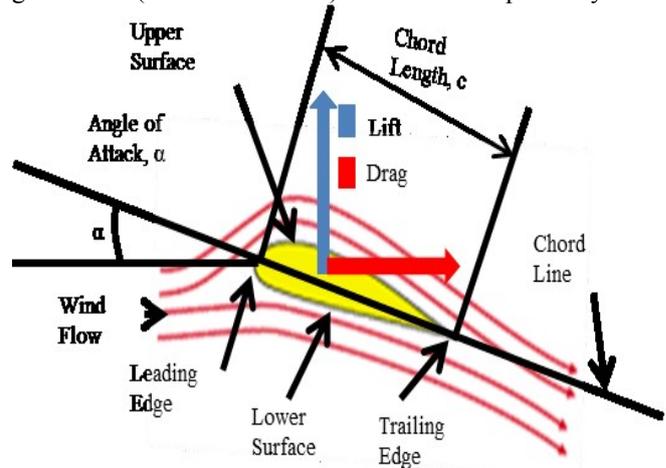


Fig. 2 Cross section of aerofoil geometry (2D) and its terms, adapted from [11, 12]

Since the upper surface is more curved than the lower surface (i.e. cambered aerofoil), it creates a lower pressure on the upper surface (also called suction side) and a higher pressure on the lower surface (also called pressure side), thus generating lift as wind passes it. Furthermore, the lift force can be dramatically increased by changing its angle (i.e. angle of attack, α) to the wind. However, the aerofoil stalls at very large angles of attack as the lift force gradually decreases. This behaviour is due to the retarding force called drag in which it increases with angles of attack. Fig. 3 illustrates the behaviour of wind flow around an aerofoil surface with respect to different angles of attack.

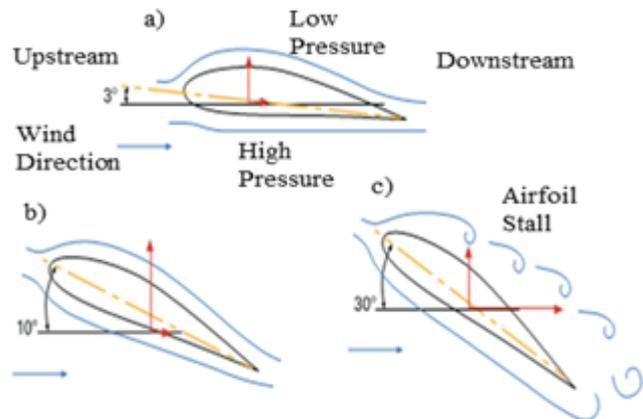


Fig. 3 The behaviour of wind flow around an aerofoil surface with respect to different angles of attack; a) low, b) medium and c) high, adapted from [11, 12]

Hence, lift and drag forces are significantly influenced by the pressures created on the lower and upper surfaces of an aerofoil. The pressures created around an aerofoil can be quantified by the dimensionless pressure coefficient, C_p [11, 12, 15]. As given in (1), pressure coefficient distribution describes relative pressure throughout the wind flow field around an aerofoil particularly in the flow adjacent to the aerofoil surface itself [11, 12].

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \rho_\infty V_\infty^2} \quad (1)$$

Where p is the pressure at the point at which pressure coefficient is being calculated, p_∞ is the pressure in the free stream wind flow, ρ_∞ is the fluid density (in this case is air which is 1.2kg/m^3) and V_∞ is the velocity of the wind.

In aerodynamics performance analysis, this pressure coefficient value is normally plotted in the form of pressure coefficient distribution (see Fig. 6-8) starting from leading edge to trailing edge of an aerofoil.

III. NUMERICAL MODELLING

The numerical technique utilised in this investigation is concisely explained in this section. Hence, further explanation on the subject is widely available in textbooks [10, 17]. Furthermore, the modelling technique of the investigation is also presented.

A. Numerical Technique

A.1. Governing Equations

A standard k- ϵ turbulence model is utilised in COMSOL Multiphysics (CFD Module) [17] as it is one of the most used turbulence models for industrial applications. This model introduces two dependant variables equations (i.e. Turbulent Kinetic Energy, k and Dissipation Rate of Turbulence Energy, ϵ) which are written as given in (2) and (3) respectively.

Turbulent Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \epsilon + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] \quad (2)$$

Dissipation Rate of Turbulence Energy

$$\frac{\partial \epsilon}{\partial t} + U_j \frac{\partial \epsilon}{\partial x_j} = C_{\epsilon 1} \frac{\epsilon}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - C_{\epsilon 2} \frac{\epsilon^2}{k} + \frac{\partial}{\partial x_j} \left[\left(\nu + \frac{\nu_T}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] \quad (3)$$

where its closure coefficients are: $C_{\epsilon 1} = 1.44$, $C_{\epsilon 2} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$ and $\sigma_\epsilon = 1.3$,

IV. PREVIOUS STUDIES CONDUCTED BY THE AUTHORS

Modelling Technique - Model Configuration and Dimension

For the previous studies, the model was simplified with the following simplifications: the flow is two dimensional, incompressible and turbulent (due to high Reynolds number – order of 10^6). A NACA 4418 aerofoil profile was selected [11] for all simulation cases (i.e. with and without protrusions) and

stationary-state simulations were performed. The whole computation zone consists of air domain with a dimension of 100 m height x 150 m width and the selected aerofoil (with 5 m of chord length) was placed at 35 m and 115 m from the inlet and outlet respectively, as depicted in Fig. 4. In addition, the aerofoil was placed in the middle of the air domain (i.e. 50 m in between top and bottom walls). The boundaries were set to avoid perturbation coming from the domain limits and to allow the air flow to be fully extended. Furthermore, the wind speed and angle of attack used in simulations are 5 m/s (i.e. cut-in wind speed for most modern wind turbine) and 5° (i.e. highest L/D ratio for NACA 4418) respectively.

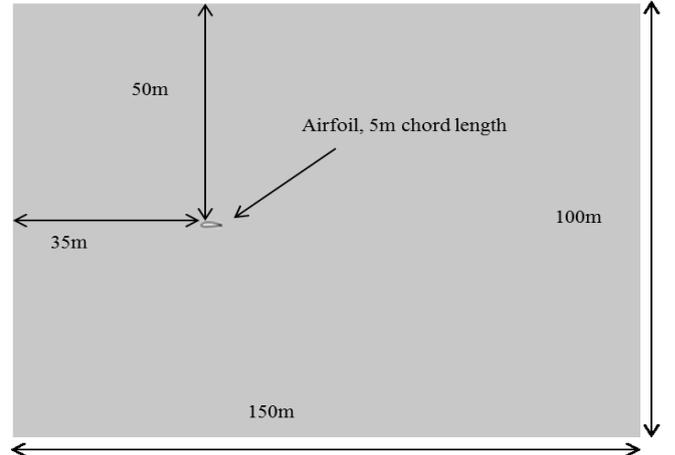


Fig. 4 Configuration of Simulation Space

In general, meshing for the simulations was configured using free triangular meshes with fine meshes in the vicinity of aerofoil surfaces and coarser meshes towards the outer boundary of the air domain. The model was simulated for two cases, namely: without protrusion (i.e. clean aerofoil surfaces with no down conductors) and with protrusions (i.e. protruded with down conductors).

Model without protrusions – Clean Aerofoil Surfaces

Further to the model configuration, simulation runs were performed on the clean aerofoil. With respect to lift and drag coefficients, the results for both simulation and experiment [11] were compared for validation and verification purposes. It was found that both are in good agreement. The results of aerodynamic properties were then used for comparison with model with protrusions.

Model with protrusions – Protruded Aerofoil Surfaces

The protrusion (i.e. down conductor) dimension is configured to comply with the typical cross section (i.e. 50mm^2) as recommended by IEC 61400-24 [1]. Hence, the down conductor has been configured with 1 mm height and 50 mm width (i.e. rectangular shape). The model was configured for two scenarios, which allowed the authors to visualise the effect of protrusions location on the aerodynamic performance.

For the first scenario (i.e. single conductor), the protrusions were first placed at 1 m from the leading edge on upper and lower aerofoil surfaces. With the same protrusion height, the simulation was then continued with other scenarios (i.e.

multiple conductors) where the protrusions were placed at intervals of 1 m between each other on upper and lower aerofoil surfaces. In all cases, the protrusions were perpendicular to the chord length.

Rationale of the Previous Studies

The degradation on aerodynamics performance can easily be obtained from L/D ratio as was presented in [6], however this is just an overall indication of an aerofoil under investigation. Since the aerodynamic performance is generally derived from pressure difference between upper and lower surfaces of an aerofoil, pressure coefficient distribution was considered which was presented in [7]. By having pressure coefficient distribution of an aerofoil, the results obtained would be more useful because they provide an indication of where changes in design might be made for improvement. In addition to pressure coefficient distribution, local pressure coefficient can also be obtained in which it will be useful too when considering an external protrusion on a specific location on aerofoil surfaces [11-13, 15].

A. Lift to Drag Ratio (L/D) and Wind Flow Behaviour of 1mm conductors height [6]

For this study, the Lift to Drag ratio (L/D), pressure contours and wind flow streamline on upper and lower surfaces of aerofoil have been investigated.

TABLE 1
TABULATED DATA OF AERODYNAMICS PROPERTIES FOR CLEAN, SINGLE AND MULTIPLE CONDUCTORS [6]

L, Clean	L, Single	L, Multiple
0.962860	0.930474	0.942036
D, Clean	D, Single	D, Multiple
0.006809	0.008643	0.009335
L/D, Clean	L/D, Single	L/D, Multiple
141.4098	107.6563	100.9144

In Table 1, the results for L/D were compared and it is found that a single conductor arrangement has given a lesser impact where the reduction of 24% in comparison to 29% of multiple conductor arrangement. A single conductor arrangement provides a simpler assembly of a lightning protection system for wind turbine blades. Fig. 5 shows that the pressure contours for single and multiple conductors are slightly changed due to the presence of conductors on aerofoil surfaces when compared to the case of no conductor. Finally, the wind flow for all cases are streamlined due to the height of conductor used is not noticeable to cause an interruption to the wind flow pattern. Overall, these indicate that it may be acceptable to have down conductors with height of up to 1 mm on the surface.

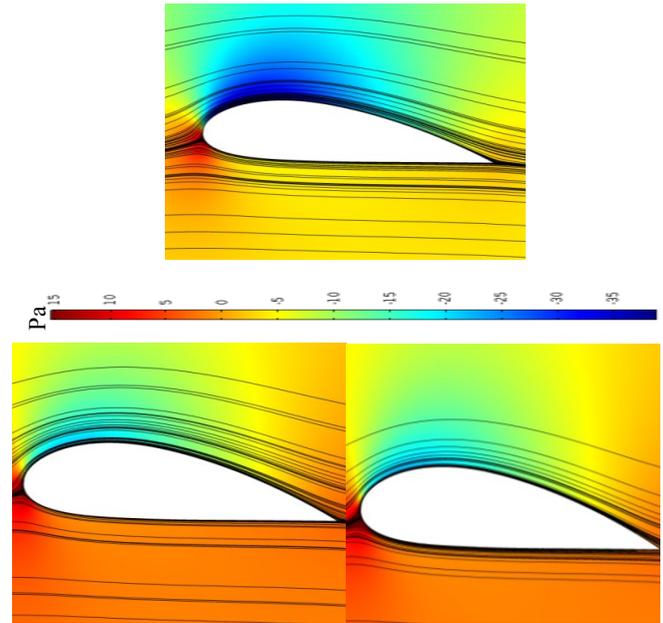


Fig. 5 A blow-out image of pressure contours and wind flow streamlines for no (top), single conductor (bottom left) and multiple conductors (bottom right).

B. Pressure Coefficient Distribution of 1mm conductors height [7]

For this study, the pressure coefficient (C_p) distribution for single and multiple conductor arrangements have been investigated.

The results of pressure coefficient distributions for all arrangements were compared. As illustrated in Fig. 6, Fig. 7 and Fig. 8 it is found that the effect on pressure coefficient distributions appeared to be local to where the conductors were placed. Therefore, in general, it can be concluded that the wind flow had swiftly recovered after passing each conductor.

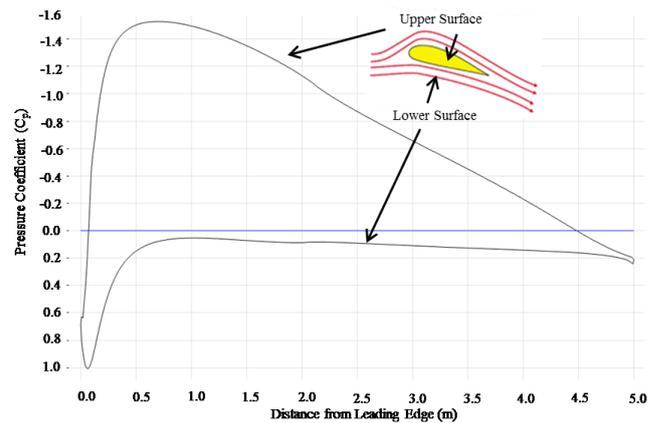


Fig. 6 Pressure coefficient distribution of clean aerofoil surface (i.e. no conductor) - inset image of an aerofoil and wind direction are for easy reference.

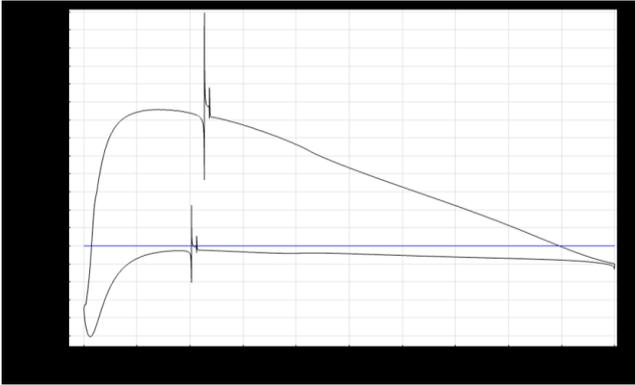


Fig. 7 Pressure coefficient distributions of 1mm protrusions at 1m from leading edge for upper and lower aerofoil surfaces (i.e. single conductor).

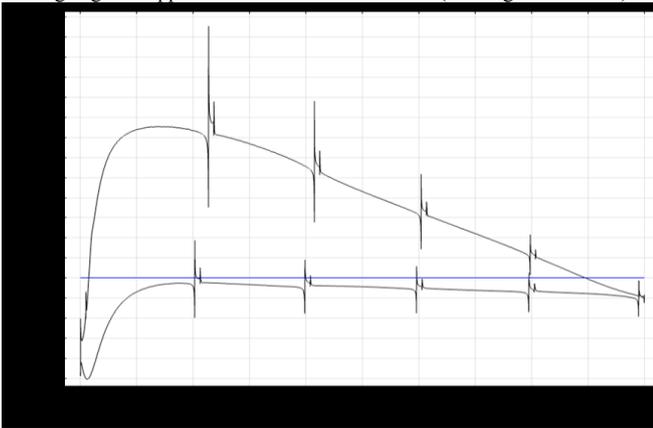


Fig. 8 Pressure coefficient distributions of 1mm protrusions placed perpendicular to the chord length (i.e. multiple conductor at 1m interval).

Furthermore, with respect to aerodynamic performance, there are several locations on the aerofoil surfaces that could be considered to be viable for external conductor installation. More importantly, it is noted that the multiple conductors case shows a larger reduction (in terms of lift to drag ratio) in comparison to clean (i.e. no conductor) and single conductors cases but not much worse than the latter case. Thus, it can be concluded that a single conductor arrangement is preferred due to smaller reduction in its lift to drag ratio and there is a possibility of optimising the performance by locating the conductors at the correct position.

V. SINGLE CONDUCTORS – RESULTS AND DISCUSSIONS

Owing to the findings as obtained previously, further work was carried out to investigate the aerodynamic performance especially on L/D ratio on single conductors of the same height (i.e. 1 mm) at different locations of an aerofoil surfaces. Using similar numerical and model configuration as previously used, the model was simulated based on the different locations as illustrated in Fig. 9.

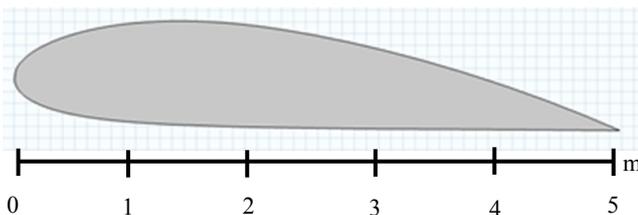


Fig. 9 Locations of conductor's perpendicular to the chord length with respect to the leading edge (denoted as 0 m)

The numbers 0 to 5 correspond to the conductors' distance (in meter) from the leading edge (denoted as 0 m). With regards to conductors located at leading edge (at 0 m), there was only one conductor modelled due to the profile of the aerofoil whereas the rest of the locations were installed with conductors on upper and lower surfaces of aerofoil. Furthermore, the results obtained from all locations were compared and tabulated in Table 2.

TABLE 2
COMPARISONS OF DIFFERENT LOCATIONS FOR SINGLE CONDUCTORS
ARRANGEMENT

Location	L/D Clean	L/D Single
0	141.3926962	121.81173
1	141.3926962	107.6451043
2	141.3926962	110.5267728
3	141.3926962	97.98417549
4	141.3926962	110.761519
5	141.3926962	122.3400849

In Table 2, the L/D ratios are different and they varied with location of the single conductors. Understandably, all locations considered have shown a reduction in the aerodynamic performance. The lowest reduction (i.e. 13.5%) of L/D ratio was obtained when single conductors were located at 5 m from leading edge whereas single conductors located at 3 m from leading edge gave the highest reduction (i.e. 30.7%) in the aerodynamic performance. The second lowest reduction (i.e. 13.9%) of L/D ratio was recorded when a single conductor was located at the leading edge. Furthermore, the L/D ratio for conductors located at 2 m and 4 m from the leading edge were reduced by 21.8% and 21.6% respectively. The results indicate that the preferred location of the down conductor should either be at the leading edge or the trailing edge.

VI. CONCLUSIONS

Study on the aerodynamics performance of external lightning protection systems for wind turbine blades is presented by considering a single conductor arrangement.

The results of a single conductor arrangement for all the different locations were compared and it is found that a conductor located at 5m from leading edge had minimal effect on the aerodynamic performance when compared to the other locations. Therefore, it can be concluded that a single conductor located at 5 m from the leading edge is the preferred location.

Although a single conductor at 5 m from the leading edge is preferred based on this work, it may not be sufficient to provide adequate protection against lightning strikes onto wind turbine blades. Therefore, a better option is to have a down conductor also at the leading edge.

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