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External Lightning Protection System for Wind Turbine Blades – Aerodynamics

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ABSTRACT

Many wind turbine blade manufacturers have installed lightning protection systems (particularly the down conductor) internally. 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 this, 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 performance. Hence, in this paper, a study of the effects of an externally mounted lightning conductor has been undertaken. Simulation studies were carried out using the computational fluid dynamics numerical method available in the COMSOL Multiphysics software package. The results of studies on single conductor arrangement have shown that the degradation on aerodynamic performance is least at the trailing edges of the blade. However, it may not be adequate for lightning protection. Therefore, using a similar numerical modelling methodology, simulations were extended and investigated on multiple conductor arrangements where conductors' locations were varied on an aerofoil surfaces. The results of the aerodynamic modelling suggested that a four conductor arrangement may be the best option as it gives more coverage for lightning protection of the wind turbine blades while still having the least reduction (of around 25%) on lift to drag ratio.

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

Nomenclature

L	Lift coefficient	k	Turbulent kinetic energy
D	Drag coefficient	ε	Dissipation rate of turbulence energy
L/D	Lift to Drag ratio	t	Time
LPS	Lightning protection system	τ_{ij}	Reynolds stress tensor
2D	Two dimensions	v	Viscous
3D	Three dimensions	τ	Turbulence dissipation time
CFD	Computational Fluid Dynamic	v_T	Kinematic eddy viscosity
NACA	National Advisory Committee for Aeronautics	U_i	Fluid velocity vector
m/s	Meter per second	U_j	Velocity fluctuation
m	Meter	x_i	Component of the coordinate vector x
%	percentage	x_j	Component of the coordinate vector y
°	Degree		

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1. Introduction

A lightning protection system (LPS) is one of the fundamental components necessary for a wind turbine. There are three essential elements in a LPS: these are lightning receptors (also called air termination points), lightning down conductors (runs through the blade) 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]. 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 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.

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 performance of the blades' surfaces (i.e. referred to as aerofoil surfaces by an aerodynamicist) [1], [3]. Typically, the system that is often implemented by the wind turbine blade manufacturers is the placement of the lightning receptors on the surface of wind turbine blades but the lightning down conductors placed within 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 an attempt to reduce the likelihood of this particular event happening, a group of researchers from the University of Strathclyde, Scotland [4]-[8] has questioned whether the installation of the down conductor on the external surface of the blade is feasible.

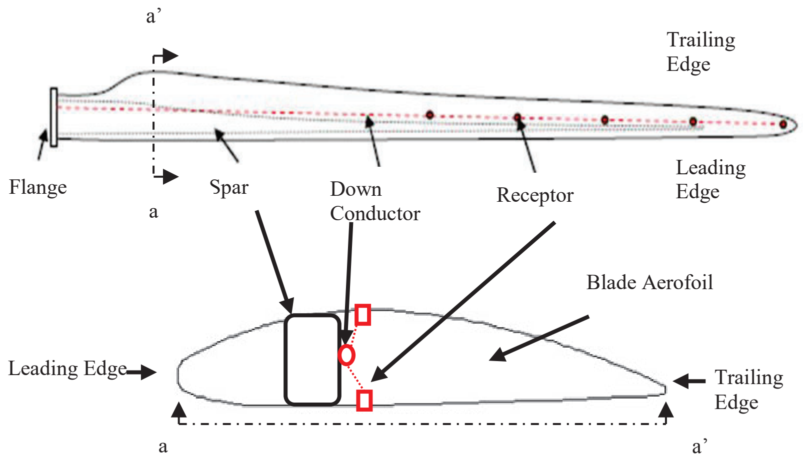

Fig. 1 Typical Lightning Receptors and Internal Down Conductor System Installation – 2D view (i.e. a, a') from blade's root, adapted from [1], [3]

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].

Furthermore, the Standard [1] has recommended that the typical cross section for down conductor is 50 mm^2 when considering a lightning protection system. Generally, this is achieved in practice (i.e. down conductor for building) by having a rectangular cross-section where the thickness is greater than or equal to 1 mm. On the other hand, previous experimental and numerical findings by other researchers on wind turbine blades 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 [9, 10]. Consequently, previous findings are not completely helpful in assessing the effect of the higher protrusions in various positions on the aerofoil surfaces (i.e. wind turbine blade). Hence, this information gap is being addressed by the authors and this paper discusses the investigation on aerodynamic performance studies when considering external lightning protection systems (LPS) for aerofoils.

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). Studies conducted on single conductor arrangement are first presented. Using a similar numerical modelling methodology, simulations have been extended and investigated on protrusions (i.e. down conductors) at different locations on aerofoil surfaces followed by analyses and discussions of the results. Finally, conclusions have also been drawn.

2. Concise background on aerodynamics

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]-[15].

2.1 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 the 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 for gliders, aircraft and wind turbine blades [11]-[14].

2.2 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 splits. Part of it goes over (i.e. upper surface) and the rest goes under (i.e. lower surface) the aerofoil respectively.

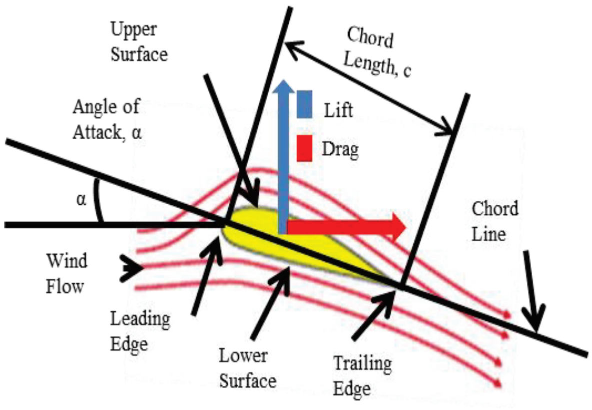

Fig. 2 Cross section of aerofoil geometry (2D) and its terms, adapted from [11], [12]

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 as this is due to the separation of the boundary layer on the upper surface and, as a consequence of this, the drag increases. Fig. 3 illustrates the behaviour of wind flow around an aerofoil surface with respect to different angles of attack.

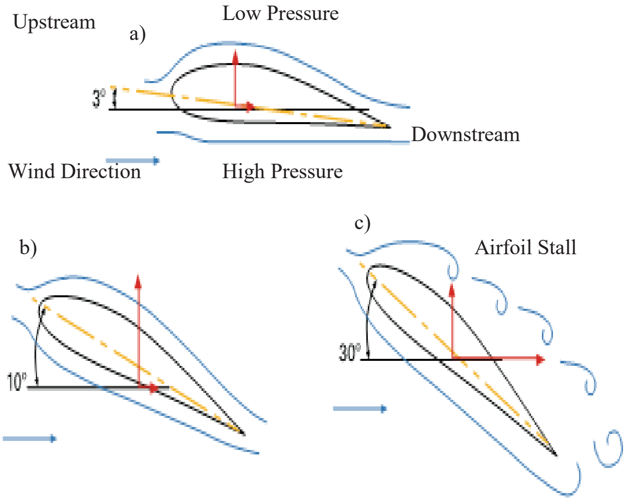

Fig. 3 The behaviour of wind flow around an aerofoil surface with respect to different angles of attack; a) low, b) medium and c) high, adapted from [11], [12]

3. Numerical and modelling techniques

The numerical technique utilised in this investigation is concisely explained in this section. Further explanation on the subject is widely available in textbooks [16], [17]. Furthermore, the modelling technique of the investigation is also presented.

3.1 Numerical technique

3.1.1 Governing equations

A standard k-ε turbulence model is utilised in COMSOL Multiphysics (CFD Module) [17] as it is one of the most widely 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 equations (1) and (2) respectively.

Turbulent Kinetic Energy

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \tau_{ij} \frac{\partial U_i}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j} [\left(\upsilon + {\upsilon_T}/{\sigma_k} \right) \frac{\partial k}{\partial x_j}] \quad (1)$$

Dissipation Rate of Turbulence Energy

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon 1} \frac{\varepsilon}{k} \tau_{ij} \frac{\partial U_i}{\partial x_j} - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} [\left(\upsilon + {\upsilon_T}/{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j}] \quad (2)$$

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

CFD, in this simulation, does not capture the laminar flow over the front of the aerofoil and assumes fully turbulent flow over the whole aerofoil which will produce higher skin friction drag than would be expected on the actual aerofoil. Hence, the wind flow in this study is considered to be turbulent, incompressible (i.e. constant flow density) and only for two dimensional (2D) flow around the 2D aerofoil geometry (i.e. cross section of an aerofoil). Turbulent flow over the whole aerofoil is justified because of the high Reynolds number (order of 10^6). A flow is considered incompressible when air (i.e. wind flow) density is constant throughout the space around the aerofoil and Mach number is less than 0.3. Furthermore, although the simulation is based on 2D flow, the results produced are still valid due to the similar airflow characteristic (determined by dimensionless Reynolds number) with three dimensional (3D) flow [11]-[15], [18] except at the blade tip and root regions. In other words, the investigation based on a 2D geometry is still valid as long as the Reynolds number remained similar to that of the 3D geometry.

3.2 Modelling Technique

3.2.1 Model Configuration and Dimension

The model was simplified by considering the following: the flow is two dimensional, incompressible and turbulent (due to high Reynolds number – order of 10^6). A NACA 4418 aerofoil profile was selected [12] for all simulation cases (i.e. with and without protrusions) and steady-state simulations were performed. The computation zone consisted of a domain with dimensions of 100 m height x 150 m width and the selected aerofoil (with 5 m of chord length which is an integer chosen to represent machines larger than 5 MW) 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.

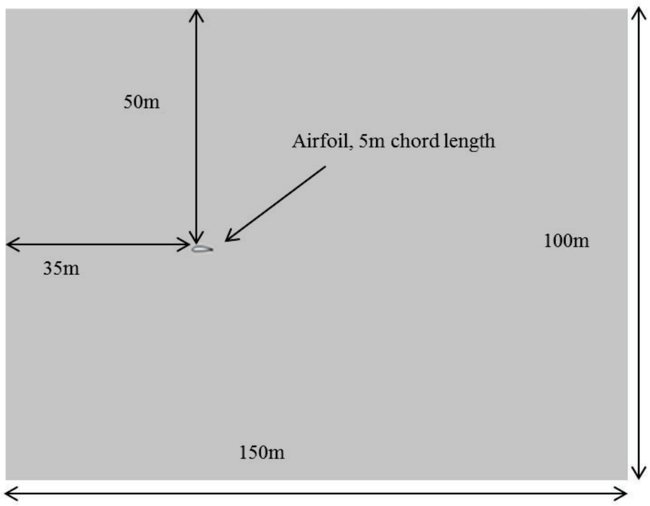

Fig. 4 Configuration of Simulation Space

In general, meshing for the simulations was configured using free triangular meshes with fine meshes (i.e. y+ value is kept between 20 and 200) in the vicinity of aerofoil surfaces and coarser meshes towards the outer boundary within the air domain. The y+ is dimensionless distance where it is often used to define the appropriate size of the mesh (coarse or fine) for a particular flow near the domain walls. In this simulation, it is used to define the distance between aerofoil surfaces to the freestream wind flow. 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).

3.2.2 Model without protrusions – clean aerofoil surfaces

Further to the model configuration, simulation was performed on the clean aerofoil. With respect to lift and drag coefficients, the results for both simulation and experiment [12] 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 a model with protrusions (i.e. with down conductors).

3.2.3 Model with protrusions – protruded aerofoil surfaces

The protrusion (i.e. down conductor) dimension is configured to comply with the typical cross section (i.e. 50 mm^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 with no bevelling at the edge of the conductor). This ensured that the worst scenario was considered.

4. Single Conductor Arrangement (References [5]-[8])

Investigation of 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 were carried out where several configurations of the model were considered and these allowed the authors to visualise the effect of protrusions location on the aerodynamic performance. A single conductor (i.e. for upper and lower surfaces) was placed at different locations for each simulation as illustrated in Fig. 5

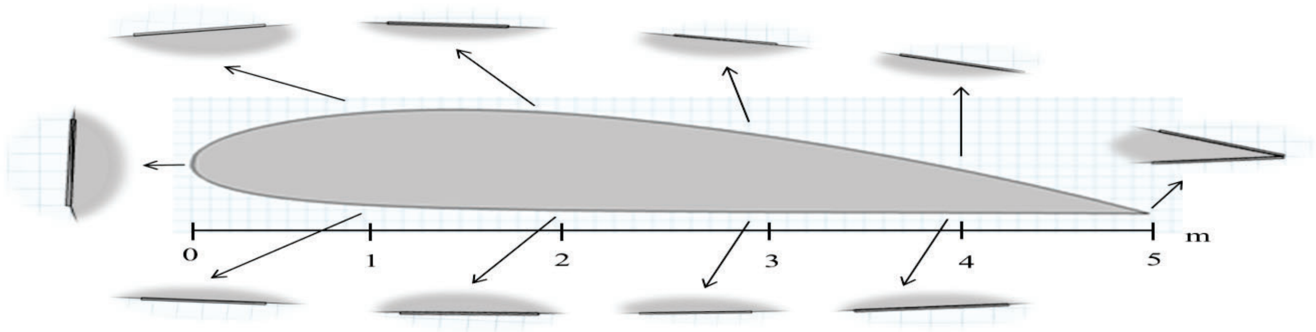

Fig. 5 A sketch of external down conductors placed at 1m interval (drawing is not to scale) - insets are the blow-out image of protrusion on aerofoil surfaces

The numbers 0 to 5 correspond to the conductor's distance (in metres) 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 at the rest of the locations conductors were installed on the upper and lower surfaces of the aerofoil. Furthermore, the results obtained from all locations were compared and tabulated in Table 1.

Table 1

Comparisons of different locations for single conductor's arrangement

Location	L/D Clean	L/D Single
0	141.39	121.81
1	141.39	107.65
2	141.39	110.53
3	141.39	97.98
4	141.39	110.76
5	141.39	122.34

In Table 1, all locations considered have shown a reduction in the aerodynamic performance. The lowest reduction (i.e. 14%) of L/D ratio was obtained when single conductors were located at the leading and trailing edges whereas single conductors located at 3 m from the leading edge gave the highest reduction (i.e. 30.7%) in the aerodynamic performance. Furthermore, the L/D ratio for conductors located at 2 m and 4 m from the leading edge was reduced by 22%. The results indicate that the preferred location of the down conductor should be at the trailing edge of the aerofoil. Furthermore, single conductor at leading edge has produced inaccurate result because of higher skin friction drag due to the aerofoil shape is very sensitive at the leading edge when subject to airflow and as well as when any shape of protrusion is added to it. Although it is not accurate (i.e. higher drag value), the result is still valid for the study and it has been considered wih caution.

5. Multiple Conductors Arrangements

The previous section describes work undertaken based on a single conductor at a particular location (i.e. one at a time) on the blade's surfaces where conductors located at the trailing edge have shown the lowest degradation on its aerodynamics performance (i.e. L/D ratio). However, it may not be sufficient to provide adequate protection against lightning strikes onto wind turbine blades [19]-[22]. Therefore, in the attempt to provide better lightning protection for a wind turbine blade, further work was carried out to investigate the aerodynamic performance especially on L/D ratio for multiple conductors arrangement 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. 5.

Two, three, four, five and six conductors on the blade surface were simulated and were denoted with respect to their location on the aerofoil's surface. The selection of conductors and their quantities are based on 2 conditions to be satisfied. One condition is the requirement for the conductors to be closed enough so that when a lightning leader attaches itself to a conductor at the leading edge, there is a high probability that the leader would be able to re-attach itself to the next conductor due to the swept-stroke effect [19]-[22]. The other condition is to investigate the effect on the wind flow behaviour and L/D ratio of nearby conductors. Hence, other combinations of conductor placement have not been considered especially, for example, a placement at 0 and at 5 for a two-conductor simulation although this might be the best for a good L/D ratio outcome. All of the arrangements were separated at 1m intervals from the leading edge. Furthermore, apart from the arrangement for six conductors, the conductors' locations were varied as tabulated in Table 2 for easy reference.

Table 2

Multiple conductors' arrangements & location variations

Two Conductors	**Three Conductors**	**Four Conductors**	**Five Conductors**	**Six Conductors**
0, 1	0, 1, 2	0, 1, 2, 3	0, 1, 2, 3, 4	0, 1, 2, 3, 4, 5
1, 2	1, 2, 3	1, 2, 3, 4	1, 2, 3, 4, 5	
2, 3	2, 3, 4	2, 3, 4, 5		
3, 4	3, 4, 5			
4, 5				

Similarly to the previous studies, there was only one conductor modelled at leading edge (at 0m) due to the profile of the aerofoil whereas the rest of the locations were installed with pairs of conductors on the upper and lower surfaces of aerofoil. Furthermore, many results of L/D ratio were obtained for these multiple conductors' arrangements. However, only the lowest and highest degradations of L/D ratio were compared with the L/D for the blade without a down conductor installed (i.e. clean aerofoil surface) and are tabulated in Table 3.

Table 3

L/D ratios for multiple conductors' arrangements – location of conductors are as parenthesized

	Clean	Lowest Reduction L/D	Highest Reduction L/D
Two	141.39	111.60 (0, 1)	103.77 (1, 2)
Three	141.39	108.09 (3, 4, 5)	102.17 (1, 2, 3)
Four	141.39	105.27 (2, 3, 4, 5)	101.23 (1, 2, 3, 4)
Five	141.39	101.20 (0, 1, 2, 3, 4)	100.61 (1, 2, 3, 4, 5)
Six	141.39	100.18 (0, 1, 2, 3, 4, 5)	

In Table 3, the L/D ratios varied according to the locations of multiple conductors. All arrangements of multiple conductors have shown a noticeable reduction in the aerodynamic performance.

For two conductors, around 21% and 28% reductions of L/D ratios were found. The latter reduction was obtained when two single conductors were installed at 1m and 2m from leading edge respectively and the former reduction was found at 1m from the leading edge and at the leading edge itself.

For three conductors, the conductors located at 3m, 4m, and 5m from the leading edge have given the lowest reduction of around 23% in comparison to conductors located at 1m, 2m, and 3m from leading edge where it has obtained the highest reduction of around 28%.

For four conductors, the lowest reduction of 25% on L/D ratio was found when the conductors were located at 2m, 3m, 4m, and 5m from leading edge. Whereas the highest reduction of 29% on L/D ratio was found when conductors were installed at 1m, 2m, 3m, and 4m from leading edge.

For five conductors, it was found that the reduction (with respect to either the lowest or the highest) of L/D ratio is fairly similar (i.e. around 29%) for either when conductors located at 1m, 2m, 3m, 4m and at the leading edge itself or 1m, 2m, 3m, 4m and 5m from the leading edge. In other words, the reduction was not so much affected by the locations of the conductors.

For six conductors, where conductors were installed at 1m interval, the reduction was found to be around 29% of the L/D ratio.

Owing to the results obtained, it can be observed that the reduction of L/D ratio is likely influenced by the number of conductors installed and locations of installed conductors. Furthermore, the highest reduction for all conductors' arrangements seems marginally similar (i.e. between 26% and 29%). Thus, it can be suggested that the locations of conductors with respect to highest reduction should be avoided. Despite five and six conductors arrangements may offer better coverage for lightning protection, unfortunately, the results of aerodynamics performance (for either lowest or highest reduction for the case of five conductors) have been reduced to a greater extent in comparison with other arrangements. Therefore, it should be avoided if the higher degradation is significant.

On the other hand, the lowest reduction appears to have increased linearly with the number of installed conductors. Amongst lowest reduction of L/D ratio, the two conductor arrangement was found to obtain the lowest (i.e. around 21%) whereas the four conductor arrangement was the highest (i.e. around 25%). Therefore, in an attempt to provide adequate protection for wind turbine blades from an impact of lightning, it can be suggested that the four conductor arrangement (i.e. 2m, 3m, 4m, and 5m from leading edge) may be the best option as it gives more coverage while still having the least reduction (of around 25%) on L/D ratio.

6. Conclusions

A study on the aerodynamic performance of an external lightning protection system for wind turbine blades has been presented by considering single and multiple conductor arrangements.

Single conductors located at the trailing edge had minimal effect on the aerodynamic performance when compared to the other locations but it may not provide adequate protection against lightning strikes.

The results for all multiple conductors' arrangements were compared and it was found that two and three conductor arrangements had the smallest effect on aerodynamics performance. However, to provide adequate lightning protection, a four conductor arrangement is suggested, as it provides more coverage for lightning protection on wind turbine blades. A future research will be done on whether the improved performance of the lightning protection system obtained with the suggested arrangement makes up for the degradation of the blade aerodynamic performance.

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8. Biographies

A. S. Ayub received B. Eng. (Hons) in Electrical & Electronic Engineering from Cardiff University, Wales, UK in 2007. In 2008, he was working in the area of cable diagnostics in the High Voltage Technologies (HVT) Group at University of Strathclyde, Scotland, UK. Currently, he is pursuing his PhD in Lightning Protection of Wind Turbine Blades at University of Strathclyde, Scotland, UK. His areas of interest include lightning protection and cable diagnostics. He is a Student Member of both IET and IEEE since 2005.

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M. Stickland is Senior Lecturer in the Department of Mechanical and Aerospace Engineering at the University of Strathclyde. He received a BSc. (Hons) In Aeronautical Engineering from the University of Manchester and a PhD from the University of Strathclyde. He is a Chartered Engineer and Fellow of the Institute of Mechanical Engineers. His research interests include computational and experimental fluid mechanics.