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External lightning protection system for wind turbine blades - Power performance

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Abstract

Previous studies conducted by the authors on the aerodynamic performance of turbine blades have shown unfavourable effects of externally mounted lightning down conductors. Owing to this, one could ask whether or not externally mounted lightning down conductors could linearly affect the power performance of the whole wind turbine as well. Therefore, this paper presents a study of the power performance of one wind turbine with an externally mounted lightning down conductor. An untwisted blade profile of NACA 4418 with and without external conductor was used on the full wind turbine model. Numerical simulations were carried out on turbine power output derived from Blade Element Momentum (BEM) theory. The results are compared and discussed. The preliminary results indicate that degradation in power performance may not be significant.

Nomenclature

a Axial induction factor	σ' Local solidity
a' Angular induction factor	θ Tangential coordinate
B Number of blades	Ω Blade rotational speed
c Aerofoil chord length	ω Wake rotational speed
C_L Lift coefficient	γ Aerofoil inlet angle
C_D Drag coefficient	p Pressure
C_p Power coefficient	P Power
D Drag force	ρ Density
F_x Axial force	R Blade tip radius
F_θ^x Tangential force	T Torque
L Lift force, angular moment	V Absolute velocity
Q Tip loss correction factor	W Relative velocity
r Radius and radial direction	x Axial coordinate
β Relative flow angle onto blades	λr Local Tip speed ratio
λ Tip speed ratio	

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1. Introduction

There are three essential elements in a lightning protection system (LPS) for a wind turbine, which are; lightning receptors (also called air termination points), lightning down conductors (runs through the blade) and grounding in the soil [1, 2], as depicted in Fig. 1.

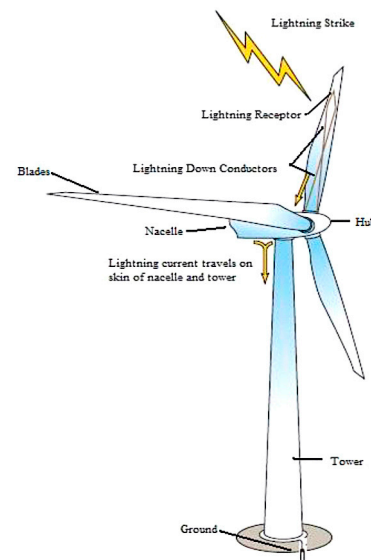


Fig. 1 Typical Lightning Protection System for Wind Turbine – adapted from [3]

According to the standards [1], [2], the lightning down conductor may be installed either on the internal or external side of the blade. Despite the choices 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 (referred to as aerofoil surfaces by aerodynamicists) [1], [2], as illustrated in Fig. 2. However, by having an internal down conductor, other problems occur (e.g. blade disintegration, burn) due to the impact of lightning strikes [1].

KEYWORDS

Lightning down conductor, power coefficient, wind turbine, wind turbine blades

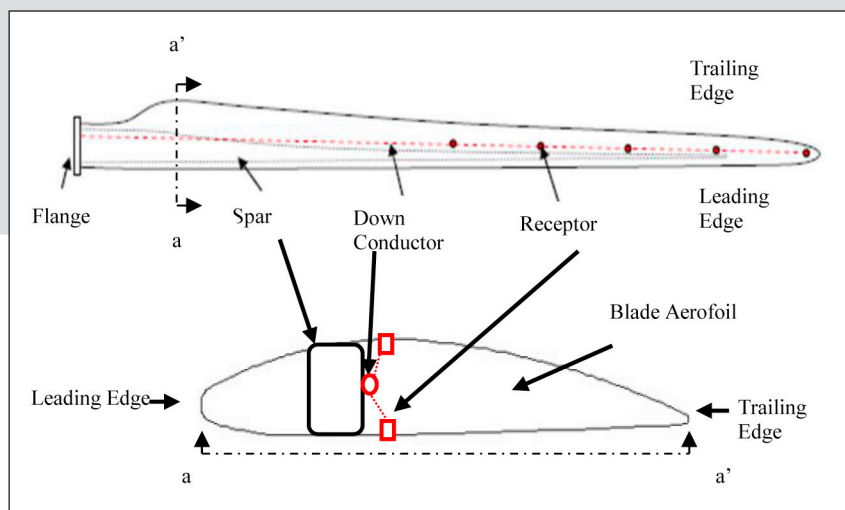


Fig. 2 Typical Lightning Receptors and Internal Down Conductor System Installation – 2D view (i.e. a, a') from blade's root, adapted from [1], [2]

At the moment, the authors have not found any literature in the public domain that quantifies the effect of having external down conductor on a wind turbine blade especially on aerodynamics and power performance. The authors have therefore performed aerodynamic performance studies on a single wind turbine blade with an externally mounted lightning down conductor. Previous studies have shown that this causes unfavourable aerodynamic effects [4]-[8].

However, the effect on the power performance, of the whole wind turbine, of externally mounted down conductors has yet to be investigated. The aim of this paper is to investigate whether or not the reduction of aerodynamic performance of a blade and power performance of a full turbine are linearly related.

In the following sections, this paper will provide a concise background on Blade Element Momentum (BEM) Theory where the power performance of a wind turbine (the whole turbine) will be derived from it. The paper then discusses the numerical modelling methodology. A study conducted on a clean blade is first presented. Using a similar numerical modelling methodology, simulations have been extended and investigated on aerofoils fitted with protrusions (i.e. down conductors) at 1m from the leading edge of the aerofoil. The results are discussed and conclusions are drawn.

2. Concise background on Blade Element Momentum (BEM) Theory

The fundamental description concerning blade element momentum theory and wind turbine power outputs are concisely presented in this section so as to provide an overview of the subject under investigation. Further information on the above-mentioned sub-topics is widely available in textbooks [9]-[18].

2.1 Blade Element Momentum (BEM) Theory – Brief Concept

The blade element momentum (BEM) theory is commonly used to analyse the aerodynamic performance of the whole wind turbine and also blade design. BEM theory is a combination of blade element and blade momentum theories. In short, blade element theory analyses the aerodynamic forces generated by lift and drag coefficients at various aerofoil sections (i.e. elements) along the blade whereas blade momentum theory examines the momentum balance on a rotating annular stream tube passing through a turbine. The latter is briefly explained below followed by the former.

2.1.1 Blade Momentum Theory

In general, the wind flow field interacts with the wind turbine rotor as it passes through it and thus transfers energy from the wind to the rotor. This behaviour may conveniently be analysed by introducing the actuator disc concept which is based on blade momentum theory. This concept in relation to wind turbine is to replace the real turbine (i.e. rotor) with an imaginary permeable disc as illustrated in Fig. 3. Fig. 3 shows four points involved in this concept.

The basic idea of this concept is governed by the balance of mass and momentum conservation (i.e. axial and tangential momenta) as a result of rotational movement (i.e. turbine rotor) and the changes of the wind flow field when it passes through the turbine. In other words, it is an interaction between the wind and the rotor from upstream to downstream. Furthermore, this concept comes with the following assumptions:

- Homogenous, inviscid and incompressible flow
- Uniform force and pressure over the disc or rotor area.
- No obstruction in the wind flow field either upstream (afore rotor) or downstream (abaft rotor).
- A non-rotating flow.
- An infinite number of blades.

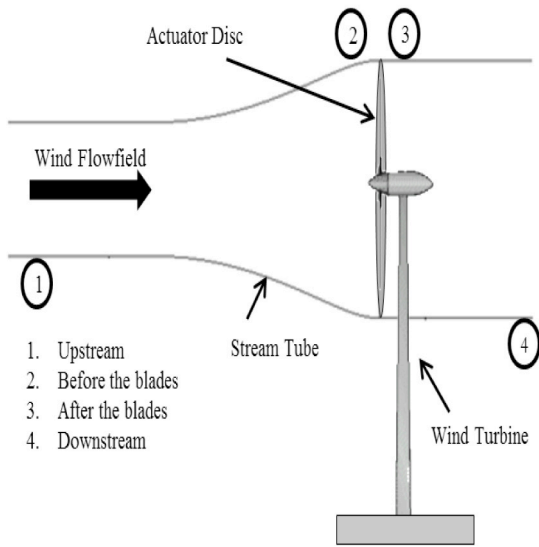


Fig. 3 Actuator Disc Concept

Equations (1) and (2) are the equations for axial and tangential force from blade momentum theory.

a) Axial force

$$dF_x = \frac{1}{2} \rho V_1^2 [4a(1-a)] 2\pi r dr \quad (1)$$

b) Tangential force

$$dT = 4a'(1-a) \rho V \Omega r^3 \pi dr \quad (2)$$

2.1.1.1 Tip Loss Correction

In actuator disc theory, as previously explained, the flow is assumed to be radially uniform. However, in practice where there are a finite number of blades, there are flow discontinuities (i.e. wind flow field losses) between before and after the disc (i.e. blades). Owing to this, the losses can be accounted for by means of a correction factor Q where the ratio varies between 0 and 1 and characterises the reduction in forces along the blade.

$$Q = \frac{2}{\pi} \cos^{-1} \left[\exp \left\{ - \left(\frac{B}{2} \left[\frac{1-r}{R} \right] \right) \right\} \right] \quad (3)$$

The Eq. (1) and (2) are rewritten to include this factor and are given in equations (4) and (5):

$$dF_x = Q \rho V_1^2 [4a(1-a)] \pi r dr \quad (4)$$

$$dT = Q 4a'(1-a) \rho V \Omega r^3 \pi dr \quad (5)$$

2.2 Blade Element Theory

Up to this point, the momentum theory is explained briefly as applied to a horizontal wind turbine blade. However, the effects of the blade geometry characteristics have yet to be considered. To account for the blade geometry blade element theory is introduced. This involves dividing up the blade into sections (i.e. elements) along the length of the blade (usually between ten and twenty elements) and calculating the aerodynamics characteristics at each one. Since the blade is divided into elements, each element experiences slightly different rotational speed, different chord length and a different twist angle. These are illustrated in Fig. 4 and Fig. 5 respectively. The aerodynamics performance of all of the individual elements is then determined by numerical integration along the blade span. This theory is based on the following assumptions:

- No aerodynamic interaction between different blade elements.
- The forces on the blade elements are solely determined by lift and drag coefficients.

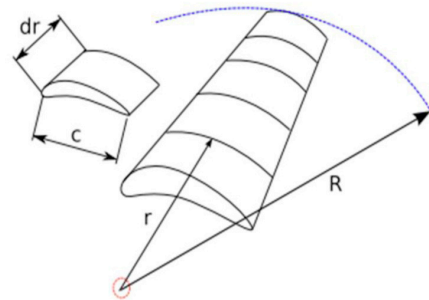


Fig. 4 The Blade Element Model

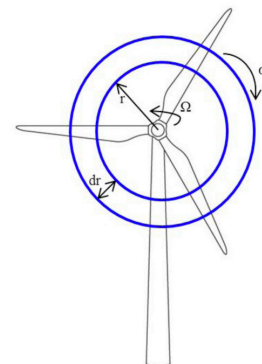


Fig. 5 Rotating Annular Stream Tube: notation

2.2.1 Relative Flow

The data for lift and drag coefficients for various aerofoils are readily available from wind tunnel testing where most of the tests are done with the aerofoil stationary. However, to obtain a more accurate and practical estimate of the aerofoil performance the flow, as in practice, is slightly turned as it passes over the aerofoil as depicted in Fig. 6.

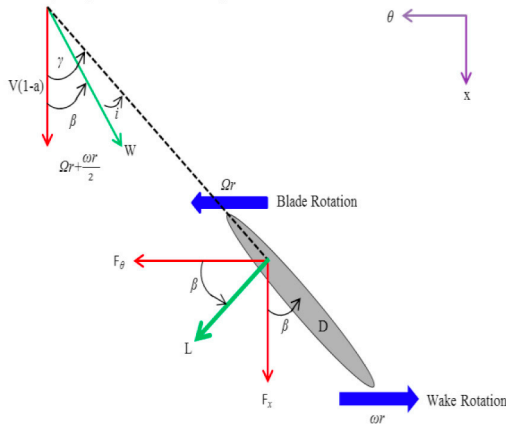


Fig. 6 Flows and forces on the turbine blade

The equations for the blade element method as listed in equations (6) and (7)

a) Axial force

$$dF_x = \sigma' \pi \rho \frac{V^2 ((1-a)^2)}{\cos^2 \beta} (C_L \sin \beta + C_D \cos \beta) r dr \quad (6)$$

b) Tangential force

$$dT = \sigma' \pi \rho \frac{V^2 ((1-a)^2)}{\cos^2 \beta} (C_L \cos \beta + C_D \sin \beta) r^2 dr \quad (7)$$

Where σ' is called the local solidity and is defined as:

$$\sigma' = \frac{Bc}{2\pi r} \quad (8)$$

Furthermore, using Eq. (7), the power coefficient C_p can be obtained directly from equations (9) and (10)

$$C_p = \frac{P}{P_{wind}} = \frac{\int_{r_h}^R \Omega dT dr}{\frac{1}{2} \rho \pi R^2 V^3} \quad (9)$$

$$C_p = \frac{8}{\lambda^2} \int_{\lambda_h}^{\lambda} Q \lambda_r^3 a' (1-a) \left[1 - \frac{C_D}{C_L} \tan \beta \right] d\lambda_r \quad (10)$$

2.3 Equations for Blade Element Momentum (BEM) Theory

As mentioned earlier, BEM theory is a combination of both momentum and elements theories. Therefore, equations (4) and (5) are equated with equations (6) and (7). Hence, the following useful relationships arise:

$$\frac{a}{1-a} = \frac{\sigma' [C_L \sin \beta + C_D \cos \beta]}{4Q \cos^2 \beta} \quad (11)$$

$$\frac{a'}{1-a} = \frac{\sigma' [C_L \cos \beta - C_D \sin \beta]}{4Q \lambda_r \cos^2 \beta} \quad (12)$$

3. Numerical and modelling techniques

The numerical technique utilised in this investigation is explained in this section. Furthermore, the modelling technique of the investigation is also presented.

3.1 Numerical Technique - Q-Blade Software

The Q-Blade software [19]-[21] has been developed by the Technical University of Berlin. It is developed as open source software for the simulation and design of wind turbines; hence, it is freely distributed under general public license (GPL) in order to facilitate research on wind turbines worldwide. It utilises BEM theory for the simulation of horizontal axis wind turbines (HAWT) and a double multiple stream tube (DMS) theory for vertical axis wind turbines (VAWT). One of the advantages of this software is that it comprises all the functionality required for analyse of the aerodynamic performance of the whole wind turbine and also blade design without the need to import, convert or process data from other sources. The functionality of this software includes the following modules:

- Aerofoil design and analysis
- Lift and drag polar extrapolation
- Blade design and optimisation
- Turbine analysis

3.2 Modelling Technique

3.2.1 Modelling Configuration

In Q-Blade software, modelling is configured as shown in Fig. 7. The arrows between the modules show the dependencies among them. Any available aerofoil

profile can be modelled. When the chosen aerofoil is modelled, it will first be simulated to find its aerodynamic characteristics (i.e. Lift and Drag Coefficients). During operation an HAWT can experience stall at very low and high angles of attack, hence, the results of lift and drag coefficients will be extrapolated through 360°. Then the wind turbine rotor is configured in blade design where it allows modifications to chord length, twist angle, edgewise or flapwise blade curvature, azimuthal angle and the twist axis of each individual aerofoil section at different radial locations. In addition, the type of power regulation (i.e. stall, pitch, prescribed) and rotational speed (i.e. single, two steps, variable) need to be defined. Furthermore, additional parameters such as cut in and cut out velocity and generator efficiency also need to be defined. When the parameters have been defined, all simulation results are analysed in post processing. The results are visualised in terms of the power performance over a range of wind speed and also the annual energy production for a given Weibull wind speed distribution is produced.

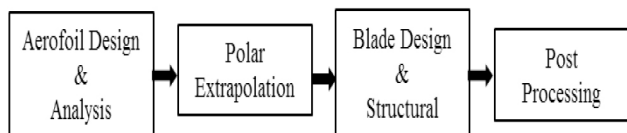


Fig. 7 General overview of modules in Q-Blade software

3.2.1.1 Model without protrusions – Clean Aerofoil Surfaces

An NACA 4418 aerofoil profile was selected [10] for all simulation cases (i.e. with and without protrusions). In addition to the modelling of the complete turbine configuration simulation of the clean aerofoil was carried out. The results (i.e. lift and drag coefficients) for both simulation and experiment [10] were compared for validation and verification purposes. It was found that both were in good agreement. Then, a fictitious wind turbine (with three blades) was configured for 3MW power output, pitch regulated, with 50m blades. For simplicity the blades were designed untwisted. The chord lengths were varied from 5m (near the root of the blade) to 1m (at the tip of the blade). This turbine was designed to operate at a nominal 10rpm and design wind speed of 13m/s. Its cut in and out wind speed were 3m/s and 20m/s respectively (see Fig. 9 Power Performance Curves of Wind Turbine with (i.e. Single Conductor)

and without protrusions with respect to wind speed). The design was based on a theoretical design incorporating a single aerofoil throughout and it was not intended to replicate actual turbine blade design. It was designed in order to investigate the overall power performance of a wind turbine with and without protrusion not as an exercise in efficient turbine design. The results of power performance were then used for comparison with a model with protrusions (i.e. with down conductors).

3.2.1.1 Model with protrusions – Protruded Aerofoil Surfaces

A turbine, of the same specification, was used for power performance modelling with protrusions on the aerofoil surface. The protrusion's (i.e. down conductor) dimension was configured to comply with the typical cross section (i.e. 50 mm²) as recommended by IEC 61400-24 [1]. This was easily achieved by configuring it as a rectangular shape of 1 mm height and 50 mm width (i.e. no bevelling at the edge of the rectangle). This ensured that the worst scenario was considered. The protrusion was configured at 1m from leading edge in the span wise direction for the upper and lower aerofoil surfaces and is referred to as 'Single Conductor' whereas the former model is referred to as 'Clean' (i.e. without protrusion).

4. Simulation results and discussions

For space economy, the most significant results only are presented in this paper. The variation of power coefficient as a function of wind speed for both cases of 'Single Conductor' and 'Clean' are as plotted in Fig. 8 Power Coefficients of Wind Turbine with (i.e. Single Conductor) and without protrusions with respect to wind speed. The result indicates that power performance of the 'Single Conductor' started to decrease as the wind speed reaches between 6m/s and 13m/s (nominal wind speed for the designed turbine, see Fig. 9 Power Performance Curves of Wind Turbine with (i.e. Single Conductor) and without protrusions with respect to wind speed) due to a reduction in the lift to drag ratio. This reduction was anticipated since the presence of protrusions at 1m from the leading edge which causes an increase in turbulence. Despite this adverse effect, both 'Clean' and 'Single Conductor' are in good agreement in the low wind speed region.

The variation of the wind power performance curve as a

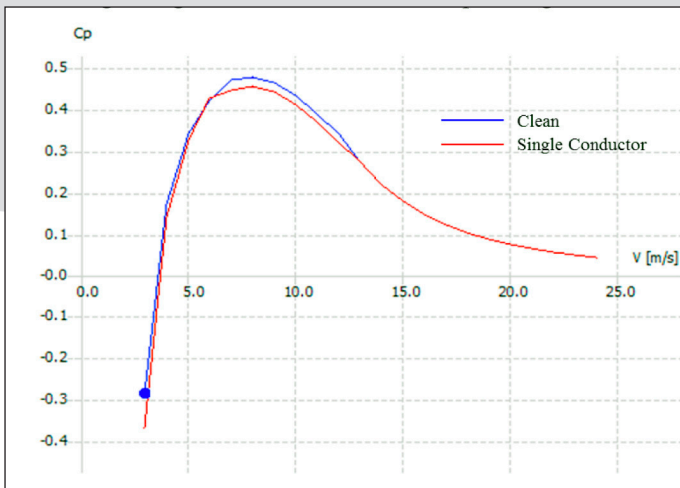


Fig. 8 Power Coefficients of Wind Turbine with (i.e. Single Conductor) and without protrusions with respect to wind speed

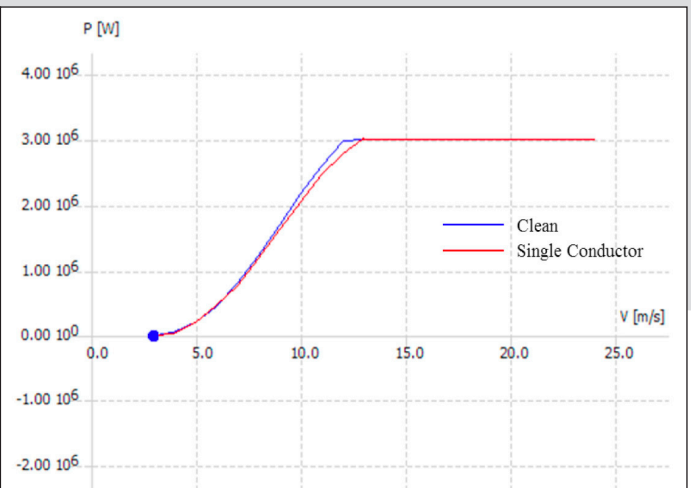


Fig. 9 Power Performance Curves of Wind Turbine with (i.e. Single Conductor) and without protrusions with respect to wind speed

function of wind speed for both cases of Single Conductor and Clean is as plotted in Fig. 9 Power Performance Curves of Wind Turbine with (i.e. Single Conductor) and without protrusions with respect to wind speed. It can be seen that the power performance curve of the ‘Single Conductor’ started to reduce when the speed reaches 6m/s. Under normal operation at a moderate wind site (Weibull parameters of k (scale) = 2, A (shape) = 6.2) in the UK, the ‘Clean’ wind turbine produces an annual yield of approximately 5325 MWh. With a current Feed-in Tariff (as of September 2017) [22] for an installed wind capacity exceeding 1.5MW of £0.81/kWh, hence, this turbine generates revenue roughly £4.3million a year. On the other hand the ‘Single Conductor’ wind turbine produces an annual yield of approximately 5092 MWh and therefore generates around £200k less revenue in comparison to the ‘Clean’ turbine. Previous work carried out by the authors [4]-[8] shows that there is approximately 30% reduction in the aerodynamic performance of a similar setup (i.e. Single Conductor). Despite this large reduction in the aerodynamic performance there is only about 4.3% reduction in the power performance.

5. Conclusions

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

A turbine fitted with a single conductor had very minimal change in power performance when compared to the power performance of a clean wind turbine. Hence, this minute reduction may not be significant in comparison to the maintenance cost and downtime that are needed for blades damaged by lightning impact. Furthermore, it is worth noting that the results achieved are on a blade which is untwisted with a single aerofoil profile and constrained by the assumptions of BEM theory. Hence, further investigation is required on blade designs where blade twisting and different aerofoil profiles along the

blade may be required to fine tune power performance of the wind turbine whilst safeguarding it from disastrous lightning impact.

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7. Biographies

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