COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF THE EFFECT OF ATMOSPHERIC ICING ON THE GENERATED POWER OF WIND TURBINES

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Abstract - Wind energy industry is expanding in many countries at large scale especially in cold regions where other resources, like solar energy, are limited. Atmospheric icing presents serious challenges to the development of wind power in the wind energy industry; these challenges include excessive vibration and output power loss. As ice loading becomes one of the important overall general loadings on wind turbines, it should be considered, in certain cold regions, as a major threat to be taken care of the fatigue and internal stresses issue, and also as fundamental structural load. Computational fluid Dynamics analysis has been conducted to investigate the effect of atmospheric icing on the generated power for the 5-MW wind turbine blades. Remarkable reduction in the output power was reported as a result of the change of geometry of the blade for both cases of regular and irregular icing profiles.

Keywords - Wind turbine; CFD; Atmospheric icing; Wind energy

I. INTRODUCTION

Atmospheric icing on wind turbine blades may induce excessive structural dynamic vibration and energy loss in production. It is therefore clear that a detailed research on the effect of atmospheric ice accretion on the dynamic performance of wind turbine blade is vital to the wind energy industry to ensure the optimum operation without compromising the safety of the wind turbine.

Ice accretion does not uniformly exist along the blade length. Ice thickness increases rapidly at the tip while less ice thickness can be observed near the root section of the wind turbine blade. The wind turbine blades angular movement and tapered shape of blades structure are the main two factors identified behind this observation [2]. Furthermore, the leading edges of the blades collect more ice around the stagnation points where the local velocity of the incoming air is zero [12]. The structural behaviour of the wind turbines considerably affected by harsh weather especially in cold regions, other potential problems like load imbalance, changing of natural frequencies, turbine vibrations and increasing of fatigue loads are often happened due to excessive ice accretion and irregular shedding, moreover, ice accretion on the blades is usually associated with increasing of drag and decreasing of lift [14]. Due to severe weather conditions, the annual power loss may be ranges from 20% to 50 % [11]. Performance losses of about 20 % were reported for a 450-kW wind turbine due to the effects of rime ice accretion [7]. The accreted ice also possesses a possible danger of being thrown away while melting and/or due to centrifugal forces as blades are rotating. Safety measures include spacing turbines apart, placing them in uninhabited locations, and avoiding too close to roads or agricultural infrastructure [8, 10].

A numerical analysis of atmospheric ice accretion on 5-MW wind turbine blade at five different sections for the rime and the glaze icing conditions had been carried out based on a computational fluid dynamics technique [13]. Accreted ice significantly increases the bending moments of the wind turbine blade. Gallardo [3] found that the maximum stresses occurred in the root area of the blade. On the other hand, ice accretion affects the fatigue performance of the wind turbine blade and creates complex load cycles. In their book, (Burton et al., 2011) [1] investigated several aspects of wind turbine including structural effects on wind turbine blade. It was interesting to notice from the survey of literature that in spite of the importance issue of the vibration due to atmospheric icing, which can directly influence the structural integrity of wind turbines, this hasn't been fully investigated. The NERL 5-MW rotor will be constructed by assembling three blades with the hub. CFD software Star-CCM+ will be used to investigate the effect of atmospheric icing on the lift and drag and the subsequent power loss of the turbine blade. The research aims to develop a further understanding of the effect of atmospheric ice accretion on the structural integrity and aerodynamic performance of wind turbine blades through numerical investigation. Investigate the loss of wind energy generation of typical 5-MW aerofoils due to icing through CFD simulation.

II. RESEARCH METHODOLOGY

To investigate vibrational behaviour of wind turbine blade under different icing events, three assumed

icing scenarios were investigated, which include a moderate icing case and two heavy icing cases according to ISO Standards (12494).

In this paper, two typical wind turbine blade aerofoils are examined to investigate aerodynamic effects due to ice accretion. Drag and lift forces are investigated for the three icing scenarios using the CFD approach. 3D-CAD models for all cases are prepared using Rhinoceros® 5 and the CFD analysis has been achieved by commercial CFD software STAR-CCM®+. All the CFD analyses have been performed for the 2D cases using the aerofoil sections at different locations in the spanwise direction of the blade.

Aerofoil Geometry and Aerodynamics

In this research the linear momentum theory is used along with STAR-CCM+ for the calculation of the aerodynamic forces and the power generated for typical aerofoils. This method, as with any other method, has a number of simplifications and idealizations, which make it practical for use.

Numerical Setup of the CFD Model

CFD simulations require a fluid domain surrounding the object of interest, which is the aerofoil in this study. The size of the domain depends on the size of the aerofoil to be analysed. The chord of the 5-MW (DU21) aerofoil is 3.26 m so the inlet of the CFD domain is 20×3.26 = 65.2 m. The top and bottom boundaries have the dimension of (8×3.26+3.26+10×3.26 = 61.9 m). Constructing the 3D-CAD model for aerofoil CFD analysis took place using Rhinoceros according to the diagram shown in Figure 1.

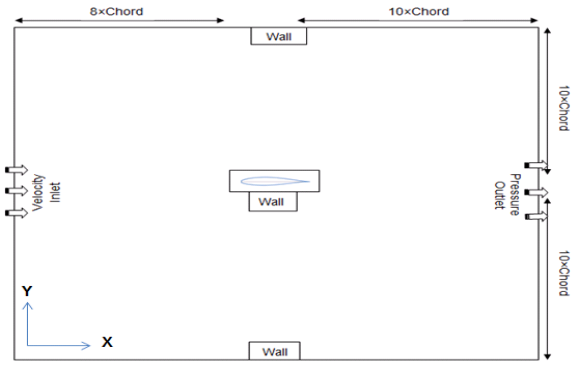


Figure 1. Schematic diagram of applied boundary conditions in the domain

In this research, the flow was considered incompressible and the (k-ϵ) turbulence model was used. A y+ value less than 10 was used near the wall for all cases. Inlet velocity is assumed to be constant and with a magnitude of 10 m/s. For simplicity, the analysis was chosen to be two dimensional under steady state condition. The moving medium is the airflow which is gas. The segregated flow reflects the pressure equilibrium at the inlet and outlet boundaries which encourages the airflow to be under the influence of gravity.

Meshing of the CFD Model

Surface remesher, polyhedral mesher and prism layer mesher were chosen from mesh model selection. The use of Polyhedral cells has an important advantage such that they have about ten neighbours, this will lead to higher accuracy [9]. Figure 2, shows the 2D mesh.

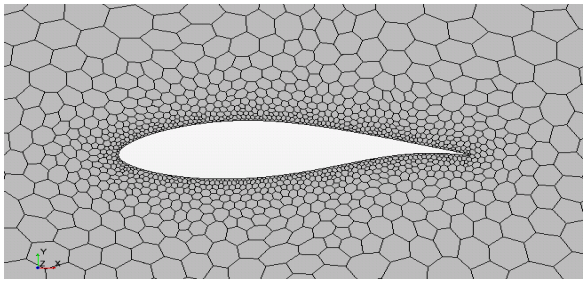


Figure 2. The 2D meshing for clean 5-MW (DU21) aerofoil profile

Aerodynamic Effect Due to the Different Icing Scenarios of the 5-MW Aerofoil Profile (DU21)

In order to study aerodynamic effects of the three assumed icing cases, one section of the 5-MW wind turbine blade, (DU21), was selected to carry out the CFD analysis. The aerofoil is selected in the middle of the assumed five icing zones. The location of the aerofoil is illustrated in Figure 3.

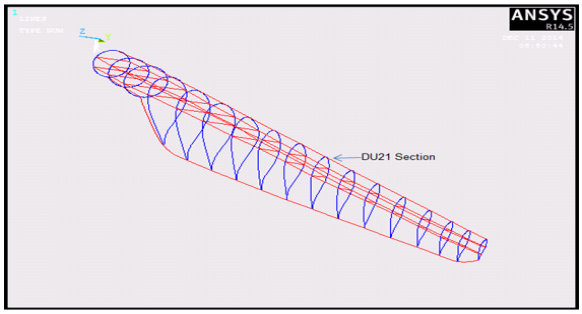


Figure 3. The 5-MW wind turbine blade with section DU21 in the middle

In order to investigate the effect of icing on the aerodynamically behaviour of the wind turbine blade, the thickness of accreted ice on the leading edge is determined by referring to ISO 94242 International Standard [5].

Based on the new approach for estimating the largest aerofoil section width $\hat{W}$, the maximum ice thickness may be calculated using the following relation [5]:

$$Ł = \frac{\hat{m}\times 4\times 10^{6}}{\pi\times\rho_{ice}\times\hat{W}} \quad (1)$$

where $\hat{m}$ is preliminary value for accreted ice mass given for different icing cases shown in Table 1, ρ_{ice} is the density of ice which will be considered as hard rime with density of 900 kg/m^3 [6]. Values of maximum ice thickness for the different icing scenarios are calculated according to equation (1) and presented in Table 1.

Table 1. Maximum ice thickness for the three assumed icing scenarios

Icing Scenario	*Preliminary value for ice mass $\hat{m}$ (kg/m)*	*Maximum accreted ice thickness (mm)*
Moderate R5	*5*	*10.5*
Heavy icing R8	*28*	*59.0*
Heavy icing R9	*50*	*105.4*

According to a typical ice accretion on wind turbine blade, the maximum thickness of the accreted ice is located at tip of the leading edge at any section of the blade due to the continuous rotation of the blades, the ice thickness gradually decreases away from the leading edge towards the middle of the blade section, the thickness actually vanishes when it reaches the middle of the section, at this point, the profile of the accreted ice touches the outer skin of the blade [5].

As numerical setup was prepared for both clean and iced blade, the accreted ice thickness associated to each icing scenario will be added to the clean profile of the blade to generate the 3D-CAD models representing the different assumed icing cases in the Rhinoceros environment.

Figure 4, shows how the new thickness profile of accreted ice has been added to the clean profile, the Figure shows a small amount of ice accumulated on the leading edge in yellow colour.

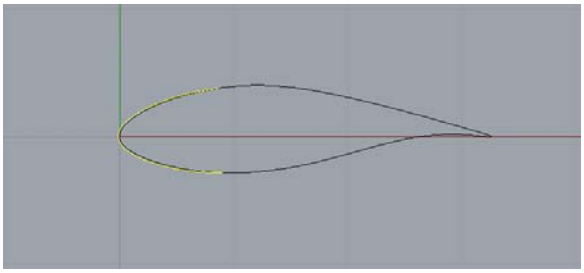


Figure 4. Icing profile added to the aerofoil for the moderate scenario

For heavy icing scenario R8, maximum ice thickness is 59 mm. Figure 5, shows the accreted ice on the aerofoil profile.

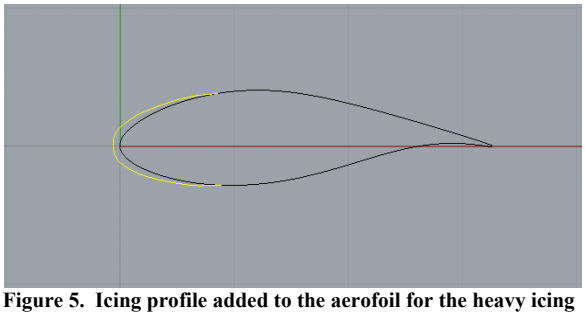


Figure 5. Icing profile added to the aerofoil for the heavy icing R8 scenario

The icing profile for the third assumed icing scenario R9 is illustrated in Figure 6. A considerable increasing in the accreted ice thickness is clear from the Figure 6.

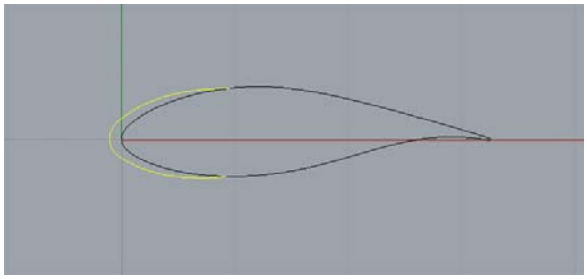


Figure 6. Icing profile added to the aerofoil for the heavy icing R9 scenario

In this study, drag and lift coefficients are numerically calculated for angles of attack (AOA) of 0º, 5º, 10º, 15º, and 20º using STAR-CCM+. The ratio of lift to drag coefficients is illustrated in Figure 7 for all assumed icing cases along with the case of clean blade, it's clear that the ratio of the clean blade case is on the top of all iced cases followed by the moderate ice case, the maximum ratio is noticed between AOA of 5^0-10^0 this mainly because the increase of lift wasn't accompanied with a decrease in drag at the same rate. All cases are almost share the same trend from AOA of 15^0-20^0 as the increase of drag coefficient happened after reaching stall angle of 15^0 along with decrease of lift.

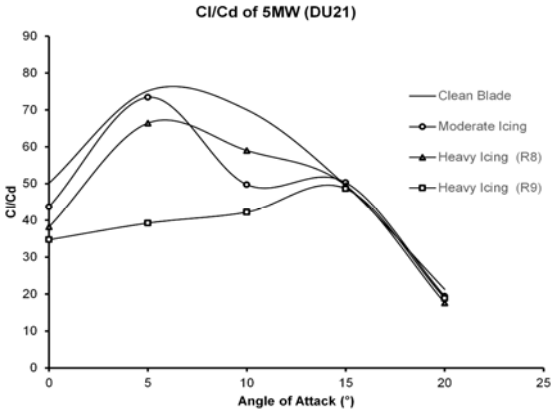


Figure 7. Ratio of lift / drag coefficients for clean and iced 5-MW (DU21) aerofoil

Effect of Icing on Power Generated by the Wind Turbine

The main goal when designing a wind turbine is to get the highest possible power output under certain weather conditions. The blade profile, the wind velocity and other weather conditions are curtail aspect to determine the amount of power that a wind turbine can generate. By applying the conservation of linear momentum to the control volume enclosing the whole system, the net force, which is equal and opposite to the thrust, $\underline{T}$, can be determined.

Power Reduction Due to Moderate Icing Scenario

By assuming air temperature -10 ºC the air density will be 1.26 kg/m3. The reference velocity and the

area for 5-MW (DU21) aerofoil were estimated by (Homola et al., 2012) [4] to be 50.7 m/s and 1.35 m2, respectively. Velocities for different (AOA) for clean and moderately iced profile are shown in Figure 8.

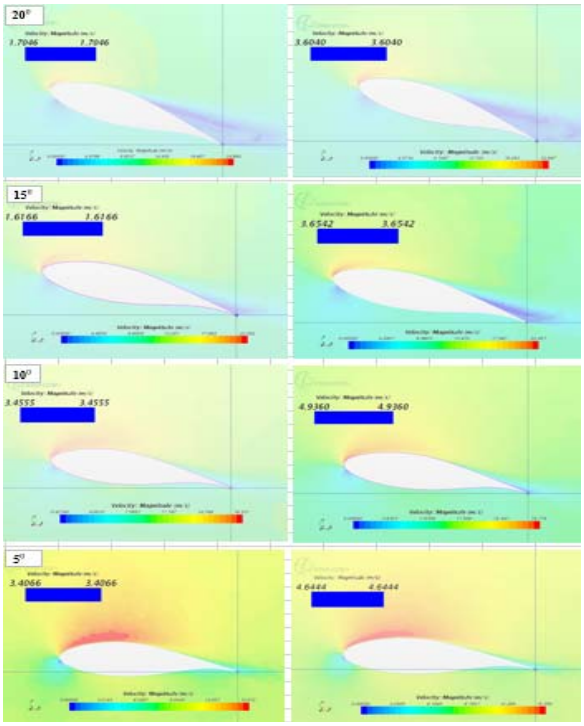


Figure 8. Velocities at trailing edge for (DU21) airfoil at different (AOA), clean profile to the left and moderately iced to the right

The velocity at the trailing edge of the aerofoil is found to be less for clean airfoil profile and more for the same iced aerofoil profile. This is due to the change in the aerodynamic behaviour of incoming airstream around the airfoil because of the change in the geometry of airfoil profile. Instead of smooth moving of airstream around the clean aerofoil profile, the accreted ice is presenting geometrical obstacle and leads to local distortions within the incoming airstream. Figure 9 gathered different arrangements for airstream velocity at trailing edge of clean aerofoil, moderately and heavy iced aerofoils profile under various (AOA). The Figure shows that ice accretion has changed the profile of the aerofoil leads to dislocation of the separation point for the flow over the top of the aerofoil, hence earlier flow separation.

Results show reductions in the generated power due to moderate icing on the aerofoil profile. With the existence of accreted ice on the leading edge, the incoming airflow separation point will move left further to facilitate earlier flow separation and introduce more drag and less lift, as severity of icing and (AOA) are increasing. This icing scenario, the thickness of ice at the leading edge of aerofoil profile has increased to 59 mm. Due to the increase of thickness the shape of the aerofoil profile experiences more change. This will encourage earlier separation in the boundary layer resulting in lift force loss. Hence, less power will be generated in the presence of more accreted ice.

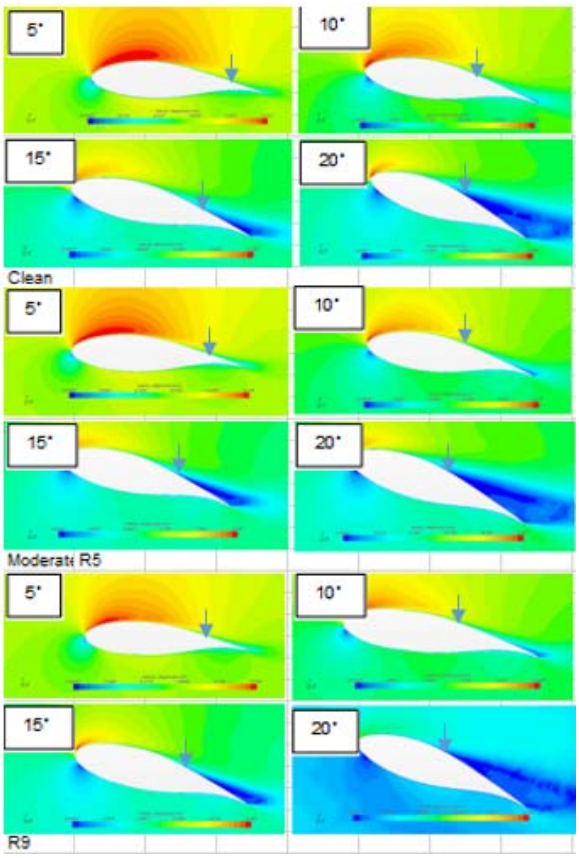


Figure 9. Airflow separation point moving left for moderate iced and R9 aerofoils as compared to clean aerofoil for different (AOA).

Power Reduction Due to the Heavy Icing Scenario R8

It can be seen that the power reduction is greater under R8 icing condition as compared to the previous moderate icing case. This is expected as the ice thickness has increased creating more change to the original aerofoil profile shape. It will affect lift force generation by displacing the path of airflow which supposed to be aligned to airfoil original profile. As the aerofoil increases its angle of attack, airflow can no longer flow smoothly over the aerofoil, causing the aerofoil to stall. Icing problem have added to this, causing more losses to the lift and encouraging more drag and hence, more power reduction.

Power Reduction Due to the Heavy Icing Scenario R9

The third case deals with heavy icing scenario R9. The ice thickness on the leading edge of the aerofoil has increased to a value 105.4 mm.

Results show greater power loss as compared to the previous two cases. The aerofoil lost about half of its generated power at the (AOA) of 15º. The aerofoil stalls at the angle of attack of 20º and loses its capacity of power generation as it's no longer able to produce lift due to the excessive ice accretion.

Power Reduction Due to the Irregular Icing Profile of the 5-MW (DU21) Section

The last case of the 5-MW (DU21) section is the irregular icing profile, results shown in figure 10. As illustrated in Figure 10, the clean blade has gained the maximum generated power, and then the case of irregular icing then moderate icing. Heavy icing cases R8 and R9 have obtained lower generated power. Power for all cases dropped after stall (AOA). It is linked to the increase of the distortion vortices over the top of the airfoil leading to an increase in the drag force.

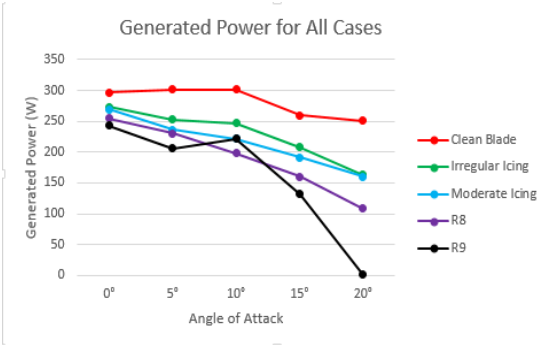


Figure 10. Generated power in the 5-MW (DU21) aerofoil due to applying all icing cases compared to clean aerofoil

It's worthwhile to mention that it was expected that the case of irregular icing profile has less generated power as compared to the moderate case Figure 11 shows the percentage of power reduction for the all icing cases with the heavy icing R9 having the highest power reduction.

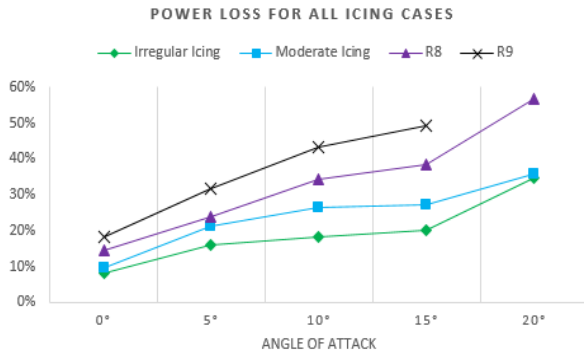


Figure 11. Power reduction percentage in the 5-MW (DU21) airfoil due to applying different icing cases

This may shed a light that, besides the danger of vibrations to the structural integrity of the wind turbine.

CONCLUSIONS

A method to estimate icing mass and profile under different weather conditions has been developed. Three icing scenarios have been identified according to the ISO Standard and the corresponding icing profiles have been established for the 5-MW wind turbine blade and its rotor to investigate their influence on vibrational behaviours of the wind turbine blade and the rotor.

Results of the drag and lift coefficients and power production under different icing scenarios and an irregular icing profile were obtained for five angles of attack. Compared with the results of the clean aerofoil profile, remarkable reduction in the power generation due to the accreted ice was observed at various aerofoil sections in the spanwise direction of the blade. It is found that ice accretion leads to a dislocation of the separation point and hence promotes earlier flow separation, leading to an increase in drag and a decrease in lift and consequently a reduction in the generated power.

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