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Numerical Study of Icing Impact on the Performance of Pitch-Regulated Large Wind Turbine

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Numerical Study of Icing Impact on the Performance of Pitch-Regulated Large Wind Turbine

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8 Abstract

This paper presents a study of the impact of icing on the performance of a pitch-regulated large wind turbine. Numerical simulations of six blade sections of the NREL 5MW wind turbine at various free stream velocities are performed. Blade Element Momentum (BEM) method along Computational Fluid Dynamics (CFD) bases multiphase numerical simulations are used for this study. Analysis shows that the simulated parameters are in good agreement with the real conditions for each blade element during operation, except for the three-dimensional effects. The analysis of accreted ice shapes and air/droplet flow fields around the blade profile sections was carried out, and the calculation of aerodynamic performance and energy production degradation was also performed. The tip of the blade is most affected by icing, it is characterized by the greatest changes in the aerodynamic performance. Maximum reduction in the wind turbine performance is estimated to be around 24%.

Keywords: Ice accretion; Wind Turbine; CFD; BEM; Power production.

1. Introduction

The Covid-19 pandemic had an impact on global energy demand in 2020. Energy consumption as well as CO₂ emissions were reduced during this period. But now economic growth and global energy demand are recovering rapidly after the impact of the pandemic. According to the Global Energy Review 2021 (The International Energy Agency, 2021) global economic output grew by 5.9% in 2021, impacting a 6% increase in CO₂ emissions. In absolute values, CO₂ emissions in 2021 exceeded the pre-pandemic 2019 emissions level by 180 megatons. At the same time, the post-Covid era is characterized by an increase in renewable energy production, which reached an all-time high in 2021 (The International Energy Agency, 2021). Wind power generation increased by 270 TWh, which shows the largest growth among all renewable energy sources. There is now 743 GW of wind power capacity worldwide, avoiding more than 1.1 billion tons of CO₂ globally, equivalent to South America's annual carbon emissions (Global Wind Energy Council, 2021).

Many places that are promising for the construction of wind power plants are located in the high north regions (Abbey et al., 2006; Alm and Nygaard, 1995). The wind turbines in cold climate regions can produce more power than those located in the other regions as air density is higher at low temperatures (Carreno-Madinabeitia et al., 2021). But high wind speeds combined with low air temperatures, and supercooled water droplets may cause ice formation on the structures of wind turbines particularly the rotor blades. Icing can lead to degradation of blade aerodynamic characteristics, losses in power production, partial or complete mechanical failure of the wind turbine, measurement errors, risk to human health and life (Parent and Ilinca, 2011). Therefore, the operation of wind turbines in cold climate conditions requires additional technical solutions and a good understanding of the physics of ice accretion.

Ice mainly accumulates along the wind turbine blades and can change their aerodynamic profile shape, increases its surface roughness, which affects its aerodynamic characteristics. Icing results in reduced lift force and increased drag force of the blade (Barber et al., 2011; Bragg et al., 2005; Homola et al., 2010; Jin and Virk, 2020). Depending on the accreted ice shape, the loss in lift coefficient can be between 10 and 65% (Ibrahim et al., 2018). The total torque decreases when the lift force of the wind turbine blades decreases, which leads to a reduction in power output (Botta et al., 1998; Kraj and Bibeau, 2010; Stoyanov and Nixon, 2020; Zanon et al., 2018). The results of field studies show that degradation of wind turbine blade aerodynamics caused by icing leads to a significant decrease in rotor speed and in some cases even shutdown of wind turbines due to the lack of sufficient torque to rotate wind turbines. Power generation losses caused by icing are strongly dependent on the duration of icing. For a 30-hour icing period, losses can reach up to 80% (Gao et al., 2021).

Ice accretion on wings and aerodynamic profiles of aircraft is widely studied (Gulick, 1938; Jacobs, 1934; Jones R and Williams D, 1936; Journal of the Franklin Institute, 1952; Pettit, 1959). At the same time, much fewer publications are devoted to icing of wind turbines. And this problem can still be considered insufficiently studied.

The type of wind turbine control system at high wind speeds affects the control strategy of the operation. Some studies are devoted to stall regulated wind turbines (Hu et al., 2018), whose blades are designed in a way that the rotor speed remains almost constant and energy production does not increase above the required limit due to the stall effect when wind speed increases. On the other hand, there are pitch regulated wind turbines (Yuan and Tang, 2017) with an active control system using where the blades are rotated around their axis to reduce the torque.

Homola et al. (2012) investigated the icing of the pitch-regulated wind turbine NREL 5MW. Shapes of the accreted ice were obtained. Aerodynamic and power performance characteristics were calculated. But the research was carried out only for an inflow velocity of 10 m/s. Han et al. (2018) studied the ice accretion along the leading edge of the blade tip. The ice accretion model was validated by comparing the simulation results with previously published wind tunnel test results. As a result of the study, the performance of the NREL 5MW wind turbine was calculated and compared before and after icing. However, the aerodynamic performance calculation was carried out only for NACA 64-

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618 airfoil and for an inflow velocity of 11.1 m/s. Etemaddar et al. (2014) studied the impact of various parameters (angle of attack, relative velocity, chord length, aerodynamic profile, temperature, liquid water content, median volumetric diameter, and relative humidity) on the shape of ice formation. But CFD calculation of the aerodynamic characteristics was performed only for two airfoils.

This paper is aimed to investigate the impact of icing on the performance of pitch-regulated large wind turbine using a combined approach – BEM method and multiphase CFD modeling at different velocity conditions. The paper will investigate icing along six sections of the NREL 5MW wind turbine blade from the root to the tip (figure 2). Simulations are performed for four different inflow velocities to assess the impact of icing on aerodynamic performance and power production of the wind turbine blade.

2. Methodology

2.1. Numerical approach

In this study, several numerical simulation tools were applied to calculate the characteristics of a horizontal axis pitch-regulated wind turbine under icing conditions. The applied workflow includes the following elements: blade element momentum (BEM) code; CFD simulations with flow, water droplet and ice solvers.

2.1.1 BEM method

The BEM methodology is widely used for wind turbine design and calculation of the main wind power characteristics (Yirtici et al., 2019). BEM is described in detail by Glauert (1935) and Hansen (2008). This approach allows to calculate the forces acting on the wind turbine blade, and accordingly the energy output of the wind turbine, using the geometric parameters of the planar sections of the blade and the characteristics of the incoming flow. In this paper, the BEM method is used to calculate the power production of a wind turbine based on the aerodynamic forces calculated by the CFD method.

The BEM method divides the blade into a finite number of sections, which are approximated by planar models. The method estimates the forces acting in the cross section on each element through ⁵⁰ 100 lift and drag coefficients as a function of geometric parameters and the inflow angle. The total force 52 101 values for the blade are determined by numerical integration along the blade span (Hansen, 2008).

54 102 The BEM theory assumes some simplifications: there is no aerodynamic interaction between the ⁵⁵ 103 elements, the blade forces are determined only by the lift and drag characteristics, the free flow is 57 104 perpendicular to the rotation plane. Thus, the BEM method does not determine the three-dimensional 59 105 influence of blade elements on each other. But it allows to use two-dimensional modeling, which saves computational resources considerably.

107 The BEM theory relates the axial and tangential induction coefficients to the aerodynamic forces acting on the turbine blade. The axial induction coefficient represents the amount of air flow passing 108 109 inside the rotor disk. The tangential induction coefficient determines how many rotations are created 110 in the flow after the rotor (Ibrahim et al., 2018). The axial a and tangential a' induction factors are 111 defined as:

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$$a = \left(\frac{4\sin^2\phi}{\sigma C_n} + 1\right)^{-1} \tag{2}$$

$$a' = \left(\frac{4\sin\phi\cos\phi}{\sigma C_t} - 1\right)^{-1}$$
(3)

where ϕ is the inflow angle, C_n is the normal force coefficient, C_t is the tangential force coefficient, 114 ²² 23 115 σ is the rotor solidity.

The thrust T and torque M on the element of thickness dr are defined as:

$$dT = Bp_n dr \tag{4}$$

$$dM = rBp_t dr \tag{5}$$

³¹ 119 where B is the number of blades, r is the radial position of the element, p_n is the normal component 32 33 34 120 of the vector sum of the lift and the drag, P_t is the tangential component of the vector sum of the lift 36 121 and the drag.

³⁷ 38 122 There are many implementations of BEM codes in software. In this paper, the open access software 39 1 2 3 QBlade was used to perform BEM calculations (Marten and Wendler, 2013). This software is 41 124 developed for design and aerodynamic calculations of wind turbine blades. New tip- and root loss 43 125 models after Shen et al. (2005) were used. The new Shen tip loss model overcomes the inconsistencies 44 126 of the Prandtl correction model, which overestimates tip loads compared to experimental data. Also, 46 127 3D correction after Snel et al. (1992) and foil interpolation were used in the simulation to get more 48 128 accurate results.

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53 1 3 1 2.1.2 CFD modeling

54 55 132 Multiphase CFD simulation codes are widely used to predict ice formation on surfaces, such as ⁵⁶ 133 aircraft wings or wind turbine blades, using a multiphysics analysis involving heat transfer and the 58 134 CFD approach. In this paper, ANSYS-FENCEP-ICE software is used for simulation of icing of a 59 60

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planar blade element of a horizontal-axis pitch-regulated wind turbine. CFD modeling allows to 2 135 predict ice accretion shapes, ice mass, calculate the flow field and forces acting on the blade. 136

137 The modeling process of ice formation and the study of the effect of icing on wind turbine performance consists of the following steps: flow solution, water droplet/ice crystal collision 138 139 modeling, ice accretion modeling, mesh displacement for the iced airfoil, re-solving the flow for the 10 11¹140 iced airfoil (see Fig. 1).



Figure 1 – Icing simulation procedure

29 143 FENSAP air flow solution is a 3D finite element Navier-Stokes analysis package. Analysis of the ³⁰ 144 icing problem begins with an airflow solution over a clean geometry and ends with a series of airflow solutions over an iced geometry to evaluate the performance degradation caused by ice accretion. 34 146 FENSAP solves steady and unsteady compressible three-dimensional Navier-Stokes equations:

$$\frac{\partial \rho_a \dot{V}_a}{\partial t} + \nabla \cdot (\rho_a V_a V_a) = \nabla \cdot \sigma^{ij} + \rho_a g$$
(6)

where ρ is the density, V is the velocity vector, σ^{ij} is the stress tensor, g is the gravity vector.

DROP3D is 3D finite element Eulerian water droplet impingement solver. DROP3D provides water concentration, droplet velocity vectors, water catch efficiency distributions, impingement patterns, shadow zone characteristics and impingement limits over the entire domain without the laborious iterative procedure of seeding droplets at injection points.

48 1 5 3 ICE3D is 3D finite volume ice accretion and water runback solver. This module based on fine-ייי 50 154 grain partial differential equations for the complex thermodynamics of ice formation. It yields 3D ice ⁵¹ 155 52 shape, water film thickness and surface temperature on any number of complex 3D surfaces.

53 1 56 This paper uses a single-shot solution methodology. The flow field and droplet solutions are 54 55 157 calculated once, and the icing solution is computed for the total icing duration as a single interval. 56 57 158 The results of the flow field calculation are used as input to the droplet solver. The droplet solution ⁵⁸ 159 is then passed to the ice accretion simulation module to predict the ice mass and shape for a single 59

160 2 icing time interval. The single-shot solution is chosen for modeling the icing process because it 3 161 requires less computational resources compared to the multi-shot solution. 4 5 162 2.2. Model features 6 7 163 The geometry of the NREL 5MW wind turbine was used in the paper as a reference model for the 8 9 164 study. According to the report of Jonkman et al. (2009) NREL 5MW blade is divided into 17 sections 10 11 165 and consists of 8 different airfoils. The main characteristics of the NREL 5MW are presented in the 12 166 Table 1. 13 14 167 Table 1 - Characteristics of the NREL 5MW 15 Rated power 5 MW 16 17 Rotor diameter 126 m 18 19 Hub diameter 3 m 20 Blade length 61.5 m 21 22 Hub height 90 m 23 24 Cut-in, rated, cut-out wind speed 3 m/s, 11.4 m/s, 25 m/s 25 26 Cut-in, rated rotor speed 6.9 rpm, 12.1 rpm 27 Six sections were chosen for this study (see Fig. 2, Table 2) to reduce the use of computing 28 168 29 30 169 resources. Most of the sections are on the outer part of the blade, since according to (Homola et al., 31 170 2012; Shu et al., 2018) ice mostly accrete closer to the blade tip section compared to the root section. 32 33 171 [insert Figure 2.] 34 35 172 Table 2 – Geometric features of sections under study 36 Twist, o Airfoil r/R Chord, m Section name 37 38 Section A DU 99-W-405 0.19 4.557 13.308 39 40 Section B DU 91-W2-250 0.45 4.007 7.795 41 Section C DU 93-W-210 0.58 3.502 5.361 42 43 Section D NACA 64-618 0.71 3.010 3.125 44 45 Section E NACA 64-618 0.84 2.518 1.526 46 Section F NACA 64-618 0.98 1.419 0.106 47 48 49 173 50 174 The CFD calculation was performed using the k-w SST turbulence model (Menter, 1993; Wilcox, 51 ⁵² 175 1988). This model is widely used, in particular for flow calculations near wind turbine blades, and 53 54 176 provides reliable flow calculations (Menter, 1994; Moshfeghi et al., 2012; Rocha et al., 2014). 55 ₅₆ 177 2.3 Mesh 57 58 178 For CFD modeling, a two-dimensional C-shaped orthogonal grid model was created. The 59 1 7 9 boundaries in front, above and below the airfoil are spaced at 15 chord lengths, and the boundary 60 behind is spaced at 25 chord lengths (see Fig. 3). The height of the first cell is calculated based on the 180

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2 181 requirement that the value of the near-wall function y+ is less than 1 for the simulated cases 182 (Gantasala et al., 2019; Zanon et al., 2018).

[insert Figure 3.]

An insufficient number of cells can increase the error of the obtained results, and an excessive 184 185 number of cells can unnecessarily increase the computation time. Therefore, a study of grid 11 186 independence on a clean NACA 64-618 airfoil was carried out. Six meshes with different number of 187 cells were constructed. To change the number of cells, the number of nodes along the main directions 14 188 - above, below, before and after the profile, and the number of nodes on the airfoil were changed.

16 189 The drag and lift coefficients were calculated for a Reynolds number of 6 million and an angle of 18¹⁷190 attack of 0°. The difference in the results of calculating the coefficients when using meshes with ¹⁹ 191 different numbers of cells and the time taken to perform simulations for a given mesh were compared. The results are shown in the Figure 4. A mesh with 153,000 cells has been selected for further 21 192 23 193 simulations considering a reasonable balance of accuracy of the results and optimal use of ²⁴ 194 25 computational resources. The delta Cl and delta Cd values for this mesh are 0.03% and 0.28%, 26 195 respectively. A mesh with 248,000 cells reduces this error, but at the same time requires almost twice 28 196 as much time per simulation, therefore it was not chosen. Zanon et al. (2018) chose a mesh with 140k ²₃₀197 cells for simulations under similar conditions. Han et al. (2018) used a 190k cell mesh but performed ³¹ 198 32 a grid independence study for a Reynolds number of 6 million and an attack angle of 6°.

[insert Figure 4.]

³⁶ 37 201 3. Results

³⁸ 202 39 The incoming flow characteristics were calculated for six different blade sections located at radial distances r/R = 0.19, 0.45, 0.58, 0.71, 0.84, 0.98 (sections A to F, respectively) along the blade of the 41 42 204 NREL 5MW wind turbine. Each section corresponds to the airfoil: A - DU40; B - DU25; C - DU21; 43 44 205 **D**, **E**, **F** – NACA64-618.

45 206 Four inflow velocities (cases 1-4) were chosen to calculate the blade aerodynamic characteristics 47 207 and wind turbine performance - 10, 15, 20 and 25 m/s. The inflow free stream velocities were chosen 48 49 208 based on the NREL 5MW wind turbine power curve. The maximum speed of 25 m/s was determined ⁵⁰ 209 51 by the cut-out speed of the wind turbine according to the power curve.

52 210 The angle of attack, axial and tangential induction factors and relative flow velocity were 53 54 211 calculated. Since the NREL 5MW is pitch regulated wind turbine for each inflow velocity the pitch ⁵⁵₅₆212 angle and tip speed ratio were calculated. The pitch angles are different from zero after reaching 57 213 nominal power on the power curve, i.e., after a nominal wind speed of 11.4 m/s. The pitch angle was 58 59 214 calculated for clean blade conditions.

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Table 3 contains the results of calculating the swept flow characteristics for Cases 1–4.

CharacteristicsSection BSection FSection FCase 1 - 10 m/sAxial induction factor0.179560.245710.254450.308560.335910.21613Tangential induction factor0.0179200.018640.011520.008640.006450.03606Angle of attack, *30.213.310.47.96.46.56.5Relative speed, m/s14.331.340.449.558.768.9Case 2 - 15 m/sCase 2 - 15 m/sCase 2 - 20 m/sCase 2 - 20 m/sCase 2 - 20 m/sAxial induction factor0.107920.075310.059470.061210.059870.04629Tangential induction factor0.077560.045280.027170.020460.012420.00028Angle of attack, *18.937.347.457.668.079.4Case 3 - 20 m/sAxial induction factor0.017560.045280.027170.020460.012420.00028Angle of attack, *16.72.0-0.6-2.1-3.1-3.8Relative speed, m/s22.739.549.259.269.488.0Case 1 - 25 m/sCase 1 - 25 m/s-0.00151-0.00032-0.00002Angle of attack, *17.22.3-1.0-3.1-4.6-5.9Relative speed, m/s27.042.251.561.171.182.0For each of the six selected sections of the	Table 5 – Characteristic	s of meoning	8 110 11				
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$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Tangential induction factor	0.08967	0.01223	0.00593	0.00405	0.00283	0.00163
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Angle of attack, ° 17.2 2.3 -1.0 -3.1 -4.6 -5.9 Relative speed, m/s 27.0 42.2 51.5 61.1 71.1 82.0 For each of the six selected sections of the NREL SMW wind turbine blade, the simulation at calculation of the aerodynamic characteristics before and after the icing event were performe Table 4 contains the icing simulation conditions. Table 4 – Icing simulation conditions. Table 4 – Icing simulation conditions 0.5 MVD (µm) 20 Water density (kg/m ³) 1000 Droplet distribution Langmuir D Ice density type Jones (glaze) Air temperature (°C) -10 Duration of icing (hour) 1 Modeling approach Single-shot The option "Sand-grain roughness - file" was selected for the flow simulation after icing. In th case, the roughness values on the wall surface are imported from the input file, which is generated during the simulation of ice formation on the surface of the airfoil. Figure 5 shows the simulated shapes of the ice accretion on the blade profiles at the inflow veloci of 10 m/s. The results show that ice accretion on the leading edge of the airfoil occurs near th stagnation point. The stagnation point i	Tangential induction factor	0.00009	0.03307	0.01020	0.00738	-0.00193	-0.00737
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Table 3 – Characteristics of incoming flow 216

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2 232 of the blade. But partially the ice formation passes to the suction side, where it has the maximum 233 thickness of $2.5 \cdot 10^{-2}$ m. These results prove that the tip section of the wind turbine blade is exposed 234 to more ice formation compared to the root section.

[insert Figure 5.]

9 236 Figure 6 presents the icing simulation results for Section F for the Cases 1–4. The Section F was 11 237 the most exposed to icing is the reason for selecting this section for the comparison of the results of 12 238 13 the four cases.

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[insert Figure 6.]

16 2 4 0 The results of the cases provided a comparison of the ice formation shapes during wind turbine 17 18 241 blade operation with the pitch control strategy for different inflow velocities. For Case 1, the ice ¹⁹ 242 20 accretion is mostly along the pressure side (inflow velocity 10 m/s) because the angle of attack is 21 2 4 3 positive. The angle of attack changes to negative after reaching a nominal velocity of 11.4 m/s and 22 23 244 simulating pitch control system conditions for a clean blade. Therefore, for cases 2–4 (inflow ²⁴₂₅245 velocities 15, 20, and 25 m/s), the ice accretion gradually moves to the opposite side of the blade. 26 246 27 At the same time, the ice accretion thickness does not change significantly for different cases.

28 2 47 Two-dimensional simulation of the flow around the airfoils was repeated after the analysis of the ²⁹ 30 248 ice shapes to assess the influence of the ice accretion on the aerodynamic performance of the wind ³¹ 249 turbine blade sections. Figure 7 shows the relative velocity distribution fields around the airfoil for 33 2 5 0 Section F (r/R = 0.98), where the greatest ice formation along the leading edge was observed. Cases 35 251 1 and 4 were analyzed before and after blade icing. For Case 1 (inflow velocity – 10 m/s, angle of ³⁶ 37 252 attack -6.5°) no significant flow changes are observed: the flow circulation around the blade is ³⁸ 253 39 generally symmetrical, there are vortices at the leading edge caused by ice formation, as well as a 40 254 slight flow separation at the trailing edge of the airfoil on the suction side. For Case 4 (inflow velocity 41 42 255 -25 m/s, angle of attack -5.9°) a non-deep stall caused by strong flow circulation near the leading 43 44 256 edge due to ice formations and flow separation was observed.

[insert Figure 7.]

47 258 A comparison of the aerodynamic characteristics before and after the icing event was performed 48 49 259 to assess the degradation of the blade aerodynamic performance. Figure 8 illustrates the change in the ⁵⁰ 260 51 lift coefficient due to leading edge icing for Sections A-F under Case 1 conditions. It is obvious that 52 261 a higher level of icing on the leading edge of the sections closer to the blade tip leads to a more 53 54 262 significant change in the aerodynamic performance. The lift coefficient for Section A does not ⁵⁵₅₆ 263 change, and for Section F it decreases by 13.39%. It is important, because sections close to the blade 57 264 tip make the main contribution to rotor performance. The results of deterioration of aerodynamic coefficients for different sections are similar for all calculated cases. 59 265

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[insert Figure 8.]

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Then, the changes of lift and drag coefficients (see Table 5) were analyzed in more detail for Cases 267 1-4 for Section F, as exposed to the most icing. Negative values indicate a decrease in the coefficient 268 269 compared to the clean profile, while positive values indicate an increase. Obviously, there is a 270 significant degradation of the aerodynamic characteristics for the inflow velocities >20 m/s.

Table 5 – Lift and drag coefficient degradation for Section F after icing

	C _L (%)	$C_{\rm D}(\%)$
Case 1	-13	76
Case 2	-6	68
Case 3	-356	687
Case 4	-152	269

16 17 272 Figure 9 demonstrates the pressure coefficient distribution for Section F before and after icing. ¹⁸273 The iced airfoil is associated with a change in the pressure coefficient distribution. The icing causes 20 274 disturbances at the leading edge, which causes a reduction of the pressure difference. This results in 21 22 275 a degradation of the blade aerodynamic characteristics.

[insert Figure 9.]

25 277 An analysis of the impact of icing on the power production of the wind turbine was the final stage 27 278 of the study. For a given wind speed, the CFD simulation results for each section are the lift and drag 28 29 279 coefficients. These coefficients are used to calculate the lift and drag forces acting on selected blade ³⁰ 280 sections. The contribution to the torque of each section is then calculated. The total blade torque value 32 281 is found by integrating the values for the sections along the blade span using BEM method. Finally, 33 34 282 the power extracted by the wind turbine is determined by multiplying the torque of one blade by the ³⁵₃₆ 283 number of blades and by the rotation speed.

37 284 Figure 10 shows the results of the power calculation for wind turbine under icing conditions. For 38 39 285 an inflow free stream velocity of 10 m/s, the reduction in power production is not significant. But 40 41 286 with increasing inflow velocity the degradation of performance gradually increases. The maximum 42 43 287 performance reduction is 24 %.

[insert Figure 10.]

47 48 290 4. Conclusion

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⁴⁹ 291 50 In this paper, the authors investigated the impact of icing on the performance of a pitch-regulated 51 292 wind turbine using a combined approach – Blade Element Momentum code and CFD modeling. The 52 53²293 NREL 5MW reference wind turbine was used as a test case for icing simulations. The study included ⁵⁴ 294 simulations for six airfoils (Sections A–F) from root to tip section along the blade span. Four cases 56 295 with different inflow velocities were considered to evaluate the impact of icing on wind turbine 57 58 296 performance and create a power curve after icing. An air temperature of -10°C and a duration of 1 ⁵⁹ 60 297 hour were used as the icing simulation conditions. The two-dimensional simulation allowed to Page 11 of 23

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2 298 simulate the flow conditions that are specific to wind turbine rotation, except for the three-299 dimensional influence of the sections on each other. Relative velocity, inflow angle, axial and 300 tangential induction factors were calculated for each section.

301 The results showed that the sections of the blade close to the blade tip were the most affected by 9 302 icing. For section A (r/R = 0.19), it was noticed that ice formation was very less. The maximum ice 10 11 303 thickness according to the simulation results was 9.7.10-4 m. The largest ice formation was observed $^{12}_{13}304$ for section F (r/R = 0.98). The stagnation point was on the pressure side, the largest area of ice 14 3 0 5 formation was on this side of the blade, but the ice had the greatest thickness on the suction side -15 2.5.10⁻² m. For cases 2–4, the ice shapes move to the upper side of the airfoil due to the change in 16 306 $^{17}_{18}\,307$ angle of attack, but the ice thickness is almost the same for different cases. The icing of the leading 19 308 20 edge of the blade causes changes in the aerodynamics of the flow – swirls appear near the leading 21 3 0 9 edge, with increasing inflow velocity the flow separation increases, and stall appears.

22 23 310 Calculation of aerodynamic characteristics demonstrated that the greatest losses are observed in ²⁴ 311 25 the sections close to the tip of the blade due to large ice formation. Also, with the increase of inflow 26 3 1 2 velocity the aerodynamic characteristics degradation raised. Accordingly, this influenced energy 27 28 3 1 3 performance – energy losses increased with increasing inflow velocity and reached a maximum of ²⁹ 30 314 24% at an inflow velocity of 25 m/s.

³¹ 315 This study was conducted using two-dimensional simulation and the Blade Element Momentum 33 316 theory, which does not take into account the aerodynamic interaction between the blade elements. 35 317 Therefore, the next stage of this study may be to conduct simulation using three-dimensional rotor ³⁶ 37 318 model and compare obtained results with the results of this work.

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42 321 The Authors declare that there is no conflict of interest.

Declaration of Conflicting Interests

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Figure 3 – Numerical domain (left) and mesh model (right)

232x111mm (96 x 96 DPI)

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1:55:12

1:26:24

0:57:36

0:28:48

0:00:00

Simulation time









197x155mm (96 x 96 DPI)

Case 1

Case 2

Case 3

Case 4

0.25

0.3







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 Case 1; clean airfoil
 Case 1; iced airfoil

 Velocity magnitude [ms]
 Velocity magnitude [ms]

 0
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 50
 60
 70
 80
 90
 100

 Case 1; clean airfoil
 Case 4; iced airfoil

Figure 7 – Flow field around Section F for Cases 1 and 4

218x157mm (96 x 96 DPI)







242x215mm (96 x 96 DPI)

Power loss [%]

