Evaluate the influence of icing on the rotor blades of a wind turbine with a horizontal axis to change its operating parameters

D Olejniczak¹ and M Nowacki¹

¹ Faculty of Machines and Transport, Poznan University of Technology, Piotrowo 3, 60-101 Poznan, Poland

E-mail: damian.a.olejniczak@doctorate.put.poznan.pl

Abstract. Currently the most commonly used wind turbines are three-blade turbines with a horizontal axis of rotation. The basic function of wind turbines is to convert the kinetic energy of the wind into mechanical energy in the form of rotational motion of the rotor. This function is accomplished by rotor blades which, similarly to the wing of the aircraft, produce a lift force directed perpendicular to the movement of the air molecules flowing the blade profile, thus forcing the rotation of the rotor. The problem of operation of wind turbines is connected with high susceptibility to weather conditions. Under atmospheric conditions close to 0°C and less, and with high humidity, the wind turbine blades may be icing. Accumulation of ice on the wind turbine blades causes a violate air flow through the profile of the blades. This condition leads to a change in the wind speed range needed to generate the rotation of the wind turbine rotor and to reduce the efficiency of the turbine. To evaluate the effect of icing on turbine rotor blades, performed a numerical analysis of the model blade profile. The results of the numerical analysis allowed to evaluate the influence of icing of rotor blades on the change of operational parameters of wind turbine. The conclusions of the numerical simulation are presented in this article.

1. Introduction

Wind turbines with a horizontal axis of rotation represent the largest share of the wind turbine market in Europe. The most popular are three-blade wind turbine. The height of the wind farm towers is 50 – 140 m [1]. However, the diameters of rotors of wind turbines 70 – 170 m [1]. The primary function of wind turbine blades is to convert the kinetic energy of the wind into mechanical energy in the form of rotational motion of the rotor. Energy conversion takes place through the blades of a wind turbine, which produce a lift force directed perpendicular to the wind direction, forcing the rotor rotation, which is then converted to electricity in the current generator. In this energy conversion system, a wind turbine plays a decisive role. It is usually built of three blades with the possibility to change the jump setting.

The pursuit of the best possible energy efficiency concerns not only wind turbines, but all energy-processing machines. This applies to electric motors, both piston and turbine engines, steam turbines, fuel cells [2-14].

The task of the turbine blade is to produce a force that creates the rotor’s torque contributes to the production of mechanical energy. The lift force is generated when the air is flowing through the wind
turbine blade profile and results directly from the pressure difference occurring on the upper and lower face of the profile. Aerodynamic profiles the wind turbine blades are designed to generate the best possible lift force. Wind turbine blades that generate higher lift force may be operated at lower wind speeds [15].

In the process of operating wind turbines it is important to maintain the profile shape and roughness of the surface of the blade. Under atmospheric conditions, when the air temperature reaches 0°C or lower and the air humidity is high, the surface of the wind turbine blades may be icing. The ice settling on the profile of the blade takes different shapes depending on the weather conditions and the operation of the wind turbine. The settling of ice on the surface of the wind turbine blade can accumulate using the profile structures (Figure 1), solid (Figure 2) or mixed. Profile icing consists of a parallel covering of the blade profile with ice. In contrast, solid icing on the surface of the blade creates an irregular structure. The most common form of ice structure covering the profile of blades is the mixed structure combining the features of profile and solid icing [16]. The ice covering the blade profile in the initial phase accumulates near the leading edge gradually covering the surfaces towards the trailing edge. Under conditions that are strongly propelling ice blades, that is, at minus temperatures and high humidity, the blade surfaces near the central part of the turbine rotor are most concentrated. Ice settling on the leading edge of the shovels under conditions of intense icing takes on solid and mixed structures. As the distance from the central portion of the wind turbine rotor towards the tip of the blade increases, the intensity of the icing is reduced. This is due to the increasing values of the speed of movement and the centrifugal forces that cause the settling of ice bodies to break, preventing the tip of the blade from covering the ice. However, under conditions of high humidity, when the air temperature is close to 0°C, the blade tips are more concentrated, where the speed of the blade is higher. These conditions determine the ice accumulation with a profile structure and the thickness of the ice sheet is less than that of the solid and mixed structures.

The phenomenon of icing of wind turbine blades negatively affects their operating parameters. The ice settling on the blades increases their mass. The uneven coverage of the ice wind turbine blades distorts the distribution of inertia forces and may cause the turbine rotor system to be undesired. The icing of the wind turbine blades causes a violate air flow through the profile of the blades and consequently the drop of the generated lift force. This condition leads to a change in the wind speed range required for the operation of the wind turbine and lowering the efficiency of the system [18].

Regular icing of wind turbine blades leads to reduced lifecycle and increased turbine component failure. Execution of the icing of the wind turbine blades can lead to lock or damage to the turbine. Atmospheric conditions strongly favoring icing on wind turbines are found in the northern part of Europe, mainly in lowland, mountainous areas and in marine areas [19] (Figure 3). In conditions conducive to the icing of the blades, there may be icing, profile, solid, or most often icing with a mixed ice structure. The structure of the wind turbine blade icing depends on the size of droplets in the air and the speed of the shovel in relation to the medium. For small water droplets and at high blade speeds, profile icings occur. On the other hand, at low velocities, shovels and large water molecules, solid icing type is more common. In mountainous areas and at high altitudes, more frequent profile icing may be expected. However, in the lowland areas, especially in the sea areas, solid icing is more common.
Figure 3. Frequency of occurrence of icing of wind turbines in Europe during the year [19].

For wind turbines operated in conditions conducive to ice icing of the blades, heating systems of de-icing similar to those used for anti-icing of aircraft are used. Heating elements of these installations are heating tapes made of a material with a high melting point. The current flows through the tapes causing them to heat up. These elements are separated from the remaining structure by an insulator in the form of a glass laminate layer. An increase in the temperature of the heating elements due to the current flow causes the melting of the ice coating [16].

The phenomenon of icing on wind turbines is also a source of danger. During the operation of the wind turbine under ice conditions, the ice cubes in the air are often torn and glided. Wind power statistics have documented a number of building damage incidents as a result of the impact of spinning ice bodies detached from wind turbine rotor components [20]. There have also been isolated cases of human injuries. In Canada, when a wind turbine working in icing condition, it is prohibited to approach the turbine for a distance of less than 305 m [21].

The problem of icing of wind turbine blades is not only related to the safety of their operation but also to the deterioration of their working parameters, which results in a decrease in their energy efficiency. Taking into account that the turbine system, blades status and settings play a decisive role, was evaluated the problem of the influence of ice blade in the selected cases on the operating parameters of the wind turbine.

2. Methodology

For the evaluation of the influence of icing on the turbine blade with a horizontal axis, the blade length $l = 44$ m was modeled. The profile of the blade model produced in the longest place is $c = 2,4$ m. In the direction of the tip of the blade, the chord length of the profile decreases. The blade model created is simplified and does not take into account the splicing of the geometric profile. In order to evaluate the impact of icing on the variation of blade operating parameters, a second model was made. The existing model of the blade was applied a few centimeter model of a layer of ice with a mixed structure. For simplicity of numerical calculations, this layer was applied along the leading edge of the blade at 90% of its length. Blade models are shown in Figures 4 – 5.
Numerical analysis was carried out on both models of wind turbine blades. For selected four sections of blade. At initial atmospheric pressure $P_a = 101300$ Pa, constant wind speed $v = 12$ m/s, and blade angles $\alpha_1 = 0^\circ$ and $\alpha_2 = 10^\circ$. As the boundary conditions of the simulation, the flow velocity $v_F = 12$ m/s and the pressure $P_{BC} = 101300$ Pa were assumed. An external flow model with an k-epsilon turbulent model was used. The density of the model mesh was set according to the Autodesk CFD tool on the value 1. The numerical analysis allowed to determine in the selected sections I, II, III, IV the distribution of pressure over the profile, and the lift force generated by the blade (Figure 6 − 7).

Figure 4. Wind turbine blade model.  
Figure 5. Wind turbine blade icing model

Figure 6. Model of wind turbine blade during numerical analysis with respect to cross sections for which the pressure distribution over the blade profile was determined and the blade lift force value at $P_a = 101300$ Pa, $v = 12$ m/s and the blade angle $\alpha_1 = 0^\circ$ and $\alpha_2 = 10^\circ$. 

Figure 7.
Figure 7. Model of wind turbine blade icing during numerical analysis with respect to cross sections for which the pressure distribution over the blade profile was determined and the blade lift force value at $P_a = 101300$ Pa, $v = 12$ m/s and the blade angle $\alpha_1 = 0^\circ$ and $\alpha_2 = 10^\circ$.

Blade models were tested under fixed simulation conditions at the same flow rate for the entire blade length without rotary motion of the blade. Simulation results were narrowed down to determine the aerodynamic force component of the blade in the form of lift force $L$. During the simulation, the values of resistance forces were not determined.

3. Analysis of the results
Conducted under known conditions, four numerical simulations of successive models: clean turbine blade at an angle of attack $\alpha_1 = 0^\circ$, icing turbine blade at an angle of attack $\alpha_1 = 0^\circ$, clean turbine blade at an angle of attack $\alpha_2 = 10^\circ$ and icing turbine blade at an angle of attack $\alpha_2 = 10^\circ$ they allowed the determination of pressure distributions over the profile of blades in selected 4 characteristic cross-sections. The distribution of pressure over the profile of the clear and icing blade at an angle of attack $\alpha_1 = 0^\circ$ is shown in Figures 8 - 11. Figure 12 shows the course of the x-axis with respect to which the pressure distributions over the blade profile are determined.
Figure 8. Distribution of pressure over the profile of the blade in section I for the angle of attack of the blade $\alpha_1 = 0^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].

Figure 9. Distribution of pressure over the profile of the blade in section II for the angle of attack of the blade $\alpha_1 = 0^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].
Figure 10. Distribution of pressure over the profile of the blade in section III for the angle of attack of the blade $\alpha_1 = 0^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].

Figure 11. Distribution of pressure over the profile of the blade in section IV for the angle of attack of the blade $\alpha_1 = 0^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].
During numerical simulations carried out for blade angle $\alpha_2 = 10^\circ$, pressure distributions over clear and icing blade profile were also determined. The pressure distribution over the profile is shown in Figures 13 – 16.

**Figure 12.** Longitudinal axis of the profile x [m].

**Figure 13.** Distribution of pressure over the profile of the blade in section I for the angle of attack of the blade $\alpha_2 = 10^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].

**Figure 14.** Distribution of pressure over the profile of the blade in section II for the angle of attack of the blade $\alpha_2 = 10^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].
Figure 15. Distribution of pressure over the profile of the blade in section III for the angle of attack of the blade $\alpha_2 = 10^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].

Figure 16. Distribution of pressure over the profile of the blade in section IV for the angle of attack of the blade $\alpha_2 = 10^\circ$: a – clean blade, b – icing blade, $P_s$ – the pressure value above the blade profile [Pa].

For blade angles $\alpha_1 = 0^\circ$, the pressure over the profile in sections I and III of the clear blade is greater than the icing blade. In section IV, where the chord of the blade profile is the most bruised over the profile of the icy blade is higher pressure than the clear blade. Conversely, for the cross-section II models, the blade pressure values above the profile are similar. For blade angles $\alpha_2 = 10^\circ$ in
sections II, III, IV, the pressure values above the ice blade profile are greater than the clear blade. The differences in pressure values over the profile of blades in the selected sections obtained from the numerical analysis are relatively small. Conversely, these changes cause a marked decrease in the icing blade lift force. During numerical analysis, the lift force values generated by the blade models were determined. By determining the total force acting in the y axis on the studied blade models directly from the CFD environment. Results are shown in Figures 17−18. Figure 17 shows the results of blade lift force values for blade angles $\alpha_1 = 0^\circ$. For the icing blade model of the wind turbine, the $L$ value decreased by 32% compared to the clear blade lift force. On the other hand, the values of the lift force for blade angles $\alpha_2 = 10^\circ$ are shown graphically in Figure 18. The ice blade model generated a 7% lower $L$ lift force than the clear blade model. Numerical analysis has also shown that, as the blade angle of attack, the lift force increases considerably.

![Figure 17. Lift force generated by blade L [N]: a – clear, b – icing, the angle of attack of the blade $\alpha_1 = 0^\circ$.](image1)

![Figure 18. Lift force generated by blade L [N]: a – clear, b – icing, the angle of attack of the blade $\alpha_2 = 10^\circ$.](image2)

4. Conclusions
The numerical analysis showed slight variations in pressure values over clear and icing wind turbine model profiles. For blade angles $\alpha_1 = 0^\circ$ the pressure values in the longitudinal axis of the blade profile are greater than the icing blade, except for section IV located near the tip of the blade. By contrast, with the change in blade angles, the pressure distribution over the profile of the models tested varies. For blade angles $\alpha_2 = 10^\circ$ in sections II, III and IV, the ice blade model generated higher pressure values than the clear blade. As the blade angle increases, the pressure distributions over the clean and icing blade profiles are more convergent and the differences between the individual values decrease. The results of the numerical analysis show that the icing of wind turbine blades results in a deterioration of their operating properties. Particularly susceptible to icing has been the model of a turbine blade with an angle of attack of blade $\alpha_1 = 0^\circ$. As the angle of attack of the modeled blade models increased, the reduction of the lift force caused by the change in the leading edge of the blade models by icing was noted. What makes possible to conclude that with the rise of the blade angle the impact of the blades icing on the decrease in the lift force produced by the blade decreases. The numerical analysis of the blade models demonstrates that the decrease of the lift force due to icing of the turbine blade with a near angle of attack of $\alpha = 0^\circ$ can reach a value of up to 30% of the force produced by the clear blade in the same conditions. At near angles of attack $\alpha = 10^\circ$, the drop in the lift due to icing is reduced by more than three times the results obtained at rake angles $\alpha = 0^\circ$. The results of the blade models' support lift forces confirm the correctness of the analysis performed, because with increased blade angles, a noticeable increase in the produced lift force occurred. The phenomenon of icing of wind turbine blades leads to a marked reduction in the blade lift force. What results in reduced efficiency of the wind turbine.
Nomenclature

- $l$ – length of wind turbine blade [m]
- $c$ – chord length of blade profile [m]
- $P_a$ – ambient pressure [Pa]
- $P_{BC}$ – boundary conditions pressure [Pa]
- $v$ – wind speed [m/s]
- $v_F$ – boundary conditions velocity [m/s]
- $\alpha_1, \alpha_2$ – angle of attack of the blades ['']
- $x$ – longitudinal axis of blade profile [m]
- $a$ – model of clear blade
- $b$ – model of icing blade
- $P_s$ – pressure over blade profile [Pa]
- $L$ – lift force produced by the blade model [N]

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