Response Analysis of a Spar-Type Floating Offshore Wind Turbine Under Atmospheric Icing Conditions

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One of the challenges for the development of wind energy in offshore cold-climate regions is atmospheric icing. This paper examines the effects of atmospheric icing on power production, overall performance, and extreme loads of a 5-MW spar-type floating offshore wind turbine during power production, normal and emergency rotor shutdown, extreme gusts, and survival conditions. Atmospheric icing is simulated by using the ice accretion simulation code LEWICE. A CFD method is used to estimate the blade aerodynamic degradation due to icing. The effects of icing on one, two, or three blades are compared, as are the effects of atmospheric icing on land-based and offshore wind turbines.

NOMENCLATURE

| CFD | Computational Fluid Dynamics |
| DLC | Design Load Case |
| ECD | Extreme Coherent gust with Direction change |
| ESS | Extreme Sea State |
| EWM | Extreme Wind Model |
| FWT | Floating offshore Wind Turbine |
| LWT | Land-based Wind Turbine |
| NSS | Normal Sea State |
| NTM | Normal Turbulent Model |

INTRODUCTION

Producing wind energy in cold climates has been a challenge for wind energy development in Europe, North America, and Asia (Ronsten et al., 2012). The icing of wind instruments, such as wind vanes and anemometers, can cause uncertainty in wind power estimation during the initial planning phase of a project, or lead to an underestimation of wind speed for the startup and shutdown of wind turbines during operation. Low-temperature materials, such as low-temperature steel, lubrication oil, and electronics, are required for wind turbines in cold climates. Icing of the rotor is the primary challenge for wind turbine designers because it reduces the efficiency of the wind turbine through aerodynamic degradation and increases the load and vibration during operation. A risk of sea icing and atmospheric icing of the wind turbine exists in offshore cold-climate regions (Battisti et al., 2006), and icing and environmental safety create challenges for onshore wind turbines in cold climates (Seifert et al., 2003); therefore, the safety of O&M personnel and other nearby personnel must be guaranteed in areas at risk of ice shedding.

Potential solutions to these challenges have been developed over the last ten years. Knowledge acquired by the aviation industry has been successfully used to solve problems in wind energy production in cold climates. Ice-free anemometers and wind vanes have been successfully tested. Most manufacturers have adapted their low-temperature wind turbines for cold-climate regions. The wind turbines are equipped with anti-icing and deicing systems to prevent icing of the blades, but these alterations increase the power production costs. In addition, if the anti-icing system fails for one or three blades, the wind turbine is again subjected to icing.

The problem of sea icing for both moving and stationary marine structures has been studied for many years (Sanderson, 1988). Mathematical models have been developed to calculate the static and dynamic forces from ice on offshore substructures (Mróz et al., 2008). The experience and knowledge obtained from the oil and gas industry can be directly applied to sea icing on offshore wind turbines. The current rules and standards IEC-61400-3 (IEC, 2009) and DNV OS-J101 (DNV, 2004) contain recommendations for the design of offshore wind turbine support structures with respect to ice loads.

To study the effects of atmospheric icing on a wind turbine, one must first specify the atmospheric icing conditions and the regions in which a risk of icing exists. While maps have been developed to specify the regions with a high risk of icing in Europe (Ronsten, 2008), Canada, China, and other areas, there is still high uncertainty in the estimation of atmospheric icing parameters due to the complexity of the phenomenon and the lack of measurements. Ice accretion and aerodynamic degradation of the rotor are two results of atmospheric icing. The experience and knowledge gained from the aviation industry have been helpful for investigating these effects. The NASA panel code LEWICE (Wright, 1995), which has been extensively verified for aircraft, has been used by many researchers to simulate the ice accretion on wind turbine rotors. The
TURBICE code (Marjaniemi et al., 2000), which was developed by VTT in Finland, has been specially developed to simulate ice accretion on wind turbines. The effects of atmospheric icing on the aerodynamic characteristics of wind turbine blade airfoils have been studied (Seifert and Richert, 1997), and the results indicate that the rime ice profiles decrease with increasing blade size. Seifert and Richert (1997) have extensively studied the effects of icing on the lift and drag coefficients of an iced airfoil to provide the technical requirements for rotor blades that operate in cold climates (Seifert, 2003). Etemaddar et al. (2011) have studied the role of varying atmospheric and system parameters on the icing of wind turbine rotors and have demonstrated that the ice load increases with the relative wind speed and decreases with the blade thickness for a variable-speed, pitch-regulated wind turbine. The additional loads and power loss are largely due to an increase in the drag coefficient, not the lift coefficient. The effects of atmospheric icing on the loads and responses of a 5-MW land-based wind turbine have been studied by Etemaddar et al. (2014), yielding results that indicate that the mean value of the responses is more affected by icing than the standard deviation, and that icing has a limited effect on fatigue damage.

Despite the large quantity of research conducted on the effects of atmospheric icing on land-based wind turbines, the effects of atmospheric icing on floating offshore wind turbines (especially under full load) have yet to be determined. The aim of this paper is to evaluate the performance of a floating offshore wind turbine under icing conditions and to analyze the extreme response of the wind turbine under atmospheric icing conditions. The variable atmospheric icing parameters are specified from the available statistical data (Makkonen, 1984). The LEWICE panel code (Wright, 1995) is used to simulate the ice accretion on the NREL 5-MW wind turbine (Jonkman et al., 2009) rotor during operation under icing conditions, which yields the ice profile on the blades and the ice mass distribution. The aerodynamic degradation of the 2D airfoil sections is estimated by using the CFD tool FLUENT (ANSYS, 2010). The effects of icing on the response and power production are investigated by using a time-domain simulation of an iced rotor from the cut-in to cut-out wind speeds. The effects of one-, two-, and three-blade icing are compared, and the extreme responses of the floating offshore wind turbine are calculated and compared to those of a land-based 5-MW wind turbine under normal and emergency shutdown, wind gust, and survival conditions.

In general, ice accretion on the blades during operation is affected by several atmospheric and system parameters (Etemaddar et al., 2011). The atmospheric parameters are time-dependent stochastic variables. Variation in each parameter can affect the shape, rate, and type of icing, according to the role of each parameter. As atmospheric parameters vary in time and space, and regional distribution of these parameters is almost unknown, this induces some uncertainty in the study. Ice profiles on the blade cause changes to both the airfoil geometry and surface roughness. Different ice types can be divided into three main groups according to their geometry and surface roughness: rime ice, glaze ice, and mixed ice. Changes in the blade geometry due to icing can be predicted with an acceptable accuracy with available icing models, while prediction of accurate surface roughness is more challenging and is the main source of uncertainty in the icing models. However, ice profiles on the blade can be quite different from time to time and place to place, but the overall effects of icing on the blades are similar. The reason is that any type of icing can change the airfoil leading edge geometry and surface roughness, which consequently reduces the rotor aerodynamic performance.

This paper is organized as follows: The Methodology section describes the theoretical background and numerical approach. The next section briefly discusses the wind turbine reference. The following section defines the environmental conditions and load case setup. The final section includes the results and discussion, followed by the conclusions.

METHODOLOGY

The numerical results for atmospheric icing conditions, as determined by Etemaddar et al. (2014), are used for this analysis. The ice profile of the blade was calculated based on 24 h of continuous operation given varying atmospheric icing conditions. A quasi-steady ice accretion simulation was performed to obtain the final ice profile after 24 h. The continuous unsteady one-day simulation was divided into 96 15-min steady simulations. The resulting ice profile for each step was used as an initial profile for the subsequent step. A previous study by Etemaddar et al. (2014) indicated that the effect of icing is negligible for the first half of the NREL 5-MW wind turbine blade from its root. Therefore, only the ice profile on the outer part of the blade is considered in the aerodynamic simulation. The ice profiles at six consequent sections on the outer half of the blade are shown in Fig. 1a.

It is worth mentioning that, in reality, ice profiles may break due to the motion of the blades, especially under extreme operational conditions. As icing is a stochastic phenomenon, ice profiles on the three blades can be different irrespective of working in the same atmospheric conditions. For simplification, it is assumed that ice profiles grow continuously on the blades and remain on the blades during operation, and ice profiles are similar on the three blades.

An average sand grain roughness of 0.5 mm was assumed for the icing profile and for the first quarter of the airfoil from the leading edge. The new lift and drag coefficients for the iced profile were calculated using the validated CFD code FLUENT. The K-ε turbulent model with a wall function and transient solver was used to calculate the aerodynamic coefficient of the airfoil after icing. The results indicate a limited effect on the linear region of the lift curve but a considerable effect on the drag bucket of the drag coefficients due to partly laminar boundary layer. The new aerodynamic coefficients of the iced airfoils at five consequent sections along the blade are presented in Fig. 1.

The validated servo-hydro-aeroelastic code HAWC2 was used to simulate the responses of a floating offshore wind turbine under the given atmospheric icing conditions. The aerodynamic model was based on the unsteady blade element momentum (BEM) method. The individual structural components were modeled using the Timoshenko beam element, and a multi-body dynamic system was used to model the interactions of the structural members through suitable constraints. The aeroelastic effects were included through the relative wind speed components that are induced by the elastic motion of the blade and the rigid body motion of the floating wind turbine in the BEM module.

Morison’s equation was used to calculate the hydrodynamic loads, including the added-mass, the Froude-Krylov force, and the second-order drag force. The dynamic pressure on the bottom of the substructure, which is based on the instantaneous wave elevation, was used to calculate the heave excitation force on the bottom of the substructure.

WIND TURBINE REFERENCE

The OC3-Hywind floating offshore wind turbine reference (Jonkman, 2010) was used as a test case in this study. The NREL 5-MW wind turbine was mounted on top of a spar-type substructure. Catenary mooring lines were used to provide station keeping. The surge and sway motions were limited by the mooring force,
whereas the pitch and roll motions were stabilized by the ballast. The three-line mooring system provided little mooring stiffness in the yaw direction; therefore, a delta line connection was added between the fairleads and each single mooring line to increase the yaw stiffness. The single-line mooring forces in the HAWC2 were modeled as a quasi-steady dynamic force component for each mooring line, as proposed by Jonkman (2007). Constant yaw stiffness equal to 98,340 kNm/rad was used to model the delta-line-connection yaw stiffness. The same controller that was used for the OC3-Hywind was used for this study, with the required subroutines added to model the normal and emergency shutdown. The shutdown was modeled by removing the generator torque and consequently pitching the blades to the full-feather position (90°). Pitch rates of 8°/s and 2°/s were used for the emergency and normal shutdown, respectively. The OC3-Hywind controller is similar to the land-based NREL 5-MW wind turbine with some modifications, as stated in the literature (Jonkman, 2010).

ENVIRONMENTAL LOADS AND LOAD CASE SETUP

The effects of icing on power production and the extreme responses of the floating offshore and land-based wind turbines were studied by comparing the responses for five design situations from IEC 61400-3, both with and without icing. Three icing conditions were considered for each load case, including one-blade (1B-ICE), two-blade (2B-ICE), and three-blade (3B-ICE) icing. The power production, normal and emergency rotor shutdown, extreme coherent gust with direction change (ECD), and parked conditions constituted the five sets of load cases. The environmental conditions from the Statfjord site (Johannessen et al., 2002) north of the North Sea were used to define the wind and wave conditions for this

<table>
<thead>
<tr>
<th>DLC</th>
<th>Design situation</th>
<th>Wind condition</th>
<th>Wave condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Power production</td>
<td>NTM</td>
<td>NSS</td>
</tr>
<tr>
<td>1.4</td>
<td>Power production</td>
<td>ECD,</td>
<td>NSS</td>
</tr>
<tr>
<td>4.1</td>
<td>Normal shutdown</td>
<td>NTM</td>
<td>NSS</td>
</tr>
<tr>
<td>5.1</td>
<td>Emergency shutdown</td>
<td>NTM</td>
<td>NSS</td>
</tr>
<tr>
<td>6.1</td>
<td>Parked</td>
<td>EWM + V₅₀</td>
<td>ESS, H₅ = kₑH₅₀</td>
</tr>
</tbody>
</table>

Table 1 Rotor speed over 24 h: one-, two-, and three-blade icing compared with a clean rotor (3-h mean and standard deviation)
SIMULATION AND RESULTS

The effect of icing on the responses of the floating offshore wind turbine was studied during power production. The 3-h mean and standard deviation in the rotor speed, tip speed ratio, and aerodynamic power and thrust before and after icing were calculated. Figure 2 provides the mean value and standard deviation of the aerodynamic power for 3B-ICE, 2B-ICE, and 1B-ICE compared with a clean rotor. As shown in Fig. 2, icing reduces the mean and standard deviation in the power at below-rated wind speeds. The controller is designed to keep the rotor close to the optimum tip speed ratio in below-rated wind speeds. Under icing conditions, the rotor’s aerodynamic torque is reduced for a given mean wind speed; therefore, less aerodynamic power is captured than that with a clean rotor. The effect of icing on the mean power is reduced as wind speed increases. The maximum power loss is 30% at a 5-m/s wind speed and drops to 10% at the rated wind speed. Near the mean wind speed of 15 m/s, the mean power of an iced rotor and that of a clean rotor are identical. The increase in the standard deviation in the power above the rated wind speed is less than 10%, which may not be observable. Therefore, the effect of icing on power at high wind speeds appears to be negligible under normal operation.

Figure 3 depicts the effect of icing on the shaft speed. Similar to the mean rotor power, the mean rotor shaft speed decreases at below-rated wind speeds and remains unchanged at the above-rated wind speeds. The standard deviation of the shaft speed is reduced at the above-rated wind speeds. To investigate the variation in the behavior at the below- and above-rated wind speeds, one should evaluate the tip speed ratio and pitch angle of the blade in these two regions.
Figure 4 depicts the change in the mean tip speed ratio and pitch angle of blade no. 1 under icing conditions. The pitch angle is zero at the below-rated wind speed. The tip speed ratio is reduced under icing conditions due to a reduction in the shaft speed that draws the rotor off the optimum operation point. At above-rated wind speeds, the rotor tip speed is unchanged and the blade pitch angle is reduced. The increased standard deviation in the power and the reduced shaft speed standard deviation may be related to the change in the pitch angle of the blade.

For a clean rotor, the aerodynamic thrust at the above-rated wind speed decreases with the wind speed, since the blade pitch angle increases with the wind speed; therefore, as shown in Fig. 4b, one can conclude that the aerodynamic thrust of an iced rotor must be larger than that of a clean rotor. Figure 5 compares the aerodynamic thrust of a rotor before and after icing. The icing increases for the rotor at above-rated wind speeds. Because the aerodynamic thrust is important for the motion of the platform, the effect of icing on the motion of the platform will also be examined. The effects of one-, two-, and three-blade icing, as compared in

![Fig. 6 Surge RAO](image1)

![Fig. 6 Pitch RAO](image2)

![Fig. 7 Sway](image3)

![Fig. 7 Roll](image4)

Figs. 6 and 7, clearly indicate that the magnitude of the effects is directly proportional to the number of iced blades.

RESPONSES OF THE PLATFORM

The effects of atmospheric icing of the rotor on the responses of the substructure are also investigated here. The JONSWAP spectra are used to generate an irregular sea state with a significant wave height \( H_s \) and a peak spectral period \( T_p \) that depend on the mean wind speed. The spectra of the surge and pitch responses for a mean wind speed of 13 m/s in LC5 are presented in Fig. 6. The aerodynamic thrust peaks near the rated wind speed; therefore, the maximum surge and pitch motions during power production should occur within this region. As shown in Fig. 6, the response under one-blade icing is smaller than that of a clean rotor, the response under two-blade icing is similar to that of a clean rotor, and the response under three-blade icing is larger than that of a clean rotor. The maximum effect occurs at the natural frequency.
Response Analysis of a Spar-Type Floating Offshore Wind Turbine Under Atmospheric Icing Conditions

Figure 8 presents the heave and yaw responses under icing conditions. The heave motion increases under all three icing conditions. The heave motion is excited due to the coupling between the heave and pitch motion, which comes from the mooring system. The yaw motion exhibits a limited effect. The peak in the yaw response at 1.2 rad/s is due to an imbalanced load on the rotor under one- and two-blade icing. An evaluation of the response at other wind speeds indicates that the responses are slightly reduced at the below-rated wind speed, and the effect of icing on the responses is negligible except in the surge and yaw motion at the above-rated response.

The roll and sway motions of the platform are limited when the wind and waves are co-directional and normal to the rotor plane. The atmospheric icing of the rotor increases the sway and roll responses, as shown in Fig. 7.

Table 2 Extreme responses in selected structural members for a clean rotor

<table>
<thead>
<tr>
<th>Bending moment</th>
<th>DLC 1.1</th>
<th>DLC 1.4</th>
<th>DLC 4.1</th>
<th>DLC 5.1</th>
<th>DLC 6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower bottom $M_x$</td>
<td>155,000</td>
<td>178,000</td>
<td>129,000</td>
<td>129,000</td>
<td>214,500</td>
</tr>
<tr>
<td>Tower bottom $M_y$</td>
<td>57,000</td>
<td>61,000</td>
<td>39,000</td>
<td>38,600</td>
<td>81,800</td>
</tr>
<tr>
<td>Tower bottom $M_z$</td>
<td>13,600</td>
<td>12,000</td>
<td>7,000</td>
<td>7,100</td>
<td>5,500</td>
</tr>
<tr>
<td>Shaft bearing $M_x$</td>
<td>6,000</td>
<td>10,600</td>
<td>5,900</td>
<td>4,300</td>
<td>4,700</td>
</tr>
<tr>
<td>Shaft bearing $M_y$</td>
<td>5,700</td>
<td>13,500</td>
<td>2,900</td>
<td>2,900</td>
<td>2,600</td>
</tr>
<tr>
<td>Blade no. 1 $M_x$</td>
<td>15,600</td>
<td>21,000</td>
<td>13,500</td>
<td>13,500</td>
<td>10,000</td>
</tr>
<tr>
<td>Blade no. 1 $M_y$</td>
<td>6,800</td>
<td>6,200</td>
<td>6,400</td>
<td>5,600</td>
<td>4,000</td>
</tr>
<tr>
<td>Blade no. 2 $M_x$</td>
<td>16,000</td>
<td>21,500</td>
<td>13,600</td>
<td>13,600</td>
<td>9,200</td>
</tr>
<tr>
<td>Blade no. 2 $M_y$</td>
<td>7,000</td>
<td>6,500</td>
<td>6,000</td>
<td>5,500</td>
<td>3,800</td>
</tr>
<tr>
<td>Blade no. 3 $M_x$</td>
<td>16,000</td>
<td>20,500</td>
<td>13,900</td>
<td>13,900</td>
<td>7,600</td>
</tr>
<tr>
<td>Blade no. 3 $M_y$</td>
<td>6,300</td>
<td>6,200</td>
<td>6,200</td>
<td>5,600</td>
<td>4,500</td>
</tr>
</tbody>
</table>

Fig. 8 Heave and yaw motion spectra of the substructure under icing conditions compared with those of a clean rotor (3 h); $U_m = 13$ m/s, $H_s = 3.42$ m, $T_p = 3.3$ s.

Fig. 9 Effects of three different icing conditions on the extreme responses of the offshore floating wind turbine (TB: Tower bottom, SB: Shaft bearing, Bi: Blade no. i)
wind speed. As shown in Fig. 8, the magnitude of the effects of icing on the responses increases with the number of iced blades.

EXTREME RESPONSE

This section discusses the effects of atmospheric icing on the extreme responses of different structural members. The results are presented as a ratio of the extreme response of an iced rotor to that of a clean rotor. For each load case, six 1-h responses are simulated, and the expected maximum response from each series is calculated as a short-term extreme response for a given load case. The short-term extreme loads in the tower, shaft, and blades for the floating wind turbine with a clean rotor are calculated for all the IEC design load cases and are listed in Table 2.

As shown in Table 2, DLC 6.1 is the design-driven load case for the tower bending moment. For the tower torsional moment, the extreme load under power production condition is the dominant load case. Extreme coherent gust with direction change induces the maximum extreme loads for the shaft bending moments. The extreme loads on three blades are almost equal. The flapwise bending moment under DLC 1.4 is the dominant load case. In the following figures, the extreme responses for 1B-ICE, 2B-ICE, and 3B-ICE are compared with those of a clean rotor.

Figure 9 provides the extreme response for DLC 1.1 and DLC 1.4. The effect of icing on the extreme loads during power production was limited to the shaft bending loads. For most of the load components, the extreme loads of the iced rotors were almost identical to those of a clean rotor. The extreme loads on the shaft were increased by 50%. Figure 9b shows the extreme responses of an iced rotor for DLC 1.4. This load case was a design driver for both the shaft loads and blade flapwise bending moment. As shown in this figure, the shaft and tower loads increased by 20–50%. The magnitude of the icing effect increased with the number of blades for nearly all load components.

Figure 10 presents the effect of icing for DLC 4.1 and 5.1, which represent the normal and emergency shutdowns, respectively. For a clean rotor, the extreme loads under normal and emergency shutdown were almost identical. Icing had the same effect on the tower and blade loads for these two load designs. The shaft extreme response was reduced under normal shutdown and increased under emergency shutdown. Therefore, normal shutdown is recommended under icing conditions.

Figure 11 depicts the extreme response under parked conditions for the three different icing conditions. The extreme loads under 3B-ICE were smaller than those of a clean rotor. The extreme loads on the shaft were always smaller under icing conditions than those of a clean rotor. The 1B-ICE exhibited the maximum effect. However, the effect of icing was generally not severe for a parked wind turbine.

Obviously, the extent of the icing can be different for offshore and onshore wind turbines, but in order to make a fair comparison
between the FWT and LWT, the same atmospheric icing condition is considered for both. The extreme responses of the land-based NREL 5-MW wind turbine for clean and iced rotors are calculated and compared with those of a floating offshore wind turbine to investigate the severity of the icing effects for each design. Figure 12 presents the effect of icing on the extreme responses of a land-based wind turbine for DLC 1.1 and DLC 1.4. For the land-based wind turbine, icing has the largest effect on the shaft and tower bending moments during power production. The shaft bending moment increases by a factor of two. The effects of icing on the blade loads are almost identical in both wind turbines. A comparison of Figs. 9b and 12b indicates that icing has a larger effect on floating offshore wind turbines than on land-based wind turbines under gust conditions. Figure 13 presents the effect of icing on normal and emergency shutdown for the land-based wind turbine.

The effects of icing on the extreme responses of a land-based wind turbine under survival conditions with extreme wind speeds over a 50-year recurrence period are illustrated in Fig. 14. Similar to the offshore wind turbine, icing has a limited effect on the extreme response of a land-based wind turbine under survival conditions.

CONCLUSIONS

This work examines the effects of atmospheric icing on the responses of a 5-MW spar-type floating offshore wind turbine. Responses under one-, two-, and three-blade icing of the rotor were compared. At below-rated wind speeds, the effect of icing was limited to power loss and a reduced aerodynamic thrust. The rated power was achieved at higher wind speeds of nearly 15 m/s for a rotor with this level of icing. An evaluation of the change in the mean value and standard deviation of the different wind turbine responses indicated that the effect of icing was proportional...
to the number of iced blades. Icing had a limited effect on the responses of the substructure. For surge and pitch motions, the responses of one-blade icing were smaller than those of a clean rotor; two-blade icing had no effect, and three-blade icing increased the response. The heave response was increased under all three icing conditions, which is mainly due to coupling between the pitch and heave response. Yaw response had only a limited effect under one- and two-blade icing due to in-balance load on the rotor.

The effect of icing on the short-term extreme responses of the offshore wind turbine and the land-based wind turbine was studied for five different IEC design load cases. The shaft is the structural component that is most affected in both types of wind turbine. Under normal operating conditions, icing has a larger effect on the shaft loads for the land-based wind turbine than for the offshore wind turbine. Under coherent gust, the floating offshore wind turbine demonstrated a greater effect from icing than the land-based wind turbine. For the offshore wind turbine, the most affected design was found to operate under extreme gust with direction change. The extreme loads on the shaft and tower increased up to 50%, and the blade loads increased more than 25%. The extreme responses under power production were increased by less than 18% for a few structural load components. A comparison of the normal and emergency shutdown indicated that one- and two-blade icing had a greater effect than three-blade icing, with the shaft bending moment loads exhibiting the most affected response. In general, normal shutdown had a smaller effect on the extreme loads than emergency shutdown under icing conditions. Icing had a limited effect on a parked wind turbine. For the offshore wind turbine, loads under three-blade icing were consistently smaller than those of a clean rotor, and the extreme response under one-blade icing was larger than that of a clean rotor.

The results and conclusions of this paper should be considered in the context of uncertainties from the atmospheric parameters and numerical models, as well as assumptions made for simplification. For practical application, the probability of icing and the uncertainty in estimating the load effect need to be included in the decision.

REFERENCES