Effects of Icing on Wind Turbine Fatigue Loads

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Abstract. The external conditions occurring at cold climate sites will affect wind turbines in different ways. The effects of ice accretion on wind turbines and the influence on the turbine fatigue loads are examined. The amount of icing prior to turbine installation needs to be estimated by using standard measurement data and considering the geometry of the proposed turbine. A procedure to calculate the expected ice accretion on wind turbines out of standard measurement data is explained and the results are discussed. Different parameters to describe the accreted ice on the turbine are examined separately in a fatigue load calculation. The results of the fatigue load calculation are discussed and selected cases are presented.

1. Nomenclature

| Symbol | Description                                      | Unit |
|--------|--------------------------------------------------|------|
| \(\alpha\) | power law exponent of the wind shear              | -    |
| \(c_{\text{max}}\) | maximum chord length                             | m    |
| \(c_{\text{min}}\) | chord length at the blade tip, linearly extrapolated | m    |
| \(H\) | height above ground                              | m    |
| \(k\) | Factor; \(k = 0.00675 + 0.3 \exp(-0.32 R/R_1)\) | -    |
| \(K_h\) | height factor                                     | -    |
| \(L\) | ice vane dimension                               | mm   |
| \(\mu_e\) | mass distribution on leading edge of the rotor blade at half the rotor radius | kg/m |
| \(m\) | Wohler slope \((\delta/\text{N}-\text{curve slope})\) | -    |
| \(m_i\) | distribution of ice per metre length at time step i | kg/m |
| \(N_{\text{ref}}\) | Reference number of load cycles                  | -    |
| \(\phi\) | flow inclination                                  | °     |
| \(R_1\) | Radius of 1 m                                    | m    |
| \(\rho\) | air density                                       | kg/m³ |
| \(R\) | rotor radius                                      | m    |
| \(\rho_i\) | density of the ice                                | kg/m³ |
| \(T_i\) | duration time for step in the in-cloud condition in hours | h    |
| \(v_i\) | wind speed at time step i                         | m/s  |
| \(V\) | wind speed at hub height                          | m/s  |
| \(W\) | width of the object                               | mm   |
### Abbreviation Description

| Abbreviation | Description |
|--------------|-------------|
| DEL          | Damage equivalent constant-range load spectra |
| DEL\textsubscript{ice} | Damage equivalent load calculated with additional ice load case DLC 1.10 |
| DEL\textsubscript{normal} | Damage equivalent load calculated for class II A conditions |
| DLC          | Design load case |
| FXHF         | Fx at hub center non rotating |
| FXT          | Fx at tower base |
| FYHF         | Fy at hub center non rotating |
| FYT          | Fy at tower base |
| FZHF         | Fz at hub center non rotating |
| FZT          | Fz at tower base |
| GL           | Germanischer Lloyd |
| IEC          | International Electrotechnical Commission |
| ISO          | The International Organization for Standardization |
| MXHF         | Mx at hub center non rotating |
| MXT          | Mx at tower base |
| MYHF         | My at hub center non rotating |
| MYT          | My at tower base |
| MZHF         | Mz at hub center non rotating |
| MZT          | Mz at tower base |
| NWP          | Normal wind profile |

### 2. Introduction

#### 2.1. Background

Wind energy is and will increasingly be used at cold climate sites. Resulting out of the external conditions at these sites several effects occur that change the wind turbine behaviour and in consequence the efficiency of a wind farm ([1], [2], [3]).

One issue to be considered is a probable change of the fatigue load level. The IEC 61400-1, 2nd edition [6] and several other design guidelines (e.g. [4], [5]) define a range of external conditions to be considered during site specific load calculation. Experience shows that cold climate conditions and the associated structural icing will affect wind turbines in several ways. Up to now no complete description is given to evaluate ice loads based on measurements on site. During the planning it must be ensured that site specific loads are less severe than the loads used for the design of the turbine.

#### 2.2. Aim of the Work

In the planning phase of a wind farm only standard wind measurement data is available. In a first step the duration of icing and the type of icing will be evaluated out of site measurement data. A simple and robust model will be used taking into account the marginal basis of meteorological parameters that normally are known out of the site measurements. This information will be used to simulate the aerodynamic effects and the effects caused by mass imbalances in a common simulation program to generate site specific turbine loads. The resulting loads are compared with the turbine loads under standard loading conditions.

### 3. Icing

Ice accretion is the process of ice building up on the surface of a structure. Different types of icing on structures can occur [7]. With respect to the aim of this work only two major types of ice accretion, precipitation icing and in-cloud icing are discussed.
3.1. Precipitation Icing
The ice type that results out of this type is glaze ice [8]. It will occur as a result of freezing rain (or drizzle) or accumulation of wet snow and it depends on the rate of precipitation, the wind speed and the air temperature.

3.2. In-Cloud Icing
In-cloud icing will occur when the structures considered are inside clouds and the water droplets in the air start to freeze on the structure. Rime ice is the most common type of in-cloud icing. Rime ice forms ice vanes on the windward side of the objects. This leads to eccentric loading by ice. In-cloud icing depends on the dimensions of the object exposed, the wind speed, the liquid water content in the air, the drop size distribution and the air temperature [7], [8].

3.3. Estimation of Ice Accretion
In ISO 12494 [7] different approaches are given to predict the in-cloud icing using metrological measurement data. Standard wind measurement contains only limited data. The liquid water content in the air and the drop size distribution are not known. Thus the empirical equation from the ISO 12494 standard is used. The amount of accreted rime ice at each time step can be calculated according to the equation [7]:

\[ m_i = 0.11 \cdot v \cdot T \cdot W \]  \hspace{1cm} \text{Equation 1} \]

In this equation only the wind speed \( v \) and the duration time in the in-cloud condition \( T \) in hours are taken into account. To obtain the distribution of rime ice per metre length the width of the object \( W \) is considered.

The accretion only takes place when the height of the cloud base is lower than the location of interest (in-cloud condition) and the air temperature is below 0°C and above -15°C. Following the suggestions in ISO 12494 it is assumed that the ice falls off when temperature rises above 0 °C, and that the rime ice accretion starts over again. If the water content in the air does not lead to further accretion, the ice will stay on the structure as long as the temperature does not rise above 0 °C.

To verify the rime ice accretion approach a measured time series was used. The measurement site is located 220 km north from Narbonne in France. A standard wind measurement was performed with measurement of wind speed at two heights, wind direction at one height, temperature and humidity at one height. The time series considered in this analysis consists of one month of data. January 2006 as a typical winter month is chosen. Figure 1 illustrates the temperature and the relative air humidity (as percent of saturation humidity) during the measurement period. Wind speed is displayed in Figure 2.

The scatter diagram of wind speed against temperature (Figure 3) illustrates that falling temperature is connected with falling wind speed. The lines of accreted ice types according to [7] are plotted to assist the interpretation. From the left to the right the types soft rime (\( \rho_{\text{ice}} \approx 400 \text{ kg/m}^3 \)), hard rime (\( \rho_{\text{ice}} \approx 800 \text{ kg/m}^3 \)) and glaze (\( \rho_{\text{ice}} \approx 900 \text{ kg/m}^3 \)) are separated.

45.3% of the samples are below 0°C, which is one of the conditions for ice accretion. 53.0% of the time the relative air humidity is above 95 %, which is used as the second condition for in-cloud icing. 34.5% of the time both conditions are fulfilled.

The time series is used to calculate the rime ice accretion on the standard ice-measuring device (reference cylinder, 30 mm diameter, 10 m above ground) according to ISO 12494 [7]. Figure 4 shows the calculated ice accretion. Basically there are three significant icing events in the time series. The most hazardous ice loading about the 2006-01-03 in Figure 4 also corresponds with a period of stuck wind vane due to icing, which gives some verification to the methodology. The maximum value of accreted ice mass is estimated to be about 0.92 kg/m, which results in a classification to the rime ice class ICR2 according to ISO 12494. The mean ice density is estimated by weighting the density calculated for each time step with the associated mass and then normalizing the sum by the total ice mass. Thus a value of about 670 kg/m³ is calculated. The duration of this event is approximately 90 h.
Figure 1 - Time series of the temperature (black line) and the relative air humidity (grey line) during the sample month

Figure 2 - Wind speed recalculated to 10 m above ground level during the sample month

Figure 3 - Scatter diagram of wind speed against temperature (10 min mean values) including the separation lines for different ice types
4. Ice Accretion on Wind Turbines

4.1. Tower

For the tower the ISO 12494 ICR2 classification (as obtained from the time series) is used to determine the additional ice masses and shapes. The tower is considered to act like a ‘large single member’. ISO 12494 allows calculating the ice vane dimensions $L$ [mm] and the ice masses $m$ [kg/m]. The ice mass $m$ changes with changing object width $W$ (here tower diameter) and height above ground. This is taken into account by calculating the ice mass for different cross sections at different tower heights and applying a height factor to obtain the ice mass at a certain height.

The result is graphically displayed in Figure 5 for selected tower station heights. The total ice mass results in an additional mass of about 1.4% of the tower self weight. The ice mass per unit length increases from about 26 kg/m at the bottom to about 40 kg/m at the top. The increase from bottom to top is mainly due to the application of the height factor $K_h$, which takes into account the variation of ice mass with height above terrain $H$ in metre (Equation 2).

Unfortunately no prove to this factor could be performed considering the site data as temperature is measured only at one height.

$$K_h = \exp(0.01 \cdot H) \quad [-]$$

Equation 2

Using this ice mass distribution in the eigenfrequency calculation of the turbine model the eigenfrequency of the iced tower will decrease with the increase in mass, respectively. For the considered turbine geometry and ice class the effect is only noticeable in the second eigenfrequency. The second eigenfrequency will decrease about 0.63%, which will not influence the loads in a severe way.
4.2. Rotor Blades

4.2.1. Methodology

For the rotor blades not only the wind speed will lead to an ice accretion, but also the relative wind speed due to the rotation of the blades. The geometrical shape of the rotor blade is assumed to act like a ‘slender object’ or ‘large object’ and thus the shape is approximated as a round bar.

In ISO 12494 it is suggested that different models of ice accretion should be applied for ‘slender’ or ‘large’ objects. The distinction is made above and below diameters of 300 mm. This is applied concerning the thickness of the actual blade section. The ice masses and vane length are calculated by calculating the wind speed at hub height, determining the rotational speed and calculating the effective wind speed at the blade station. Then the ice mass is estimated according to Equation 1 for each blade station. The mass is used to predict the ice vane length. The estimated ice masses and ice vane length at the different blade station length are given in Figure 6 and Figure 7.

![Figure 6](image1.png)

**Figure 6** - Predicted ice vane length (black diamonds) and blade thickness (grey triangles) over the blade length

![Figure 7](image2.png)

**Figure 7** - Predicted maximum ice mass (black diamonds) and blade mass (grey triangles) over the blade length

4.2.2. Guideline Approach

In the GL’s Wind Guideline [4] it is suggested that the mass distribution (mass/unit length) is assumed at the leading edge of the rotor blade. It increases linearly from zero in the rotor axis to the maximum value \( m_E \) at half the radius, and then remains constant up to the outermost radius. This is also
confirmed by measurements and recalculation of other authors [9], [12]. The value $\mu_E$ is calculated as follows:

$$\mu_E = \rho_E \cdot k \cdot c_{\min} (c_{\max} + c_{\min})$$

Equation 3

4.2.3. Discussion Rotor Blade Icing

The obtained masses and vane length by considering the ISO 12494 approach for the ice accretion on the rotor blades seem to be overestimated. Also the mass distribution over the blade length deviates from what was found by other authors [9], [11] and [12]. This also because the model used is based on simple empirical equations not representing the water collection of the blade geometry and surface in detail. Looking at the ice vane length it is obvious that on the rotor blade the shear force between ice and blade will lead to limited ice vane length due to the attack of the wind. This was not taken into account during the calculation. The discussion about the limitation of the ice vane length is also presented in [9], [10] and [11]. It was tried to figure out a straightforward method that can be applied on the measurement data without estimating other input values, but it turns out that the results need to be interpreted with care. Thus for the fatigue loading the ice formation according to GL’s Wind Guideline is used.

5. Fatigue Loads

The estimation of the fatigue loads is performed using a 2 MW example turbine. The turbine model is the model of a generic 2 MW example wind turbine prepared for this study. The fatigue load calculation is performed taking into account a three-blade system, with a rotor arranged on the windward side with power output limitation by blade adjustment and active yaw. All relevant parameters of a control and safety system are taken into account during the power production and idling load cases.

The fatigue loads are calculated according to GL’s Wind Guideline [4]. For the fatigue load calculation the commercial simulation software package ‘Bladed for Windows’ [13]. The modelling of rotor aerodynamics provided by Bladed is based on the treatment of combined blade element and momentum theory.

The estimation of the parameters needed for ice loading on the rotor blades by applying rules and guidelines given in the ISO 12494 on standard measurement data is difficult. Thus for the fatigue load calculation the different input assumptions are altered in a parametric study to determine the influence on the turbine fatigue loading.

5.1. External Conditions and Load Cases

The fatigue load is calculated according to DLC 1.2 of GL’s Wind Guideline. Deviating from the guideline no start-up or shutdown procedures are considered to calculate the overall fatigue loads. For fatigue load calculations a three-dimensional turbulent wind field is used. Idling below cut-in and above cut-out wind speed is considered. The discretization of the wind speed intervals (bins) was chosen with 2 m/s. The basic parameters for load calculation are assumed as for GL’s Wind Guideline class II A. Thus the annual mean wind speed is 8.5 m/s and the wind distribution is a Rayleigh type. The characteristic value of turbulence intensity at 15 m/s is 18%.

The resulting load cycles of the simulated time histories are counted with the aid of the rainflow counting method. This is performed using the wind speed distribution for a 20-year lifetime and summed up. These load spectra are converted, assuming $^{5/3}$-curve slopes of $m = 10$ (rotor blades) and $m = 5$ (other components) and a reference number of load cycles of $N_{ref} = 1.0 \times 10^7$, into damage-equivalent constant-range load spectra (DEL) for the relevant load components. The results of the fatigue load calculation including the ice load case are compared to the fatigue loads calculated according to IEC class II A using the similar wind fields to avoid differences in loading due to different characteristic of wind.
The ice load case, DLC 1.10, is simulated with a normal wind profile. The parameters of ice formation are altered (section 4.2). The basic conditions for DLC 1.10 are summarised in Table 1.

### Table 1. - Basic parameters for ice load case

| External condition                      | Value and unit |
|----------------------------------------|----------------|
| $V$ (wind speed at hub height)          | 13.0 m/s       |
| Wind conditions                         | NWP            |
| $\alpha$ (power law exponent of the wind shear) | 0.2            |
| $\phi$ (flow inclination)              | 8 °            |
| $\rho$ (air density)                   | 1.225 kg/m³    |
| $\rho_{\text{ice}}$ (ice density)      | 700 kg/m³      |
| Ice mass distribution on blades         | GL type        |
| hours per year                          | 7 days         |

5.2. Variation of Parameters

For the fatigue load calculation different effects of interest are taken into account by a parameter study. For the ice accretion on the rotor blades the following effects concerned with the ice mass are altered independently and the influence on the loads are compared separately:

- Mass imbalance (2 blades iced)
- Duration of icing situation
- Distribution of ice on the blade
- Wind speed during ice event
- Ice density / type of ice

The following Parameters have been investigated but are found to be of minor interest:

- Ice centre of gravity with respect to chord length
- Turbulence intensity of the wind during ice event

The effects concerned with the aerodynamic properties are altered independently and the influence on the loads is compared separately:

- Iced aerodynamic coefficients
- Aerodynamic imbalance

The aerodynamic effects are taken into account by changing the airfoil data of the blade sections. The effects concerned with the aerodynamic properties are also altered independently and the influence on the loads is compared separately. Therefore the original airfoil data is changed according to the suggestions in [11]. Additionally, as some of the results obtained with the changed airfoil data are not satisfying, new airfoil data is created considering the changed blade geometry due to the ice vane length using the ‘JavaFoil Application’ [14]. Aerodynamic imbalance is simulated using misalignment in blade angles.

5.3. Coordinate Systems

The two coordinate systems need for the load comparison are the hub coordinate system given in Figure 8 which has its origin at the rotor centre and does not rotate with the rotor and the tower bottom coordinate system Figure 9 which has its origin at the intersection of the tower axis and the upper edge of the foundation, and does not rotate with the nacelle.
5.4. Results
The fatigue load results are evaluated for all relevant components in the GL coordinate system (section 5.3). The different results of the parameter variation are compared with each other in order to see the influence of different ice formations on the turbine fatigue loading. The consideration of aerodynamic effects of the icing turned out to be time consuming when using standard simulation software.

The main load increase is due to the unbalance in the rotor when considering two blades iced and one free, which is a worst case consideration. This is also discovered by other authors [9], [15]. The influence of the additional mass without imbalance is without importance. A maximum load increase of 2.3 % was found. The most significant load increase is found in the direction perpendicular to the thrust force direction as the imbalance will lead to the accelerations in this direction. As the mass imbalance is modelled in the centre of the hub no effect of the mass imbalance is found on the loads for the rotor blades.

Selected results of the fatigue load calculation are given in Figure 10 to Figure 17. The DELs were compared using the following equation:

\[
\%_{\text{蒋松}} = 1 - \frac{\text{DELT}}{\text{DELnormal}}
\]

Equation 4

The load increases with the duration of the icing event (Figure 10 and Figure 11) here a linear increase is present. The load also increases with increasing ice density. The maximum ice density used in the simulations was 900 kg/m³ and it created the highest load increase for all concerned cases (Figure 12 and Figure 13). Increasing wind speed during the icing event increases the load until the wind speed is above rated wind speed (Figure 14 and Figure 15). These Figures show that the highest loads occur at rated wind speed (13 m/s).

A significant decrease in load level due to presumption of ‘iced’ aerodynamic coefficients is not found (Figure 16 and Figure 17). Manipulating the drag coefficient it was noticed that the turbine model reacts very sensitive to changes in drag coefficients, which made the implementation of the ‘iced’ airfoil data very time consuming. Also no increase in loads due to aerodynamic imbalance is found.
Figure 10 - Deviations of loads ($\delta_{N}$ slope = 5) in non-rotating hub coordinate system, dependence on duration of icing event (days/year)

Figure 11 - Deviations of loads ($\delta_{N}$ slope = 5) at tower base coordinate system, dependence on duration of icing event (days/year)

Figure 12 - Deviations of loads ($\delta_{N}$ slope = 5) in non-rotating hub coordinate system, dependence on ice density

Figure 13 - Deviations of loads ($\delta_{N}$ slope = 5) at tower base coordinate system, dependence on ice density
Figure 14 - Deviations of loads ($\delta_N$ slope = 5) in non-rotating hub coordinate system, dependence on wind speed

Figure 15 - Deviations of loads ($\delta_N$ slope = 5) at tower base coordinate system, dependence on wind speed

Figure 16 - Deviations of loads ($\delta_N$ slope = 5) in non-rotating hub coordinate system, influence of aerodynamic changes

Figure 17 - Deviations of loads ($\delta_N$ slope = 5) at tower base coordinate system, influence of aerodynamic changes

6. Conclusion

6.1. Results Summary
The estimation of the parameters needed for ice loading is possible using standard measurement data by applying rules and guidelines given in the ISO 12494. The duration of ice events and the ice masses on the standard ice measuring device have been approximated fairly well. For the tower the application of the ice classes and the estimation of the associated ice masses could be performed in a reasonable way. The ice accretion on the rotor blades, especially the ice vane length and the ice masses, lead to results that need to be interpreted carefully before applied to the fatigue load calculation.
Several types of ice loading are used for a fatigue load calculation. The main load increase is due to the unbalance in the rotor when considering two blades iced and on free, which is a worst case consideration. Load increases occur mainly at the following components (GL coordinate system):

- Hub stationary shear force (non-rotating hub Fy)
- Hub stationary vertical force (non-rotating hub Fz)
- Tower top shear force (tower top Fy)
- Tower top vertical force (tower top Fz)
- Tower base bending moment (tower base My)

Also considering the changed aerodynamic blade properties during turbine simulation is executed to take into account the influence on the loads. This included the interaction with the turbine control system during normal operation. The load decreasing effects of the changed aerodynamic blade properties is not as considerable as presumed. Thus the load increase due to mass imbalance is still present in the combined calculations. Annotated is that the modeling of the aerodynamic effects in the simulation program was very time consuming and is therefore not performed for all cases in detail. The reason for this is related to some extent in the controller characteristics.

6.2. Further Prospects

The key difficulty is the pre-estimation of the duration of icing events and the type of icing from standard measurement data. The results obtained by the procedure seem reasonable but could not be proved with measured data. Therefore special measurements, e.g. ice measurements according to ISO 12494, are suggested to get certainty about the calculation of the ice accretion.

Calculating the ice accretion on the rotor blades gives results that need some further refinement.

Modeling the aerodynamic effects, e.g. aerodynamic imbalance, proves to be time consuming and can not be implemented straight forward into the turbine model. Here the boundaries of the turbine control and the aerodynamic control need to be examined in more detail.

The blade section loads are not examined in detail, as the shape of ice formation on the blades is not altered much.

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