Assessment of Production Losses Due to Rotor Blade Icing

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Summary

A procedure for predicting long-term energy production losses of wind turbines due to rotor blade icing has been developed in the frame of the validation of a rotor blade de-icing system. The test set-up allowed an investigation under which conditions rotor blade icing appears. A key outcome is that icing of unheated rotor blades must not appear at high relative air humidity and temperatures below freezing, but the probability of blade icing is increased under such conditions. Consequently, a generalised probability matrix has been developed, which describes the probability of rotor blade icing as function of air temperature and relative air humidity. By long-term correlating site specific air temperature and wind data and correlating wind, temperature and humidity data, this matrix allows predicting the probability of rotor blade icing and to assess expected production losses due to rotor blade icing. The procedure has been successfully verified at two test sites with frequent rotor blade icing. Furthermore, the method has been applied at various sites, leading to plausible values for the frequency of blade icing and the associated production losses.

1 Introduction

The annual energy production of wind turbines can be reduced significantly by rotor blade icing. The assessment of to be expected icing losses is linked to a variety of difficulties. A methodology for the assessment of to be expected long-term icing losses at planned wind farm sites has been developed on the basis of test data as available from a validation of a rotor blade de-icing system.

2 Basis for Development of the Procedure

Data from two test wind farms, both located at sites with harsh icing conditions in the North of Sweden and the Erz Mountains in Czech Republic, form the basis for the development of the procedure for assessing energy production losses due to rotor blade icing. At both wind farms, a wind turbine of type Enercon E-82 with rotor blade de-icing system was operated adjacent to an identical turbine without rotor blade de-icing system in the strong winter 2009/2010. Rotor blade icing is detected by Enercon turbines on the basis of comparing the actual power output and rotor blade angle with target values for the actual wind speeds as trained under non-icing conditions for each individual turbine. An analysis of events, where rotor blade icing was indicated by this system, proofed being reliable, showing about 10 times more frequent appearance of rotor blade icing at the machines without blade de-icing system compared to the adjacent turbines with de-icing system. Enercon turbines are switched off once rotor blade icing is detected.

The test turbines where equipped with traceably calibrated sensors for air temperature and relative air humidity. Furthermore, ice sensors were used on the nacelles of some test turbines. This test set-up allowed investigating under which atmospheric conditions rotor blade icing appears.

3 Appearance of Rotor Blade Icing

The conditions for rotor blade icing of the turbines with and without rotor blade de-icing system have been analysed. The results presented here are related to the test turbines without rotor blade de-icing system. It turned out that cold air temperatures combined with high relative air humidity do not necessarily lead to rotor blade icing. However, the combination of cold air temperatures and high relative air humidity increases the probability of rotor blade icing. Consequently, a matrix, which describes the probability of rotor blade icing as function of air temperature and relative humidity, has been calculated for both tests sites. As the matrices of the two test sites showed much similarity, a generalised matrix has been developed as follows:

- The probability of rotor blade icing for matrix elements covered by both test sites has been averaged for the generalised matrix.

- The probability of rotor blade icing for matrix elements covered only by one test site has been overtaken for the generalised matrix.
- The probability of rotor blade icing for matrix elements covered only by one test site has been overtaken for the generalised matrix.
- For matrix elements not covered by the test conditions, the probability of rotor blade icing has been overtaken conservatively from adjacent matrix elements covered by the test conditions as shown by the blue numbers in Table 1.

The so derived generalised probability matrix is believed being representative for all wind turbines without blade de-icing or blade icing prevention system.

One important finding is that, in contrast to an often seen belief, blade icing appears with high probability also at very low air temperatures (below -10°C).

The width of the classes of the probability matrix has been carefully tested. A width of 2°C and 5 % relative air humidity turned out being sufficient for the purpose of assessing the probability of rotor blade icing.

T/H	[%]	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5	62.5	67.5	72.5	77.5	82.5	87.5	92.5	97.5
[°C]																					
-29		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
-27		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0
-25		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0
-23		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	100.0	100.0
-21		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	27.1	27.1	27.1	27.1	27.1	8.3	100.0	100.0
-19		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	61.5	61.5	61.5	61.5	61.5	44.6	56.1	100.0
-17		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.3	28.0	0.0
-15		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	44.1	66.5	80.0
-13		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0	25.8	44.7	86.6
-11		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	42.2	41.8
-9		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.6	1.1	4.7	3.9	42.2	51.6
-7		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	1.2	8.0	8.7	19.3	14.5	29.7	52.3
-5		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	20.7	27.7	14.9	1.6	5.3	7.7	43.4
-3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	38.8
-1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	45.8
1		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	6.1
3		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	0.3
5		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.2	0.0	0.2	0.0	0.4
7		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0
9		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.4	0.0
11		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 1: Probability of rotor blade icing as function of air temperature and relative air humidity in percent. The conditions illustrated by black numbers were covered by the test data. The blue numbers represent suggested interpolations and extrapolations of the probabilities (same values as shown for -29°C and +25°C suggested to be used below -30°C and above +26°C, respectively).

4 Prediction of Long-Term Probability of Rotor Blade Icing and Losses due to Rotor Blade Icing

4.1 Prediction of Long-Term Probability of Rotor Blade Icing

The long-term probability of rotor blade icing for a specific wind farm site can be assessed based on long-term data of the air temperature and relative humidity by calculating the site specific joint probability matrix of air temperatures and relative air humidity with the same class definitions as applied for the generalised probability matrix shown in Table 1. The sum over products of the matrix elements of this probability matrix of air temperatures and relative air humidity and the associated matrix elements of the generalised probability matrix for rotor blade icing (Table 1) is the site specific probability of rotor blade icing (see illustration in Figure 1).

The air temperature and relative air humidity is normally measured at planned wind farm sites in the frame of wind resource assessments for typically one or a few years. However, the appearance of icing conditions can be very different from year to year. Thus, the air temperature and relative air humidity measured at a wind farm site must be long-term correlated for the assessment of the probability of rotor blade icing. The long-term correlation of site specific air temperature data by using long-term air temperature data from nearby long-term stations or reanalysis data is in most cases unproblematic, as the site specific air temperature normally correlates well with regional air temperature data. However, this is not the case for the relative air humidity. The relative humidity measured at a wind farm site can often hardly be correlated to regional data as available form long-term stations. This problem can be overcome by the following scaling method:

a) The probability of rotor blade icing is first calculated for the period covered by the measurements at the wind farm site and based on the air temperature and air humidity as measured at the wind farm site.
b) A correction of the air temperature from regional data (long-term data set) to the air temperature measured at the wind farm site is established from the common data period. The probability of rotor blade icing is then calculated for the period covered by the measurements at the

wind farm site based on the corrected air temperature from regional data and based on the uncorrected air humidity from regional data.

c) The probability of rotor blade icing is further calculated for the long-term period covered by the regional (long-term) data based on the corrected air temperature from regional data and based on the uncorrected air humidity from regional data.

d) The result gained from step c) is scaled by the ratio of results gained from step a) and b) in order to assess the long-term site specific probability of rotor blade icing (Figure 2).

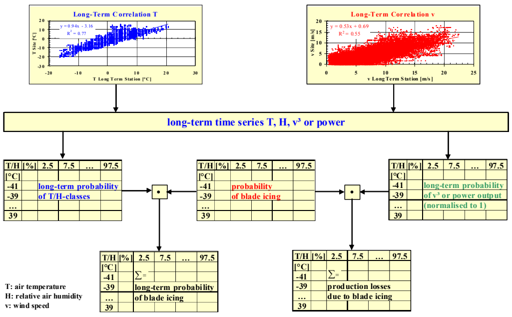

Figure 1: Illustration of procedure for predicting the long-term probability of rotor blade icing and production losses due to rotor blade icing on the basis of meteorological measurements at a wind farm site and regional long-term data.

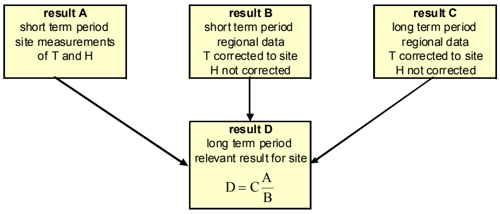

Figure 2: Illustration of scaling method for overcoming the problem of poor correlation of site specific air humidity and humidity data from regional long-term data sets.

4.2 Prediction of Long-Term Production Losses due to Rotor Blade Icing

The calculation of long-term production losses due to rotor blade icing is based on a classical MCP of the wind speed as measured at the wind farm site (MCP=Measure Correlate Predict). By means of MCP, a long-term time series of the wind speed at the wind farm site is assessed. This wind speed time series, together with a long-term time series of air density, is converted to a time series of wind turbine power output by utilising a power curve, or a long-term time series of the wind energy density is calculated based on the wind speed and air density time series. The simulated power output / wind energy density is then classified according to the air temperature and relative air humidity using the same data classes as implemented in the generalised probability matrix for rotor blade icing shown in Table 1. The mean values of the simulated power output / wind energy density per data class are calculated. This matrix is multiplied element by element with the long-term joint frequency distribution of air temperature and relative air humidity (blue matrix in Figure 1). The product in each matrix element is normalised by the sum of products of all matrix elements, i.e. the sum over all normalised products is then unity. This results in the probability matrix of energy yields (green matrix in Figure 1). The sum over products of the matrix elements of this probability matrix of energy yields and the associated matrix elements of the generalised probability matrix for rotor blade icing (red matrix in Table 1) is the percentage production loss due rotor blade icing (see illustration in Figure 1).

Also for the assessment of long-term production losses due to rotor blade icing, the problem of poor correlation of site specific air humidity data with regional long-term data must be overcome by applying the scaling method illustrated in Figure 2

5 Verification of Procedure

The model for predicting the probability of rotor blade icing and blade icing losses has been verified with the data from the two test wind farms in the North of Sweden and in the Erz Mountains in Czech Republic. The true production losses due rotor blade icing were here evaluated by comparing the production of the turbine with blade de-icing system with the adjacent turbine without blade de-icing system. The results are shown in Table 2 together with the results gained from the prediction model.

The observed probability of blade icing in the winter 2009/2010 agrees well with the predicted probability. The agreement in terms of icing losses is considered as being reasonable.

feature	**unit**	**reality**	**model**
North of Sweden			
standstill due to blade icing	[%]	20.4	18.6
relative gain in production by blade heating system	[%]	33.8	26.0
Erz Mountains, Czech Republic			
standstill due to blade icing	[%]	24.7	23.6
relative gain in production by blade heating system	[%]	25.7	29.0

Table 2: Real and modelled probability of rotor blade icing at the two test sites in the winter 2009/2010. Instead of production losses due to blade icing, the gain in production reached by Enercon's blade heating system has been assessed based on real data and modelled analogous to the above approach.

6 Exemplary Long-Term Results

Some exemplary results of the application of the model for predicting losses due to rotor blade icing are shown in Table 3. At those exemplary sites where wind farms are operated, the results mostly agree well with experience from operating of the wind farms.
Another result of this analysis is that the percentage of blade icing can vary significantly from the percentage of production loss due to blade icing, depending on whether blade icing conditions appear more frequently at low wind speeds or high wind speeds.

Site	**Probability Blade Icing**	**Production Losses**
[-]	[%]	[%]
Netherlands	0.6	0.2
Fritzlar, Centre of Germany	2.5	0.9
Switzerland 1600m ASL	6.5	6.0
Black Sea, Ukraine	4.1	6.4
Winnipeg, Canada	9.0	8.8
Switzerland 1200m ASL	9.9	10.0
Erz Mountains, Czech Republic	9.2	10.3
Switzerland 1300m ASL	8.9	11.3
Dragaliden, North of Sweden	13.7	13.0

Table 3: exemplary results for different sites

7 Conclusions

- Even at high air humidity and temperatures below freezing point, rotor blade icing appears with limited probability.
- A generalised matrix has been developed, which describes the probability of rotor blade icing as function of air temperature and relative air humidity. This matrix is believed being applicable for all turbines without blade de-icing or blade ice protection system.
- Based on this matrix, predictions of the probability of blade icing and the associated production loss is possible for virtually any site. The method provides at least an indication of to be expected standstills and losses due to blade icing.
- In contrast to the general belief, rotor blade icing appears also at very low air temperatures.