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The effect on noise emission from a wind turbine due to ice accretion on rotor blades

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Summary

Swedish EPA noise guide-lines suggest that equivalent A-weighted noise levels must not exceed 40 dBA at residents. In the planning of new wind farms and their location it is hence crucial to estimate the disturbance it may cause to nearby residents. Wind turbine noise emission levels, which are used for calculation of noise immission at nearby dwellings, are guaranteed by the wind turbine manufacturer only under ice-free conditions or for clean blades. If the real emission levels, for some time periods, are higher than the guaranteed values an increased risk of disturbance can occur.

The purpose of the project is to evaluate the effect on wind turbine noise emission due to ice accretion. This is done by trying to quantify the ice accretion on the rotor blades and correlate it to any change in noise emission. The rotor blades are to be considered the primary noise source. Ice accretion on rotor blades is consequently assumed to be the main influence on noise character.

A field study is performed in two parts; as a long-term measurement based on the method out-lined by IEC 61400-11, and as a short-term measurement in strict accordance with IEC 61400-11. With this outline of measurements, noise emission levels for the case of icing conditions and ice-free conditions (reference conditions) as well as background noise levels are obtained.

Analyses are performed, which set out to correlate ice measurements with wind turbine performance and noise emission. Data reduction procedures are performed according to IEC 61400-11.The apparent sound power levels are evaluated. The analyses are performed both for the case of icing conditions and for the case of ice-free conditions. A statistical evaluation of icing events is carried out for measured free-field sound pressure level (SPL).

The results show that ice accretion on wind turbine (rotor blades) may lead to drastically higher noise emission levels. The sound power levels according to IEC 61400-11 show an average increase of 10.6 dB at 8 m/s. However, increases are shown to occur at all wind speeds from 6 m/s to 10 m/s. These increases may be caused by very small amounts of ice accretion. Statistically, increases in momentaneous (1-minute averages) SPL of 8 dB or higher, relative ice-free conditions, are to be expected 3 % of the time during the winter or 1 % of the time during one year for the wind turbine studied.

Taking into account the guide-line value of 40 dBA at residents, as is recommended by Swedish EPA, the increased levels of wind turbine noise due to

(the risk) of ice accretion may force the power production to a halt to avoid disturbances for these time periods. Another solution could be to install a deicing system, which would most likely reduce this problem to some extent.

1. Introduction

1.1 Background Although the benefits of wind power being many, and with the environmental aspect perhaps being the largest, there are also consequences. Wind turbine noise, and its effect on physical and mental health is frequently debated. Swedish EPA noise guide-lines have been established, suggesting that the equivalent A-weighted noise level (caused by wind turbines) may not exceed 40 dBA at residents. To keep wind turbine noise levels from exceeding 40 dBA, different types of measurements and calculations may be performed before and after a wind farm has been built:

- immission measurements (at resident)
- emission measurements (at wind turbine)
- immission calculation (noise propagation calculation)

The first and second types require *in situ* measurements, thus there must be one or more wind turbine(s) acting as measurement object(s). These may therefore only verify actual noise levels. The method of measuring noise emission, is out-lined in international standard IEC 61400-11 [IEC].

The third type aims to evaluate noise levels at a resident by calculating how the noise propagates. Calculation models used are often considering the atmospheric conditions (wind direction and speed, atmospheric pressure, air humidity etc) as well as the topography surrounding an actual or an imaginary wind turbine. This may require an in situ measurement to verify the actual noise emission, but may also be calculated by using the guaranteed noise levels (sound power levels) provided by the wind turbine manufacturer. The latter proves to be important when planning new wind farms and the location of the individual wind turbines.

The wind turbine noise levels (sound power levels) provided by the wind turbine manufacturer, is often only guaranteed under ice-free conditions or for clean blades. This is most likely because of the risk of higher noise levels, which would exceed the guaranteed levels for example for icing conditions. Since the guaranteed noise levels may have been used when planning the location of a wind turbine/farm, ice accretion on wind turbine may lead to increased wind turbine noise levels at nearby residents, exceeding 40 dBA for these time periods.

1.2 Purpose and limitations The purpose of the project is to evaluate the effect on wind turbine noise emission due to ice accretion. This is done by trying to quantify the ice accretion on rotor blades and correlate it to any change in noise emission. The rotor blades are considered to be the primary noise source. Ice accretion on rotor blades is hence assumed to be the main influence on noise character. The project has the following limitations:

- 1/3 octave band analyses are not part of this project. Neither are any other frequency analyses.
- Analyses of tonality are not part of this project.
- Analyses of the immission of wind turbine noise at longer distances from the wind turbine are not part of this project.

1.3 Method A field study is performed in two parts. These are:

- a long term measurement based on the method *out-lined* by IEC 61400-11
- a short term measurement in *strict accordance* with IEC 61400-11

The goal is to obtain noise emission levels for the case of icing conditions and ice-free conditions (reference conditions) as well as background noise levels. By gathering data during the field study, an analysis sets out to correlate ice measurements with wind turbine performance and noise emission. Measured sound pressure levels (SPL) of wind turbine noise are corrected for the influence of background noise. The apparent sound power levels are evaluated. This is performed for the case of icing conditions as well as for the case of ice-free conditions. A shorter statistical evaluation of icing events is carried out.

2. Field Study

A long-term noise measurement set up *similar* to that of IEC 61400-11, and which can withstand harsh weather conditions, enables a study of the entire icing process, from full power production to a standstill. If weather conditions allow, ice accretion on wind turbine, and the rotor blades in particular, can cause severe losses in the power production which may drop from maximum to zero in a matter of hours.

Complementary short-term noise measurements are carried out in *strict accordance* with IEC 61400-11. The purpose is to get a reference of ice-free conditions as well as verification and validation of the long-term measurement data which are performed on a stand 2 m above ground. Both short-term as well as long-term measurement use the same measurement position relative to wind turbine, and differ only in instrumentation setup (see Sections 2.4 and 2.5).

The use of an ice detector system which makes concurrent (time synchronized) measurements parallel to the noise measurements allows for an objective quantification of the ice accretion. They do not actually measure the amount of ice on the rotor blades themselves. Although an assumption is made that there exists a strong correlation between the ice detector indications and the actual amount of ice on the rotor blades.

2.1 Measurement object The measurement object is a Vestas V90 wind turbine. This turbine features a horizontal axis, and has a maximum electric power production capacity of 1.8 MW. The maximum production capacity of a Vestas V90 wind turbine is normally 2 MW but the measurement object has been regulated to a production maximum of 1.8 MW. Between the two types, it is only a matter of differences in software configuration. Some basic information about the Vestas V90 wind turbine is given in Table 2.1. The manufacturer guaranteed sound power level of this perticular wind turbine is 104 dBA, this is for clean and ice-free rotor blades.

Vestas V90-1.8 MW (2.0 MW)	
Rated (max.) output power	1.8 MW
Cut-in wind speed	4 m/s
Rated wind speed	12 m/s
Cut-out wind speed	25 m/s
Lowest operating temperature	-20 °C
Power control type	Active
Axis orientation	Horizontal

Rotor diameter	90 m
Nominal rpm	14.5 rpm
Operational interval rpm	9.3-16.6 rpm
Tower height	95 m
Total height	140 m

Table 2.1 Concise specification of a Vestas V90 wind turbine.

2.2 Measurement site The topography of the measurement site in the nearest 1 km is hilly, however closer to the measurement object it is more flat. Under normal conditions the site features a mixture of low pine forest and/or bushes, lower vegetation (rough grass) closer to the measurement object. During measurements, however, the site is covered in approximately 1.5 m of snow with very smooth surface, covering smaller bushes and trees (see Figures 2.1 and 2.2). No sand or water surfaces. The measurement site roughness length is set to 0.05 m. There are no larger reflecting structure(s) nearby. Since snow has covered the trees, background levels due to vegetation noise is expected to be low.

2.3 Measurement position From a statistical point of view, the dominating wind direction for the wind turbine of interest is from the north-west. Converted into degrees (°), with north being the reference (0 °), this wind direction would correspond to 315°. Hence, the measurement position is chosen to be south-east of the wind turbine. The basic layout of the measurement position is displayed in Table 2.2.

Horizontal distance to turbine, R_0	138 m
Slant distance to turbine, R_1	163 m

Table 2.2: Measurement layout parameters, notations according to IEC 61400-11.

2.4 Long-term wind turbine noise measurement As previously mentioned, the acoustical measurements consist of two separate measurement setups. To gather long-term noise data a Sigicom Infra Master system logs the SPL in the measurement position. For a time period starting on December 1 2011 and ending on March 23 2012, noise data are logged continuously as:

- equivalent A-weighted sound pressure level (SPL), L_{Aeq} (dBA), in 1-minute (time) averages as a total of 163,140 data points

The long-term measurement setup is displayed in Figure 2.4. A microphone is mounted on a stand, approximately 2 m above ground, and is connected to an Sigicom Infra Master system which logs the measured SPL data. A primary (cell foam) and a secondary (Rycote) wind screen is used. Both are of spherical shape. The influence of the wind screens (primary and secondary) on the measured SPL is recorded to be around −0.8 dB.

2.5 Short-term wind turbine noise measurement The short-term noise measurement is carried out in strict accordance with international standard IEC 61400-11. Of interest is the A-weighted SPL (dBA) at reference position. The short-term measurement is carried out during a time period starting on February 20 2012 and ending on February 23 2012. The short-term measurement logs data as:

• equivalent A-weighted sound pressure level (SPL), L_{Aeq} (dBA), 1-second (time) averages as a total of 4,166 data points (1-minute averages)

The short-term measurement setup, and its immediate surroundings, is displayed in Figure 4.1.5. As for the long-term measurement, the influence of the wind screens (primary and secondary) on the measured SPL is recorded to be around -0.8 dB.

Figure 2.1: Long-term noise measurement setup and the immediate surroundings. The Sigicom Infra Master system is covered by snow and is not visible.

Figure 2.2: The short-term measurement setup and the immediate surroundings. A photo of the microphone and wind screens on the measurement board, the microphone is connected to a Norsonic AL140 sound level meter.

2.6 Background noise measurement Background noise measurements are performed via the long-term measurements. The measurement object has for various

reasons been at standstill, which enables for extraction of background noise data during these time periods.

2.7 Wind turbine production data Along with the noise measurement data, concurrent (time synchronized) wind turbine data are provided by wind turbine control system as a continuous log of wind speed and direction at rotor hub, electric power production and rotor rpm. These data along with a so called power curve (see Figure 3.1), provided by the wind turbine manufacturer, establishes a relation between noise emission and power output. The wind turbine data are

- measured (active) electric power, P_m (kW)
- wind speed measured by the nacelle anemometer, V_H (m/s)
- wind direction, θ_{nacelle} (°)
- rotor rpm3, n_{rotor} (min^{-1})

These data are available in both 1-minute and 1-second averages, to comply with the two different measurements covered in Sections 2.4 and 2.5.

2.8 Ice data Ice and temperature data are provided by a weather mast located approximately 70 meters from the measurement object. The measurements are performed continuously at a height of 58.3 meters above ground. Data are logged in 10 minute averages. The data contain:

- ice accretion data, m_{ice} (g)
- temperature data, T_C, T_K (°C, K)

Ice data is registered by a Combitech IceMonitor. It consists of a vertical metal rod, which at its base is mounted on a weight/pressure transducer. The rod is subject to icing when weather conditions allow, and may rotate freely around its vertical axis. As ice accretes on one side of the rod, it is possible for the wind to make it rotate. The bearing is electrically heated for a constant temperature of 1°C. Table 2.3 presents the specifications of the IceMonitor.

Sensor surface area	0.05 m^2
Measuring range	0-50 kg or 0-100 kg
Accuracy	±50 g
Lowest operating temperature	-40 °C

Table 2.3: Combitech IceMonitor specifications.

2.10 Weather data Weather conditions, such as atmospheric pressure and air temperature, effects the performance of wind turbines. Hence, [IEC 61400-11] suggests a standardization of the measured wind speed with respect to both these parameters to reference conditions. A weather station near the measurement site, provides long-term data of the atmospheric pressure and the relative air humidity.

The data contain:

- atmospheric pressure, p (kPa)
- relative air humidity, (%)

3.0 Analysis

To enable processing of large amounts of measurement data, the analysis is performed solely in MATLAB. Table 3.1 displays the imported raw data types, along with their respective notations (according to IEC 61400-11) and units.

Measurement data type	Notation	Unit	Avg.time
Time	t	min, s	1 min, 1s
Equivalent A-weighted sound pressure level (SPL)	L_{Aeq}	dBA	1 min
Measured active electric power	P_m	W	1 min
Wind speed at hub height	V_H	m/s	1 min
Nacelle direction	$\theta_{nacelle}$	°	1 min
Rotor rpm	n_{rotor}	min^{-1}	1 min
Ice accretion	m_{ice}	g	10 min
Air temperature	T_C, T_K	°C, K	10 min
Atmospheric pressure	p	hPa	10 h

Table 3.1: The raw data types imported to and analyzed in MATLAB.

3.1 Time synchronization To time synchronize the different kinds of data, adjustment to the same averaging times is necessary. Table 3.1 shows the averaging times of the different kinds of measurement data before treatment. The target averaging time is 1 minute. The data points are assigned a certain date and time, which indicates the end of an averaging time period.

The measurement data which have longer averaging times than the target time of 1 minute, is treated with linear interpolation to fill out empty time points. Since some of the SPL data, L_{Aeq}, have shorter averaging times than the target time, these need to be adjusted by logarithmic averaging.

The data type series are checked to determine the earliest and the latest common time points for which there is a complete set of data. The redundant, incomplete, data are removed and the time synchronized data are compiled into matrix form.

3.2 Measured electric power and wind turbine power curve According to IEC 61400-11, there exists a strong correlation between the measured electric power and the measured sound pressure level (SPL), and hence the sound power of the wind turbine, in the power production range of 5 – 95 % of rated power. For the measurement object, having a rated power of 1.8 MW this corresponds to

- a measured electric power, P_m, of 90 – 1710 MW

Time periods of the wind turbine not running, may be used to evaluate background noise levels.

The wind turbine power curve holds the correlation between the wind speed at hub height and the electric power production. The standard power curves of a Vestas V90-2.0 MW, along with the power curve of the measurement object, a Vestas V90-1.8 MW, are shown in Figure 3.1. The latter is used in the subsequent analysis. The power curves are provided by the wind turbine manufacturer (Vestas) as discrete values at integer wind speeds. To find points on the power curve in-between the discrete values, a linear interpolation is performed.

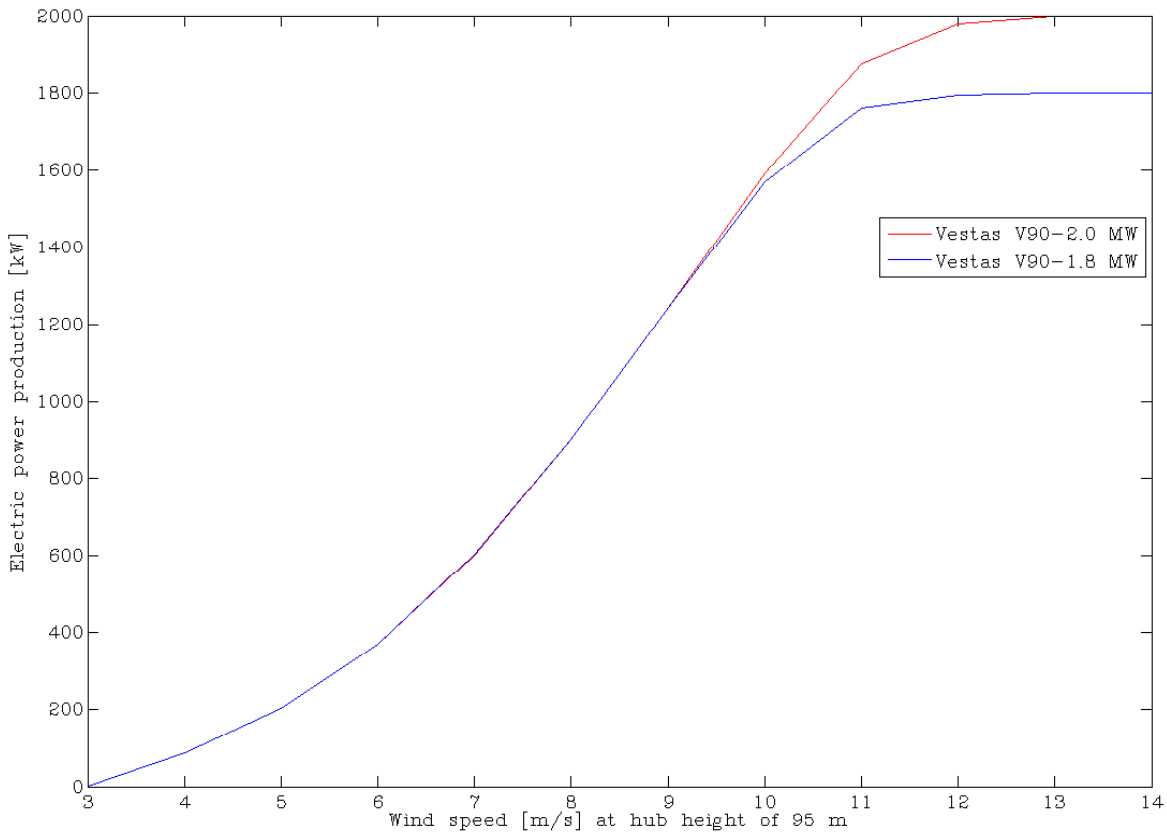

Figure 3.1: Power curves of Vestas V90-2.0 MW and Vestas V90-1.8 MW.

3.3 Wind direction, wind speed and binning As partly discussed in Section 2.3 the wind direction, according to IEC 61400-11 and the measurement position chosen in the field study, is optimally 311 ± 15°.

In accordance with IEC 61400-11, for the cases of the turbine actively producing electric power wind speed is binned at around integers from 6 to 10 m/s.Each bin is set to be 1 m/s wide.

Wind speed bin, *k*, (m/s)	Wind speed range (m/s)
$k = 6$	$5.5 \leq V_H < 6.5$
$k = 7$	$6.5 \leq V_H < 7.5$
$k = 8$	$7.5 \leq V_H < 8.5$
$k = 9$	$8.5 \leq V_H < 9.5$
$k = 10$	$9.5 \leq V_H < 10.5$

Table 3.2: Wind speed bins and the corresponding wind speed range. Wind speeds at 10 meters height.

3.5 Wind sensitivity ratio As previously mentioned, ice accretion on wind turbine rotor blades may decrease its performance, resulting in power production losses of various magnitudes. This problem is commonly referred to as a degradation of the wind turbine power curve. A degraded power curve means that the measured electric power production is less than expected taking into account wind speed and other atmospheric conditions at the time of measurement. Hence, the quotient between measured electric power, P_m, and power production under reference conditions, P_D may be a good indicator of degraded power production, P_m / P_D.

By using the standard power curve for a specific wind turbine together with the measured electric power production, one may obtain the corresponding wind speed under reference conditions. If taking into consideration the air temperature and atmospheric pressure at the time of the measurement, and by utilizing the wind speed correction according to IEC-61400-11, one may compare the performance of the wind turbine from an atmospheric conditions point of view.

For the purposes of this study, the wind sensitivity ratio (WSR) is introduced as V_H / V_n, where V_n is the measured wind speed at hub height and V_H is the wind speed at hub height derived from the standard power curve (corresponding to P_m) standardized to the atmospheric conditions at the time of the measurement.

V_H / V_n < 1	• Wind turbine producing below normal rate
V_H / V_n = 1	• Wind turbine producing at normal rate
V_H / V_n > 1	• Wind turbine producing above normal rate

Table 3.3: Simplified interpretations of the wind sensitivity ratio (WSR).

3.6 Analysis of apparent sound power level The analysis of the equivalent A-weighted SPL data may be separated into three categories, depending on the type of investigation:

- Turbine operating under ice-free conditions
- Turbine operating under icing conditions
- Turbine not operating - background noise

The measured equivalent A-weighted SPLs are corrected for the influence of background noise according to IEC 61400-11. Since the difference is greater than 6dB, this is performed by logarithmic subtraction. Further, the SPL is corrected for the influence of the wind screens (primary and secondary), see Sections 2.4 and 2.5. The apparent sound power levels for each wind speed bin are calculated according to IEC 61400-11. The SPL measured during the long-term measurement, under approximate free-field conditions, are correlated to those measured during short-term measurements, with the microphone on a measurement board, and has for the calculation of noise emission levels been adjusted by a factor to be in accordance with IEC 61400-11.

4.0 Results & Discussion

4.1 Difference in apparent sound power levels As the purpose of the project, the effect on noise emission from wind turbines due to ice accretion on rotor blades is calculated. This is done by using the long-term measurement data, acquired by using a Sigicom Infra Master system. These measurement data contain only the equivalent A-weighted sound pressure level (SPL). Hence, no frequency data are available.

Various filtering criteria are applied to non-acoustic data to enable an evaluation of the ice accretion on the wind turbine. Further, the correlations between the measured data are investigated. Subsequently, SPLs are determined for time periods of icing conditions, as well as for ice-free conditions. It is assumed that during the long-term measurements the circumstances are unaltered/identical regarding

- Measurement equipment, setup and position
- Measurement site (background noise, reflecting objects etc)
- Measurement object (without changes to configurations etc)

These assumptions enable a simple subtraction of apparent sound power levels between time periods with icing conditions and time periods with ice-free conditions. This is believed to be the most accurate calculation, regarding the circumstances of the measurement. Section 3.6 provides the measurement data. Table 4.1 shows the resulting difference in apparent sound power levels. It shall be noted that these sound power levels are evaluated only for data in accordance twith IEC 61400-11 regarding wind direction.

Results	Bin, *k*, (m/s)				
	6	7	8	9	10
$L_{WA,k}$ Ice-free conditions	100	100.2	100.3	100.3	100.2
$L_{WA,k}$ Icing conditions	109.4	110.7	110.9	110.0	108.2
Difference (dB)	9.4	10.5	10.6	9.7	8.0

Table 4.1: The difference in apparent A-weighted sound power level due to ice accretion on wind turbine (rotor blades).

4.3 Statistics To determine the possibility of higher measured SPL of 50−65 dBA, an analysis is performed using histograms for the data from the long-term measurement, free-field conditions. This analysis includes all data collected during the long-term measurements, including data for wrong wind directions according to IEC 61400-11. For ice-free conditions the corresponding value is approximately 47 dBA, which equals a noise emission level around 100 dBA when analyzed according to IEC 61400-11. If evaluating over the entire long-term measurement period, and since a single data point represents one minute of measurement time (averaging time) the results may be converted into percentile time data. Table 4.2 displays the results.

Range of measured SPL	# of data points	% of total # of data points
Measurement time	156800	100 %
0 dBA to 65 dBA	86777	55.3 %
50 dBA to 65 dBA	16089	10.3 %
55 dBA to 65 dBA	4283	2.73 %
60 dBA to 65 dBA	741	0.47 %

Table 4.2: Statistics of higher noise levels during the long-term measurement, when the wind turbine is running.

If assumed that the long term measurement period equals winter-time, and that all icing occurrences appear during winter-time, then for an entire year one would expect noise levels of 60 dBA or higher during 0.1% of the time, and 55 dBA or higher during 0.8% of the time.

4.4 Case study January 18-19, 2012 As an example of a short-term study of an icing event, January 18-19, 2012 is an excellent choice. During just a few hours the wind turbine (measurement object from Section 2.1) goes from a maximum production rate to a standstill as the ice accretes. Simultaneously, the measured equivalent A-weighted SPL increases while the wind sensitivity ratio (WSR) decreases (see Figure 4.1).

This show that very high noise levels of around 60 dBA SPL is possible for a relative increase of ice of only 200 g. As the wind turbine approaches a standstill, noise levels are as high as 65 dBA. Also evident is the behavior of the WSR for ice-free (around unity), as well as for icing conditions (well below unity). Further, one may conclude that the correlation between IceMonitor indication and measured SPL proves to be stronger for short-term measurements of icing events.

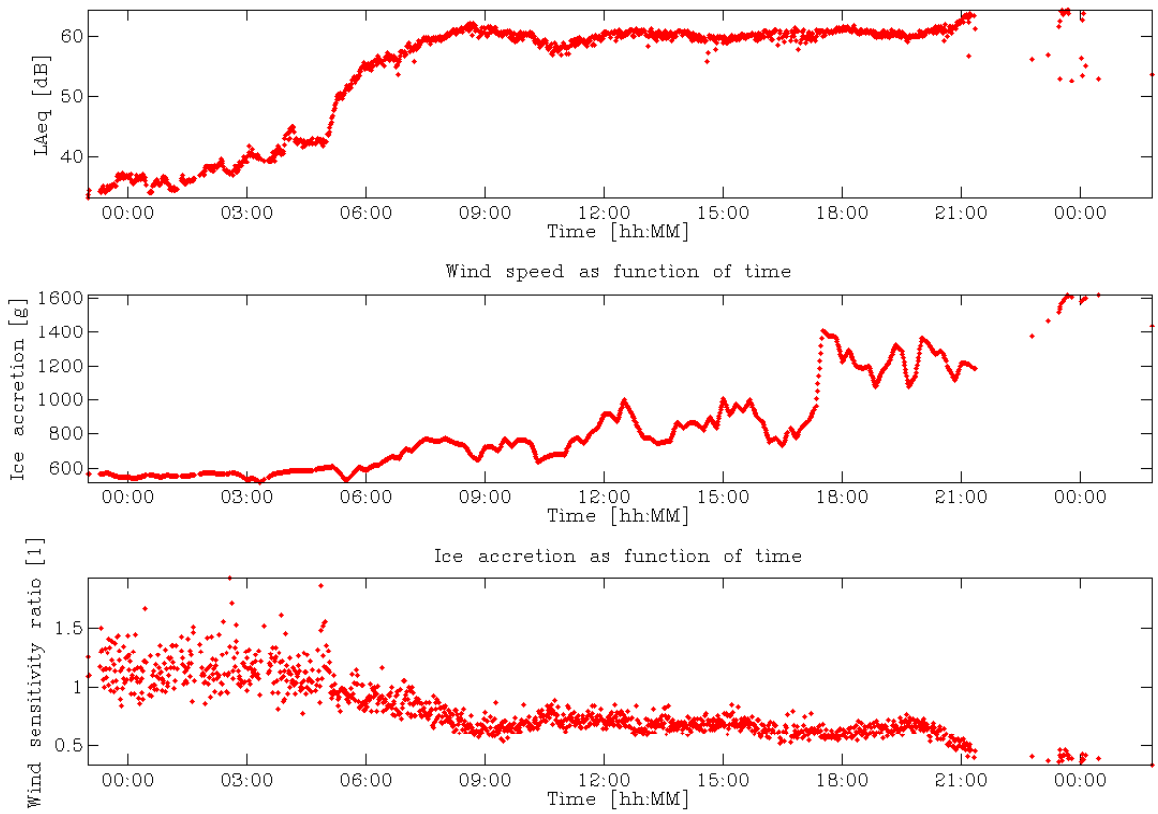

Figure 4.1: Noise emission, ice accretion and wind sensitivity ratio as function of time during an icing event of January 18-19, 2012. Ice accretion, as indicated by IceMonitor, is to be interpreted as a relative scale.

5.0 Conclusions

From the results presented in Section 4, one may conclude the following:

1. Ice accretion on wind turbine (rotor blades) may leads to drastically higher noise emission levels compared to the case of normal, ice-free wind turbine running conditions. These can result in an average increase of around 10 dB for all wind speed bins from 6 m/s to 10 m/s. In severe icing conditions an increase of noise emission of up to around 18 dB may occur, for small periods of time. This is however, associated with large amounts of ice, which usually leads to a production standstill.

2. Occurrences of higher levels of noise, in the range of 50 to 65 dBA SPL, are not common. If assuming that all wind turbine icing events have been registered during long-term measurement, noise levels exceeding 50 dBA are to be expected 10,3% of the time during the winter. This corresponds to 3% of the time during one year.

3. Taking into account the guideline value of 40 dBA SPL at residents, as is recommended by Swedish EPA , the increased levels of wind turbine noise under icing conditions may force the power production to a halt to fulfill the noise limits set by the EPA.

References

IEC. IEC 61400-11 *Wind turbine generator systems – Part 11:Acoustic noise measurement techniques.* Geneva, Switzerland : International Electrotechnical Commission, 2006-11.