6th International Conference
on
Wind Turbine Noise
Glasgow 20-23 April 2015

Icing of wind turbines and the effect on noise – Long-term measurements

Paul Appelqvist, ÅF Infrastructure, Frösundaleden 2A, SE-16999 Stockholm. E-mail: paul.appelqvist@afconsult.com

Peter Arbinge, ÅF Infrastructure, Frösundaleden 2A, SE-16999 Stockholm. E-mail: peter.arbinge@afconsult.com

Summary

Initial results show good agreement with previous studies on the topic. The final results from the measurements are to be ready early spring 2015, and finally reported in the summer of 2015.

1. Introduction

1.1 Background The project is a continuation of the work presented in the master's project thesis *4B1015 Master's Project in Technical Acoustics - The effect on noise emission from wind turbines due to ice accretion on rotor blades*, which was a collaboration between ÅF and the Royal Institute of Technology during 2011 and 2012.

The project is a part of the Swedish Energy Agency's (SEA) research program *Wind power in cold climate* and financed by the SEA, ÅForsk (ÅF's foundation for research and development) and ÅF-Infrastructure AB.

1.2 Purpose and limitations The project aims to further investigate the correlation between wind turbine (WT) noise emission and ice accretion on its rotor blades. Three main objectives can be distinguished:

- Further verification of increase in noise emission by additional measurements on different WT types and locations (1). Also, the noise frequency characteristics are studied.
- Quantification of the effect of passive de-icing systems on WT noise emission (2)
- Investigating the sound propagation in cold climate over greater distances, up to 800 – 1000 m from the nearest WT in the wind farm, equal to 40 dBA equivalent SPL (3). This is to evaluate the fulfillment of the WT noise immission guideline value, as suggested by the Swedish EPA, during icing events.

1.3 Method Long-term sound measurements are performed during 15 months (starting in December 2013) at four different wind farms in the north, middle and south of Sweden. The wind farms have different WT types of which two has passive de-icing systems. This enables investigations of WT/site-specific differences as well as regional differences. The locations are known to be having occurrences with icing during winter time, most often in January – March, sometimes leading to longer periods of production losses.

The long term measurements are performed in both sound emission measurement positions, based on the method out-lined by IEC 61400-11, and in sound immission measurement positions 800 – 1000 m from the nearest WT.

The sound data obtained by the long term measurements is time-synchronized with other data such as production data from nearest WT (or entire wind farm), including active power production, wind speed, wind direction, rotor RPM, rotor pitch angle etc., as well as weather data such as temperature, temperature gradient, atmospheric pressure and air humidity.
All data is imported into MATLAB and is analyzed using different filtering criteria.
By doing this it is possible to distinguish time periods with icing and correlate these to WT performance and noise emission

2. Field Study

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. Two different measurement setups are used, see table below. Pictures of the measurement setup for one immission point and one emission point is presented in figure 1-2.

Specification/parameter	Norsonic System	Sigicom Infra System
Time resolution	1 second	5 second
Frequency spectrum	1/3-octave band 6.3 Hz – 20 kHz	1/3-octave band* 6.3 Hz – 1 kHz
Equivalent sound pressure level (SPL), L_{Aeq}	Yes	Yes
Maximum sound pressure level (SPL), L_{AFmax}	Yes	Yes
Percentiles	Yes	No
Sound recording	Yes	Yes*
Remote monitoring	Yes	Yes
Remote acquisition of data	Yes	Yes

* When triggering a sound recording, frequency data up to 1000 Hz is obtained.

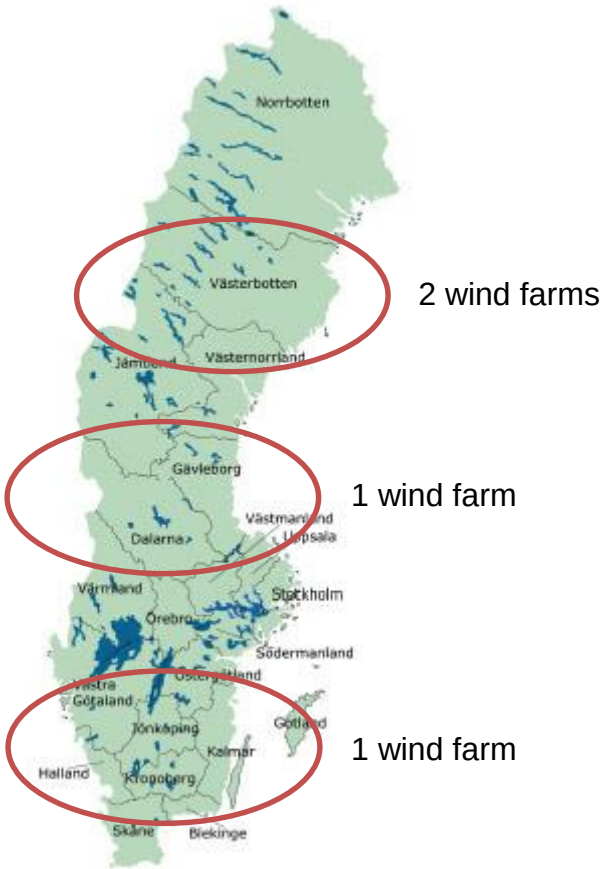

Figure 1 Measurement setup in one immission point, Sigicom Infra System.

Figure 2 Measurement setup in one emission point, Norsonic System.

2.1 Measurement objects The five measurement objects are horizontal axis WTs of various sizes (2-3 MW) and from different manufacturers. WT tower heights are around 100-120 m. Two of the WTs are equipped with passive de-icing systems.

2.2 Measurement sites The topography of the measurement sites are of relatively the same type; hilly with low to medium high pine forest and/or bushes, lower vegetation (rough grass) closer to the measurement object. During wintertime it's possible with large amounts of snow, specifically on the measurement sites located in the north of Sweden. The effects on sound propagation caused by snow on the ground are not fully known, however recent studies shows little influence for downwind conditions, (Larsson 2014).

Measurement site 1 – northern Sweden
Sound measurements were initiated 2013-12-11. Measurements are performed in sound emission measurement position on two different WTs. One of these is equipped with passive de-icing system. The measurements aim to quantify the effects on WT performance and noise emission due to de-icing capabilities. The measurement setup enables frequency analysis of measured sound. Probability of icing events during winter is considered very high.

Measurement site 2 – northern Sweden
Sound measurements were initiated 2013-12-12. Measurements are performed in sound emission measurement position on one WT, which is not equipped with a de-icing system. Measurements are also performed in a sound immission measurement position around 1000 meters from the WT. The measurements aim to quantify the effects on WT performance and noise emission due to icing, as well as studying the effect on the propagation of sound. The measurement setup does not enable frequency analysis of measured sound. Probability of icing events during winter is considered very high.

Measurement site 3 – middle of Sweden
Sound measurements were initiated 2013-12-17. Measurements are performed in sound emission measurement position on one WT which is equipped with a passive de-icing system. Measurements are also performed in a sound immission measurement position around 800 meters from the WT. The measurements aim to quantify the effects on WT performance and noise emission due to icing, as well as studying the effect on the propagation of sound. The measurement setup enables frequency analysis of measured sound. Probability of icing events during winter is considered high.

Measurement site 4 – south of Sweden
Sound measurements were initiated 2013-12-18. Measurements are performed in sound emission measurement position on one WT which is not equipped with a de-icing system. Measurements are also performed in a sound immission measurement position around 850 meters from the WT. The measurements aim to quantify the effects on WT performance and noise emission due to icing, as well as studying the effect on the propagation of sound. The measurement setup enables frequency analysis of measured sound. Probability of icing events during winter is considered moderate.

2.7 Wind turbine production data Along with the sound measurement data, concurrent (time-synchronized) WT production data is provided by a wind turbine control system as a continuous log. These, along with the power curve of each WT establish a relation between noise emission and power output. The wind turbine data are:

- Measured active (electric) power (kW)
- Wind speed measured by the nacelle anemometer (m/s)
- Wind direction (°)
- Rotor rpm (min^{-1})
- Rotor blade pitch angle (°)
- WT power curve (kW/(m/s))

These data are specified as 10-minute averages.

2.10 Weather data Weather conditions, such as atmospheric pressure and air temperature, effect 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. For some of the measurement sites data from local wind masts has been obtained, providing long-term data of the atmospheric pressure and the relative air humidity. The data contain:

- Ambient (air) temperature (°)
- Temperature gradient (°C/m)
- Atmospheric pressure (kPa)
- Relative air humidity (%)

3.0 Data analysis

Basic analysis To enable processing of vast amounts of measurement data, the analysis is performed solely in MATLAB. According to IEC 61400-11, there exists a strong correlation between the measured electric power and the measured sound pressure level (SPL) and the WT power curve holds the correlation between the wind speed at hub height and the electric power production. Thus, there is a correlation between measured SPL and wind speed at hub height. For the cases of the turbine actively producing electric power the analysis calculates wind speed in bins at around integers from 4 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)
$k = 4$	$3.5 \leq V_H < 4.5$
$k = 5$	$4.5 \leq V_H < 5.5$
$k = 6$	$5.5 \leq V_H < 6.5$
$k = 7$	$6.5 \leq V_H < 7.5$
$k = 8$	$7.5 \leq V_H < 8.5$
$k = 9$	$8.5 \leq V_H < 9.5$
$k = 10$	$9.5 \leq V_H < 10.5$

3.1 WT relative production As an indicator of potential and possible occurrence of ice on the WT rotor blades a parameter called WT relative production is introduced. It's a fact that ice accretion on WT rotor blades may cause power production losses of various magnitudes, a problem which is referred to as a degradation of the WT power curve. More specifically, this 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 P_m / P_D between measured electric power, P_m, and power production under reference conditions, P_D is a good indicator of degraded power production. For the purposes of this project, the WT relative production derived and defined 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. To utilize the power curve in-between the discrete values, a linear interpolation is performed. The work-flow may be explained as follows:

1. Using the standard power curve for the WT together with the measured electric power production, one may obtain the corresponding wind speed under reference conditions.
2. 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. This results in the WT relative production parameter.

The WT relative production parameter, V_H / V_n, may in a simplified manner be interpreted according to the table below. For individual WTs it can be shown that regular performance, during ice-free conditions, may well exceed unity (1). And vice versa, performance below unity does not always suggest degraded performance, i.e. due to ice-accretion on rotor blades.

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

4.0 Results & Discussion

4.1 Difference in apparent sound power levels Preliminary results show increases in measured SPL due to icing of around 5 dB during longer time periods to 10 dB for shorter occurrences. When utilizing 10-minute averaged data during analysis results are more conform, showing a typical increase of around 5 dB during icing events. When looking at 1- to 2-minute averaged data one may distinguish shorter periods with larger increases in measured SPL, up to 10 dB. A typical characteristic is a fluctuation of the SPL during icing events as can be seen in figure 3, showing a time period of 10 minutes with 1 second data.

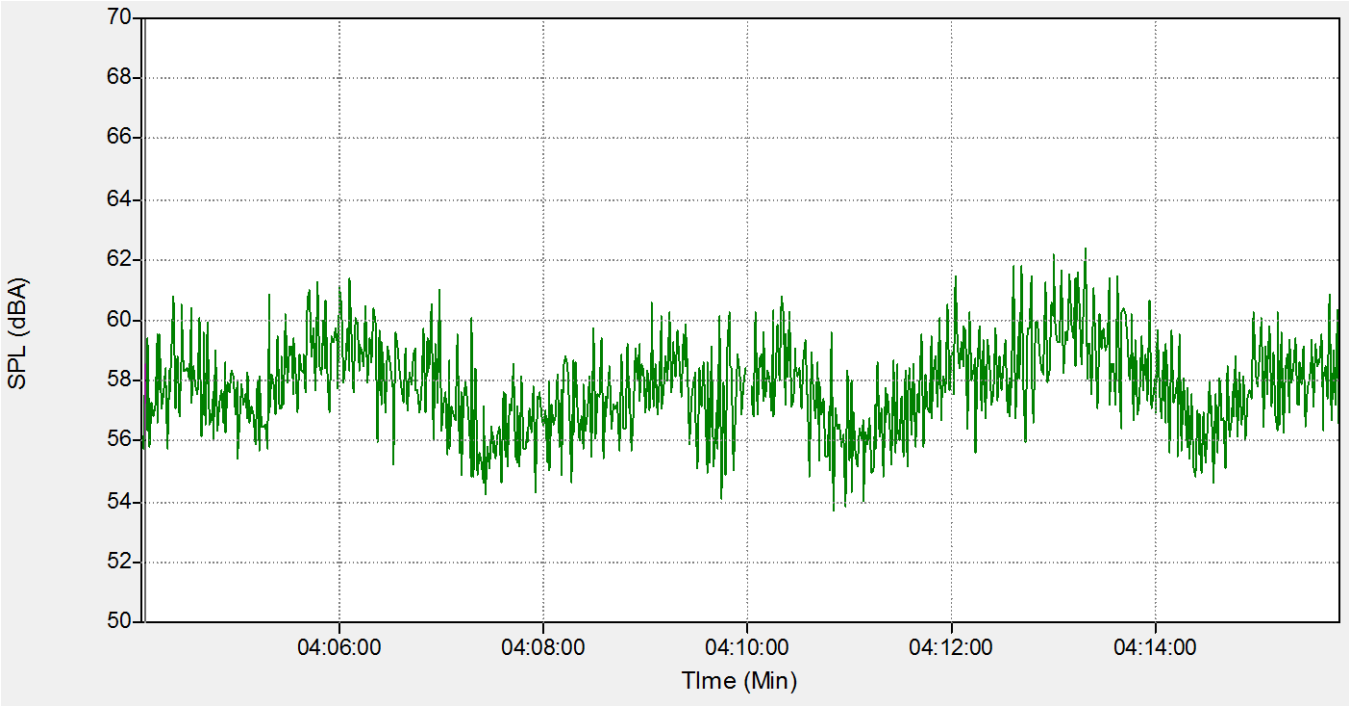

Figure 3 Measured 1 second SPL as a function of time showing the typical fluctuation in SPL during icing events.

Figure 4 below shows an example of a measured SPL of around 59 dBA at 9 m/s at 10 m height during an icing event at Measurement site 1 (emission measurement position). Figure 5 shows an example of a measured SPL of around 53 dBA at 8 m/s at 10 m height during ice-free conditions. Analysis is for the same WT at Measurement site 1 (emission measurement position) for similar wind speed and wind direction). This indicates an increase of around 6 dB due to icing of the rotor blades for this example.

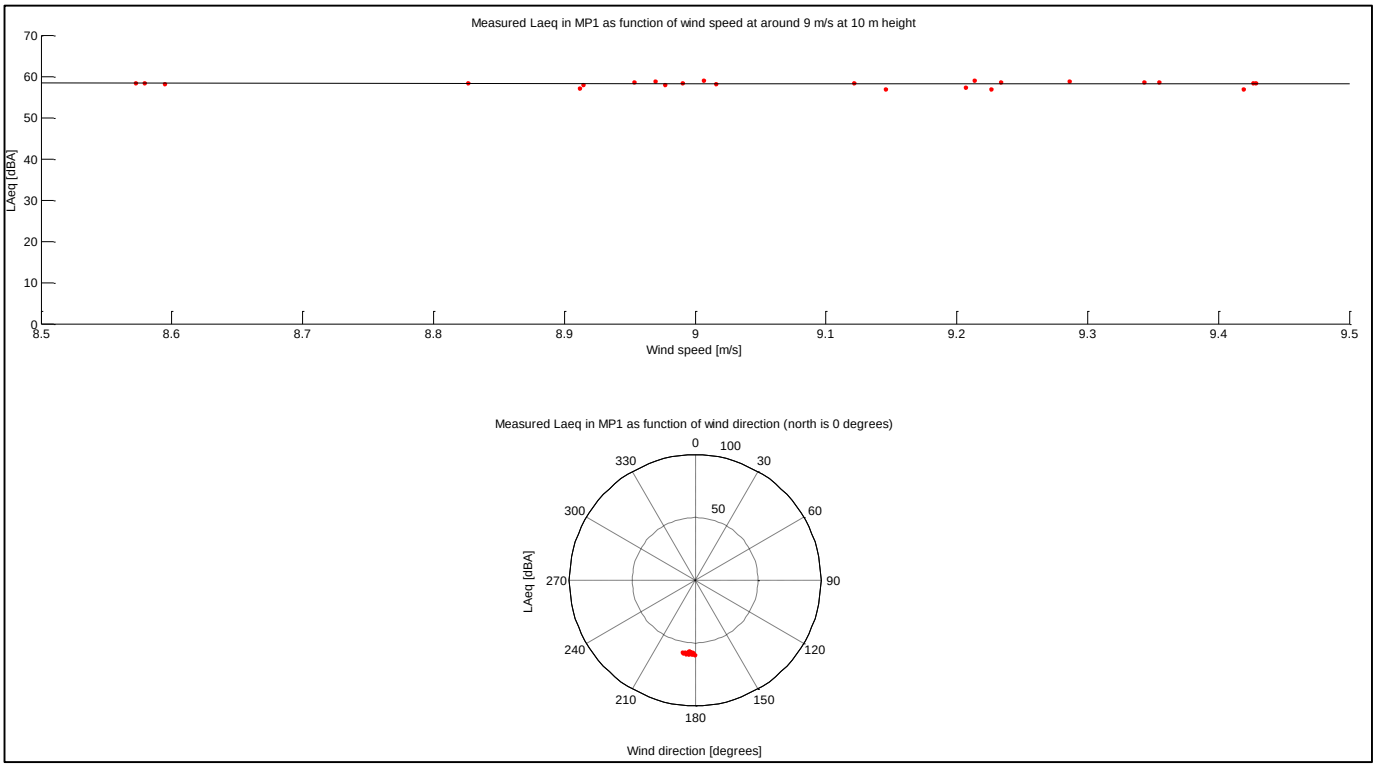

Figure 4 Measured SPL of around 59 dBA at 9 m/s at 10 m height

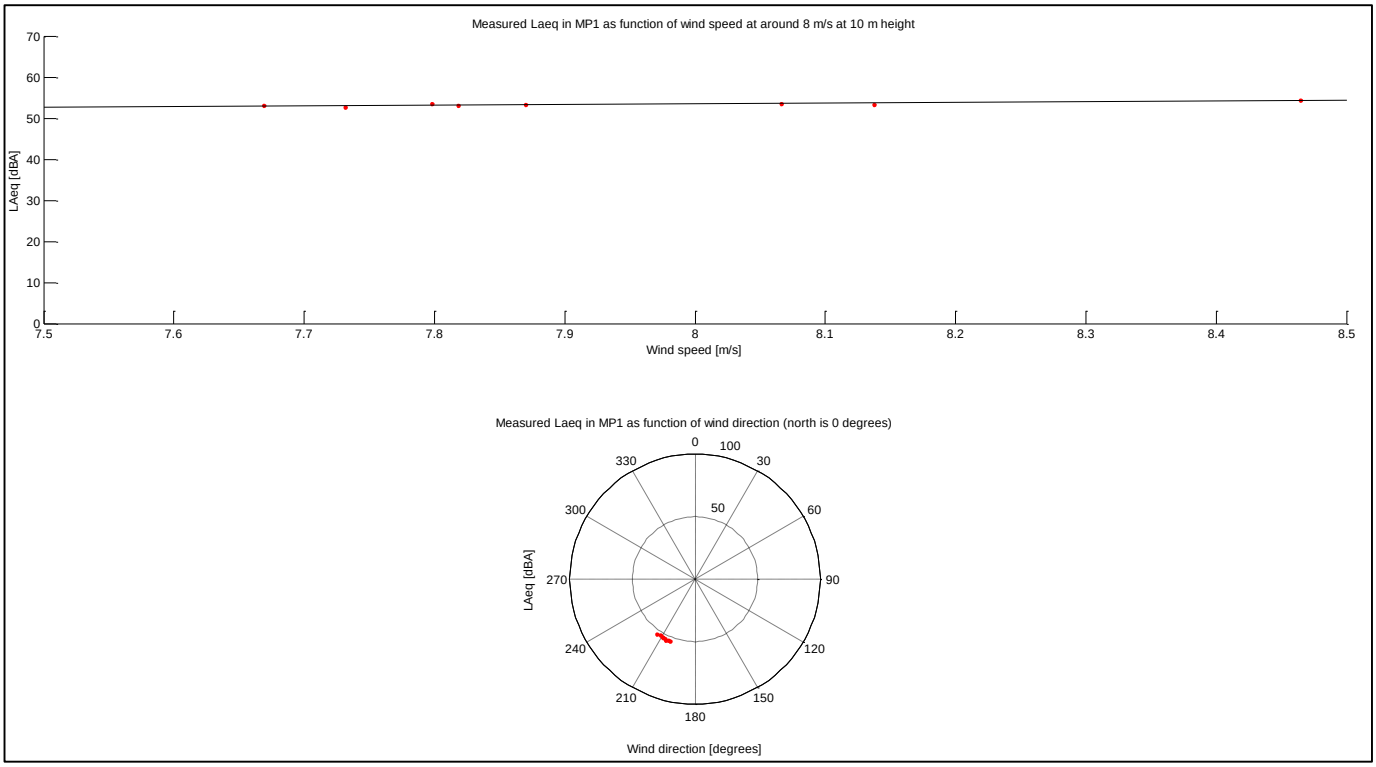

Figure 5 Measured SPL of around 53 dBA at 8 m/s at 10 m height

Important to remember when performing analyzes is to keep as many parameters as possible constant, or at least within certain boundaries, this to be able to compare one result to another. To manage vast quantities of data various filtering functions are required to keep the data structured. Various filtering criteria are applied to non-acoustic data to enable an evaluation of the ice accretion on the wind turbine, and to correlate this to sound emission.

When analyzing data from different time periods one must assume that certain measurement conditions remain constant. The following conditions are assumed constant and unchanged:

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

These assumptions enable a simple subtraction of measured SPLs between time periods with icing conditions and time periods with ice-free conditions.

4.2 Frequency characteristics and estimated transmission loss The sound with ice on the rotor blades has typical high frequency characteristics which can also be seen in the frequency spectrum. In figure 6 an example of two frequency spectrums, 10 minute averages, with and without ice are shown. The difference in SPL in this example is 10 dBA and the wind speed is 6 m/s at 10 m height. What is also noticeable is that the low frequencies with ice are reduced compared to the case without ice, this is consistent locking at other periods.

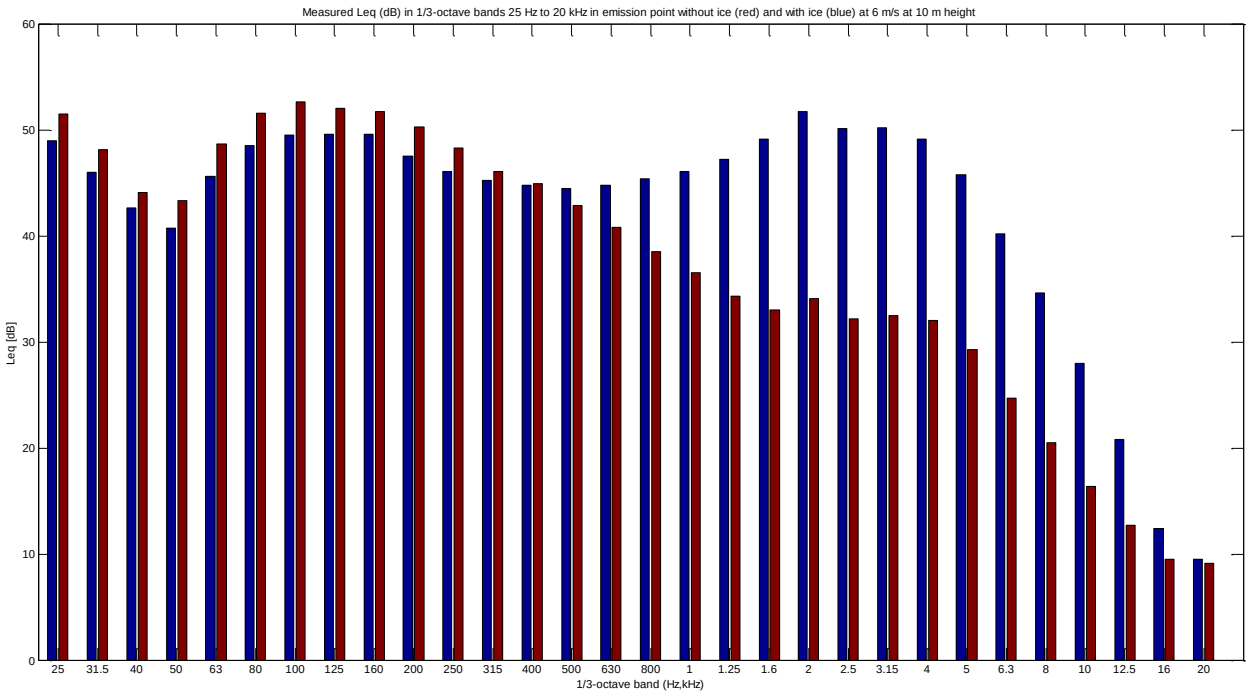

Figure 6 1/3-octave band spectrums with and without ice for the wind speed 6 m/s, difference in SPL is 10 dBA.

The frequency characteristics will also influence the transmission loss (TL) and thus the immission level, for example at nearby dwellings. To illustrate this calculations of the difference in SPL for a simple situation are performed with the 1/3-octave band spectrums in figure 6. The calculations are done for downwind conditions using the Nordic prediction method Nord2000, implemented in the SoundPlan 7.3 software. One wind turbine with a hub height of 100 m is assumed as well as typical conditions when ice accretion could be expected, for example snow cover on the ground, a temperature of 0°C and a relative humidity of 90%. The result is presented in Figure 7 as the difference in SPL with and without ice for the two frequency spectras in figure 6.

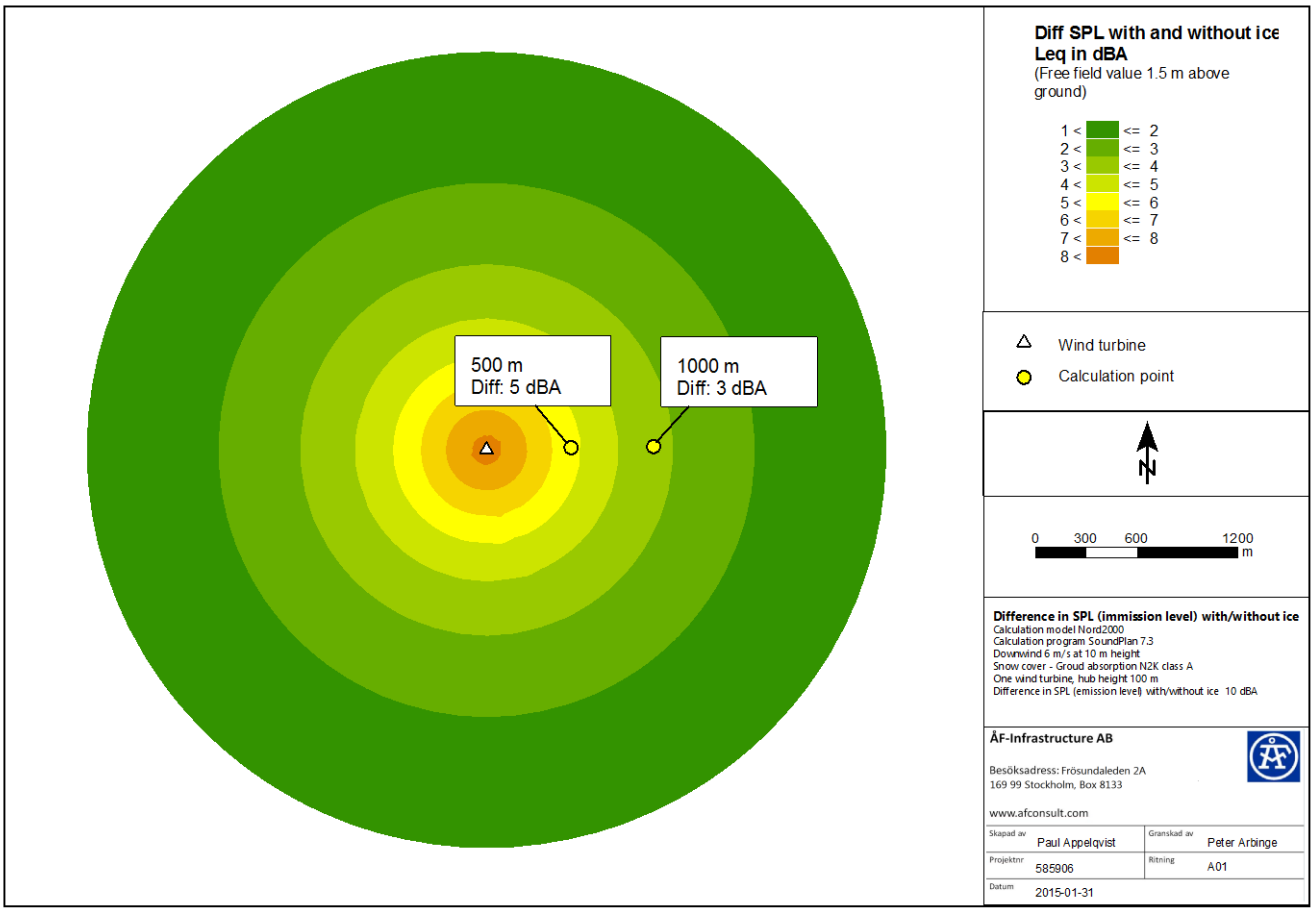

Figure 7 Noise map showing the difference in SPL with and without ice, also presented in detail for 500 m and 1000 m from the sound source.

The conclusion from the calculations and the noise map in figure 7 is that the TL decreases with distance for the ice situation compared to no ice. This was also expected locking at the high frequency contribution that can be seen with ice on the rotor blades. The difference in SPL which was 10 dBA in the emission point is only 5 dBA at 500 m from the source and 3 dBA at 1000 m. Thus although a high increase of SPL at the source can be seen this increase is not automatically transferred to greater distances, which is important for noise permits. The increase can still be noticeable to nearby residents both as a level increase and for the change in noise characteristics.

To make a good approximation of the increase in SPL due to ice accretion, using an existing noise emission spectrum, the example values in the table below can be added to the spectrum when performing noise calculations. This represents a 10 dBA increase that could be expected for shorter time periods with extensive icing on the rotor blades. A more general spectrum will be presented when all measurements has been analyzed.

Example of SPL difference with and without ice applicable for noise calculations.

25 Hz	31,5 Hz	40 Hz	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz	200 Hz
-2,5	-2,1	-1,5	-2,6	-3,1	-3,1	-3,1	-2,4	-2,1	-2,8
250 Hz	315 Hz	400 Hz	500 Hz	630 Hz	800 Hz	1 kHz	1,25 kHz	1,6 kHz	2 kHz
-2,2	-0,9	-0,1	1,6	4,0	6,9	9,6	12,9	16,1	17,6
2,5 kHz	3,15 kHz	4 kHz	5 kHz	6,3 kHz	8 kHz	10 kHz	12,5 kHz	16 kHz	20 kHz
17,9	17,7	17,1	16,5	15,5	14,1	11,6	8,1	2,9	0,4

4.3 Measured transmission loss Although no conclusion has yet been made on this topic, preliminary results show that depending on wind conditions the sound propagation varies greatly from WT to immission measurement position. Figure 8 (upper graph) shows an SPL of around 59 dBA, measured in the emission measurement position at wind speeds 6 m/s to 10 m/s at 10 m height during an icing event at Measurement site 2. These results would indicate an increase

in WT sound emission by around 5 dB due to icing. Figure 8 (lower graph) shows an SPL of around 37 dBA, measured in the immission position at wind speeds 6 m/s to 10 m/s at 10 m height during the same icing event at Measurement site 2. This position has been calculated to have an equivalent SPL of around 40 dBA, but the measured result is around 3 dB below. This with consideration taken to the 5 dB increase in WT sound emission.

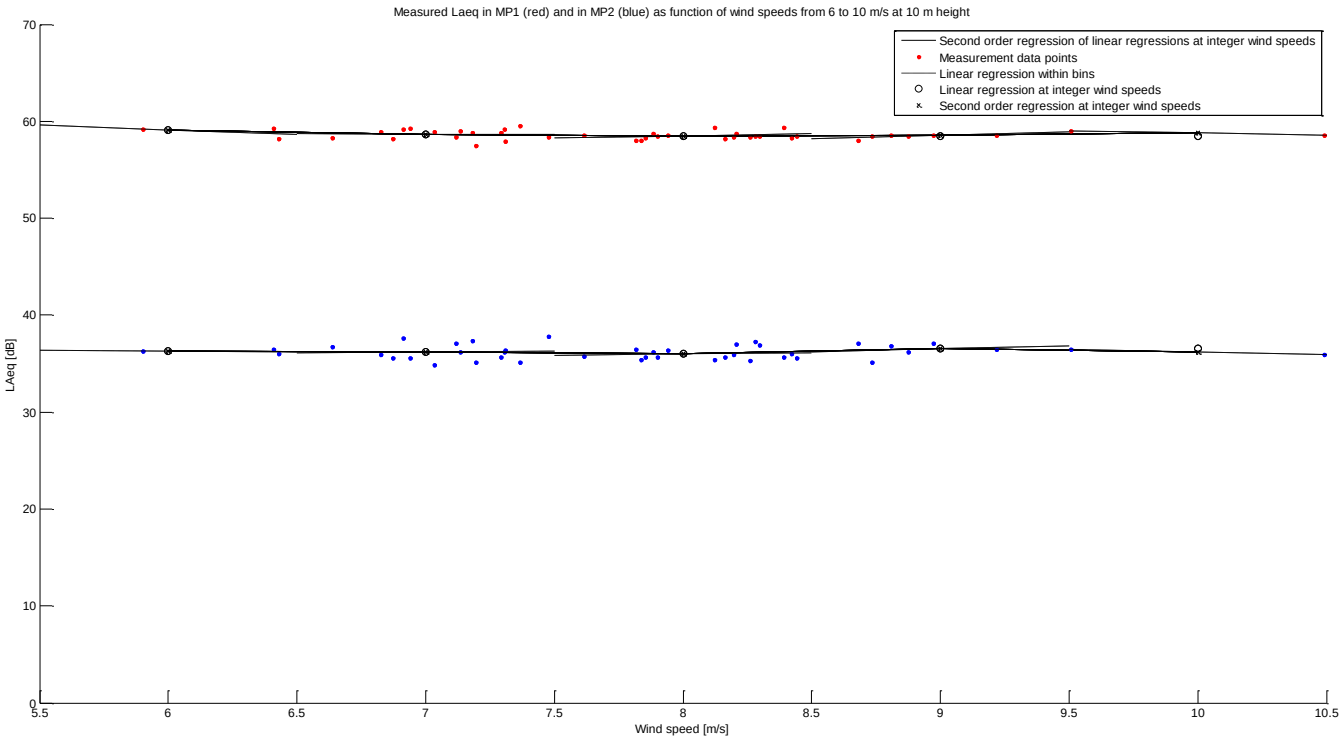

Figure 8 Comparison of immission and emission measured SPL.

Meteorological factors play an important role in sound propagation and further investigations will yield more precise results and conclusions. The main conclusion that will be further investigated is that, due to the high frequency contribution during icing, the same increase in SPL that are measured in the emission point cannot be directly transferred to an immission point on a longer distance. This is also indicated by the calculations presented in chapter 4.2.

5.0 Conclusions

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

1. Preliminary results show that ice accretion on wind turbine rotor blades may lead to increases in sound emission of typically around 5 dB, during longer time periods, up to 10 dB for shorter moments. Data averaging times affect the conformity of the results. 10-minute averaged data yields more conform results revealing data trends while 1- to 2-minute averaged data reveals more momentaneous peaks in SPL data.

2. Ice on rotor blades gives an increased SPL mainly in higher frequencies. This also influence the transmission loss meaning that the same increase in SPL as measured in the emission point cannot be expected at longer distances. The transmission loss decreases with distance as exemplified by calculations. Although nearby residents could probably recognize an increase in SPL as well as a change in sound characteristics during icing events.

The measurements and the analysis in the project are ongoing and are planned to be finished in early spring 2015, this result will also include the comparison for WT with and without passive de-icing systems.

References

Larsson, C (2014) *Ljud från vindkraftverk, modellvalidering-mätning, Slutrapport Energimyndigheten projekt 32437-1*